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SOLID ELECTROLYTE OXYGEN REGENERATION SYSTEM

INTERIM REPORT

by

J.W. Shumar, G. G. See, F. H. Schubert
and J. D. Powell

July, 1976

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Prepared Under Contract No. NAS2-7862

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

AMES RESEARCH CENTER
National Aeronautics and Space Administration
Moffett Field, California 94035

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

The development described in this report was performed by Life Systems, Inc. under NASA Contract NAS2-7862. The work was performed during the period beginning September 26, 1973 through March 31, 1976. The Program Manager was J. W. Shumar. Technical support was provided as follows:

Personnel	Area(s) of Responsibility
Gary G. See	Mechanical design
J. David Powell	Electrical design
Franz H. Schubert	Mechanical and system design
Glenn A. Little	Ground Support Accessories layout and fabrication, and component testing
Rick A. Wynveen, PhD	Program administration, electrochemical support
Kamal K. Kacholia	Chemical engineering support

The contract's Technical Monitor was P. D. Quattrone, Chief, Environmental Control Research Branch, NASA Ames Research Center, Moffett Field, CA with assistance from Layton Ingelfinger, NASA Ames Research Center.

The solid electrolyte oxygen regeneration concept was based upon the work performed by Applied Electrochemistry, Inc., Sunnyvale, CA, in designing, developing, fabricating and delivering the solid electrolyte cells for incorporation into the Solid Electrolyte Oxygen Regeneration System. This work was conducted under NASA Contracts NAS2-4843 and NAS2-6412.

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SUMMARY

A program to design, develop, fabricate and assemble a One-Man, Self-Contained, Solid Electrolyte Oxygen Regeneration System (SX-1) incorporating solid electrolyte electrolyzer drums that were designed, developed, fabricated and tested under Contracts NAS2-2810, NAS2-4843, and NAS2-6412 was completed. The SX-1 is a preprototype engineering model designed to produce 0.952 kg (2.1 lb)/day of breathable oxygen (O_2) from the electrolysis of metabolic carbon dioxide (CO_2) and water vapor. The CO_2 supply rate was established based on the metabolic CO_2 generation rate for one man of 0.998 kg (2.2 lb)/day. The water supply rate (0.254 kg (0.56 lb)/day) was designed to be sufficient to make up the difference between the 0.952 kg (2.1 lb)/day O_2 generation specification and the O_2 available through CO_2 electrolysis, 0.726 kg (1.6 lb)/day. The SX-1 was successfully designed, fabricated and assembled. Design Verification Tests (DVT) or the CO Disproportionators, H_2 Separators, Control Instrumentation, Monitor Instrumentation, Water Feed Mechanism were successfully completed. The erratic occurrence of electrolyzer drum leakage prevented the completion of the CO_2 Electrolyzer Module and Water Electrolyzer Module DVT's and also prevented the performance of SX-1 integrated testing. Further development work is required to improve the solid electrolyte cell high temperature seals.

The SX-1 was designed with electronic Control and Monitor Instrumentation to carry out operating mode change sequences, regulate performance, analyze and display performance trends and detect faults.

Other major components that were designed, fabricated, assembled, tested, and incorporated into the SX-1 include the Carbon Monoxide (CO) Disproportionators in which CO is converted to CO_2 and solid carbon, Hydrogen (H_2) Separators which remove excess H_2 from the SX-1 feed gas and recycle loop gas, a high temperature Recycle Loop Bellows Pump which provides the recycle loop gas flow, Hot Gas Valves which allow servicing of the CO Disproportionators, and a Water Feed Mechanism which provides the water vapor for the Water Electrolyzer Module at a stable steam flow rate.

The Ground Support Accessories (GSA) required to test the SX-1 were designed, fabricated, assembled and functionally checked out. The GSA were designed to simulate the actual spacecraft interfaces for three candidate CO_2 removal systems: the Electrochemical Depolarized Concentrator (EDC), the Molecular Sieve and the Steam-Desorbed Solid Amine. The GSA consisted of a Fluid Supply Unit (FSU), a Space Vacuum Simulator (SVS), a Gas Products Monitor (GPM), a Ground Checkout Unit (GCU), component checkout stands and a Carbon Deposition Cartridge (CDC) activation facility.

A Product Assurance Program incorporated quality assurance, reliability, maintainability, safety and materials control. Activities included conducting design review meetings, preparing a Failure Mode Effects and Criticality Analysis (FMECA), preparation of safety design criteria, and monitoring of system design and fabrication with regard to quality control maintainability and materials compatibility.

Program testing consisted of performing component checkout tests and major component DVTs.

- The CO Disproportionator was successfully tested for 28 days at operating temperatures ranging from 773 to 843K (932 to 1058F) and at feed gas flow rates from 683 sccm (0.02 scfm) to 3670 sccm (0.13 scfm). The CO Disproportionator conversion efficiency exceeded the design goal of 36%.

- The H_2 Separators were successfully tested at temperatures from 611 to 650K (640 to 711F). The feed gas H_2 Separator exceeded the design H_2 removal rate goal by 67% and the recycle loop H_2 Separator exceeded the design H_2 removal rate goal by 27%.

- The Water Feed Mechanism was successfully tested for 60 hours at its design operating temperature. The Water Feed Mechanism delivered steam in a stable flow mode at feed rates up to 1.8 times the design water vapor feed rate of 0.245 kg (0.54 lb)/day.

- The Control Instrumentation mode transition sequences and control functions were tested. All mode transitions were successfully accomplished and all control functions performed satisfactorily at their design points.

- The Monitor Instrumentation was tested by simulating sensor outputs from the SX-1 and verifying the Monitor Instrumentation setpoints that were set for the individual printed circuit (PC) cards.

- Leak tests were performed on the electrolyzer drums that were produced under NAS2-6412. The results indicated that several of the drums leaked. This erratic occurrence of electrolyzer drum leakage prevented the performance of integrated SX-1 testing.

- Other testing successfully completed included checkout tests on the Hot Gas Valves at their operating conditions, checkout tests on all SX-1 off-the-shelf components including valves, pressure transducers, pressure regulators, thermocouples, thermistors and flow restrictors.

As part of parallel technology activities, the methods for analyzing the SX-1 recycle loop and product gases were established and a computer program for calculating the gas composition at various points in the SX-1 recycle loop was developed.

INTRODUCTION

There is a definite need for systems that can recover oxygen (O_2) from metabolically produced carbon dioxide (CO_2) for future extended duration manned spaceflights. Such a system could reduce flight weight by eliminating the need for carrying stored O_2 (in the form of water or equivalent) at launch.

Several concepts which partially or completely perform this function have been proposed and studied. Some of these are the Fused Salt concept, the Solid Electrolyte concept, the Bosch Reactor concept, the Sabatier-Methane Dump concept, the Sabatier-Methane Decomposition concept, and the Sabatier-Acetylene Dump concept. The results of the study[1] for evaluating and selecting life support systems for a 500-day non-resupply mission revealed that the most promising route for O_2 recovery from CO_2 was electrolysis using solid oxide electrolyzers and Carbon Monoxide (CO) Disproportionators with replaceable cartridges. Several features of the Solid Electrolyte concept led to its selection. The Solid Electrolyte Oxygen Regeneration System (SEORS) combines the function of two separate subsystems that are required in alternate Oxygen Regeneration Systems (ORS); a CO_2 Reduction Subsystem such as a Bosch or Sabatier reactor and an Oxygen Generation Subsystem (water electrolyzer). In the solid electrolyte concept, both CO_2 reduction and water electrolysis are carried out in the solid electrolyte electrolyzer cells. As a result, an ORS based on the solid electrolyte concept has a low equivalent weight, a minimum of interfaces, simplified instrumentation and an absence of condensor separators.

Background

The concept of O_2 ion transfer through solid electrolytes was first investigated by Nernst and Reynolds in the early 1900's.[2] However, it was only recently that the unusual electrical properties of solid electrolytes had been put to practical use. This is generally attributed to the recent development of high temperature materials and sealing techniques which are required for the application of products based upon the solid electrolyte concepts.

Initial work involving the application of solid electrolyte cells for O_2 regeneration was carried out by Chandler and Pollara[3] in the early 1960's. They built and operated a system that produced 150 cc/min (5.3×10^{-3} cfm) O_2. The life of their system was short and a deterioration in the catalytic activity of their carbon deposition reactor was observed.

More recently Weissbart and Smart,[4] conducted investigations on alternate solid electrolyte materials and also designed, developed, fabricated and tested electrolyzer drums based on a flat plate solid electrolyte configuration.[5,6] A six-drum, 12-cell, 24-ampere electrolyzer module was operated continuously for over 2,000 hours. The Faradaic current efficiency was 100% and O_2 produced contained less than 0.4% CO_2 as an impurity.[7] The test program included the integration of the electrolyzer module with a carbon deposition reactor.

Elikan and co-workers, during the same time period, designed, developed, fabricated and tested multicell electrolysis batteries, a carbon deposition reactor and palladium (Pd) foil hydrogen (H_2) diffusers. The electrolysis batteries of the "bell and spigot" design, as well as the continuous carbon deposition reactor, operated independently for periods exceeding 100 days.[8]

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(1) Numbers in parentheses are references found at the end of this report.

Subsequent to this work, a 1/4-man SEORS, consisting of an electrolyzer with "bell and spigot" cells, a carbon deposition reactor and Pd H_2 Separator were designed, fabricated and tested.[9] The system was operated for 180 days. However, the O_2 purity decreased with operating time. The major impurity in the O_2 was CO_2 with lesser amounts of water, nitrogen (N_2) and CO. The SAE Bioenvironmental Systems Advisory Committee, in a study of alternate methods for reclaiming O_2 from CO_2, attributed the relatively high CO_2 content in the product O_2 to the questionable adequacy of the "bell and spigot" cell sealing techniques.

System Description

A block diagram which describes the One-Man, Self-Contained, Solid Electrolyte Oxygen Regeneration System (SX-1) operation and depicts the major SX-1 components is shown in Figure 1. The major components are the CO_2 and Water Electrolyzer Modules which convert CO_2 and water into CO and O_2, and H_2 and O_2, respectively; the CO Disproportionators in which CO is converted into CO_2 and solid carbon; H_2 Separators which remove excess H_2 from the SX-1 feed gas and recycle loop gas; a high temperature Recycle Loop Bellows Pump which provides the recycle loop gas flow; Hot Gas Valves which allow servicing of the CO Disproportionators, and a Water Feed Mechanism which provides the water vapor for the Water Electrolyzer Module at a stable steam flow rate. The SX-1 also incorporated electronic Control and Monitor Instrumentation to carry out operating mode change sequences, regulate performance, analyze and display performance trends and detect faults.

Program Objectives

The objective of this program was to design, develop, fabricate, assemble and test an SX-1, incorporating electrolyzer drums that were designed, developed and fabricated under Contracts NAS2-2810, NAS2-4843 and NAS2-6412. 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, develop, fabricate and assemble a one-man, preprototype engineering model of the SX-1. This task included (a) defining the system and its operating modes, (b) designing, fabricating, and assembling CO_2 and Water Electrolyzer Modules, CO Disproportionators, H_2 Separators, Control and Monitor Instrumentation, Hot Gas Valves, valves, regulators and transducers, and (c) designing the system packaging to ensure optimum system performance, maintainability, safety and reliability.

2. Design, fabricate, assemble and functionally check out the Ground Support Accessories (GSA) required for performing the parametric and endurance test on the system. The GSA consists of:

    a. A Fluid Supply Unit (FSU) which contains the valves, flowmeters and pressure regulators required to control the H_2, CO_2, water, N_2 and O_2 supplies required to simulate the interface from three CO_2 Collection Systems: The Electrochemical Depolarized Concentrator (EDC), the Steam-Desorbed Solid Amine and the Molecular Sieve

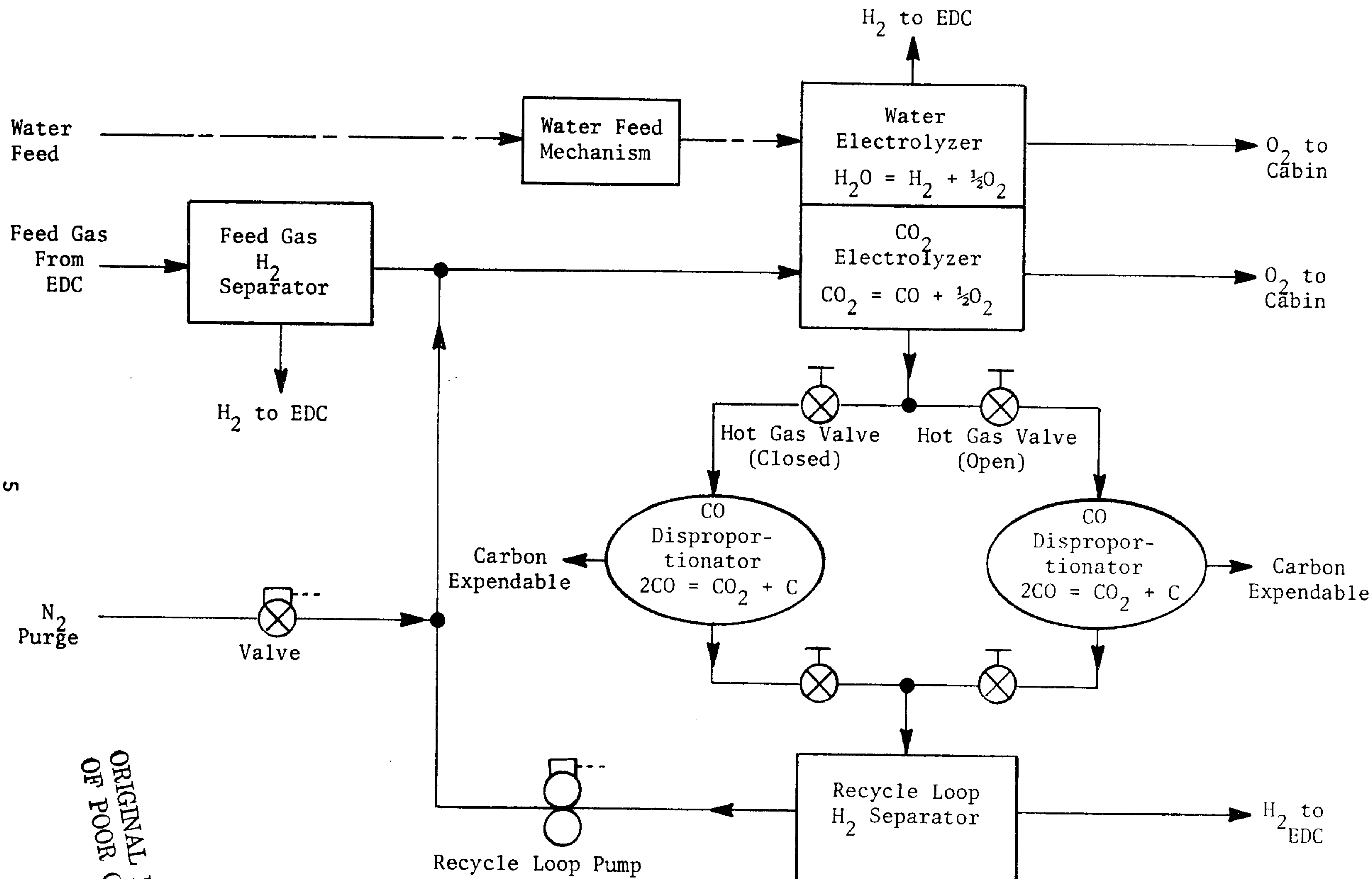

FIGURE 1 SOLID ELECTROLYTE OXYGEN REGENERATION SYSTEM

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b. A Space Vacuum Simulator (SVS) which contains the vaccum pumps, pressure gauges and traps required to simulate H_2 venting to space vacuum

c. A Gas Products Monitor (GPM) which includes H_2 and O_2 flow, pressure, temperature and purity monitoring provisions

d. A Ground Checkout Unit (GCU) which consists of meters, switches and displays required to measure system performance in engineering units

e. A Carbon Deposition Cartridge (CDC) activation facility

f. Component checkout stands

3. Conduct a Product Assurance Program to ensure that the concepts of quality control, maintainability, safety and reliability were incorporated into the design and fabrication of the SX-1.

4. Conduct the program testing including component checkouts, calibration and Design Verification Tests (DVT).

5. Carry out supporting studies associated with the SX-1 system development. Supporting studies consisted of establishing analytical methods for analyzing the feed gases, the recycle loop gases and product gases.

The following sections summarize the results of the program and the conclusions and recommendations reached.

SX-1 SYSTEM DESIGN

System Function

The function of the SX-1 is to generate 0.952 kg (2.1 lb) of breathable O_2/day. This is accomplished by electrolyzing the metabolic CO_2 produced by one man, 0.998 kg (2.20 lb/day) and water vapor that is available from the spacecraft Water Management System and from water vapor carried by the exhaust of the CO_2 Collection System. The O_2 obtained from the electrolysis of the metabolic CO_2 is 0.726 kg (1.6 lb/day). To supplement this, 0.254 kg (0.56 lb/day) of water is electrolyzed to yield 0.22 kg (0.5 lb/day) of O_2. The net reactions describing the electrolysis of CO_2 and water are

$$CO_2 = CO + \tfrac{1}{2}O_2 \tag{1}$$

and

$$H_2O = H_2 + \tfrac{1}{2}O_2 \tag{2}$$

As a result of the CO and H_2 produced in the electrolysis reaction, it is necessary to include a CO Disproportionator and a H_2 Separator in the recycle loop of the SX-1. The function of the CO Disproportionator is to convert CO produced in Reaction 1 to CO_2 and solid carbon. This ensures the maximum recovery of O_2 from the CO_2. The reaction taking place in the CO Disproportionator is

$$2CO = CO_2 + C \qquad (3)$$

The solid carbon is collected in replaceable cartridges which are discarded. The function of the H_2 Separator is to remove H_2 from the recycle loop. Hydrogen is introduced into the recycle loop in two ways: (1) it is carried along by the exhaust of the CO_2 Collection System, and (2) it is created in the CO_2 Electrolyzer Modules by electrolysis of water vapor carried along by the feed gases. It is important that the excess H_2 be removed from the recycle loop, otherwise it would accumulate and cause an increase in loop pressure and dilute the volume percentage of CO_2 in the electrolyzer. Eventually the SX-1 would experience a high CO_2 electrolyzer drum voltage shutdown caused by H_2 blanketing the cathode or a high pressure shutdown.

System Capacities

The capacities and operating characteristics of the SX-1 are described in the system design specifications presented in Table 1. This data is based on the SX-1 interfacing with an EDC CO_2 Collection System. A system block diagram showing components and system interfaces based on interfacing with the EDC CO_2 Collection System was shown in Figure 1. The SX-1 was designed to be capable of operating with the feed gas interfaces from three CO_2 Collection Systems: EDC, Molecular Sieve and Steam-Desorbed Solid Amine. Table 2 lists the interfaces for the three CO_2 Collection Subsystems.

System Schematic

The SX-1 system schematic is shown in Figure 2. The major components of the system are an Electrolyzer Subassembly containing a Water Electrolyzer Module and three CO_2 Electrolyzer Modules, a Water Feed Mechanism, two CO Disproportionators, Recycle Loop Bellows Pump, two H_2 Separators, four Hot Gas Valves, Control and Monitor Instrumentation, and a N_2 Purge System.

Water Electrolyzer

Water from the GSA is supplied through the deionizer, DE101, and solenoid valve, SV101, to the Water Feed Mechanism, FB101. The Water Feed Mechanism is a zero gravity design that utilizes a flash orifice and a pre-heater and super-heater section to convert the water to water vapor for entry into the Water Electrolyzer Module. The water vapor is decomposed in the water electrolyzer. The net reaction is

$$H_2O = H_2 + \tfrac{1}{2}O_2 \qquad (4)$$

TABLE 1 SYSTEM DESIGN SPECIFICATIONS[a]

Number of Crew (Continuous)	1
Oxygen Produced, kg/s (Lb/Day)	
From CO_2 Electrolysis	8.502×10^{-6} (1.618)
From Water Electrolysis	2.533×10^{-6} (0.482)
Total	11.035×10^{-6} (2.100)
Oxygen Purity, %	
CO_2	<0.5
CO	None Detectable
Hydrogen Produced, kg/s (Lb/Day)	
From Water Electrolyzer	0.315×10^{-6} (0.060)
Separated from Recycle Loop	0.074×10^{-6} (0.014)
Separated from Feed Gas	0.100×10^{-6} (0.019)
Total	0.489×10^{-6} (0.093)
Hydrogen Purity (excluding water vapor), % H_2	>98
Carbon Produced, kg/s (Lb/Day)	3.158×10^{-6} (0.601)
Feed Gas Composition, kg/s (Lb/Day)[a]	
CO_2	11.560×10^{-6} (2.200)
H_2	0.163×10^{-6} (0.031)
Water	0.105×10^{-6} (0.020)
Water Supply	
Flow Rate, kg/s (Lb/Day)	2.848×10^{-6} (0.542)
Pressure, N/m^2 (Psia)	31.030×10^4 (45)
Temperature, K (F)	277.6 to 291.5 (40 to 65)
Nitrogen Purge Supply Pressure, N/m^2 (Psia)	31.030×10^4 (45)
Recycle Loop	
Pressure, N/m^2 (Psia)	10.3×10^4 to 11.0×10^4 (15 to 16)
Flow, m^3/s (Slpm)	5.1×10^{-5} (3.08)
Cabin Atmosphere	
Total Pressure, N/m^2 (Psia)	10.1×10^4 to 10.4×10^4 (14.7 to 15.2)
Temperature, K (F)	291.5 to 297.0 (65 to 75)
Dew Point Temperature, K (F)	280.9 to 287.0 (46 to 57)
O_2 Partial Pressure, N/m^2 (Psia)	2.1×10^4 to 2.3×10^4 (3.04 to 3.28)
Heat Rejection Sink	Ambient Air
Purge Sink	Vacuum

(a) Based on EDC interface.

TABLE 2 CO_2 COLLECTION SUBSYSTEM INTERFACES

	Flow Rate, kg/s (Lb/Day)	Percent
EDC		
CO_2	11.56×10^{-6} (2.200)	97.8
H_2	0.16×10^{-6} (0.031)	1.4
Water	0.10×10^{-6} (0.019)	0.8
Molecular Sieve		
CO_2	11.56×10^{-6} (2.200)	99.0
O_2	0.02×10^{-6} (0.004)	
N_2	0.08×10^{-6} (0.016)	1.0
Water	Trace (Trace)	
Steam Desorbed Solid Amine		
CO_2	11.56×10^{-6} (2.200)	94.4
O_2	0.05×10^{-6} (0.010)	0.5
N_2	0.26×10^{-6} (0.050)	2.1
Water	0.37×10^{-6} (0.070)	3.0

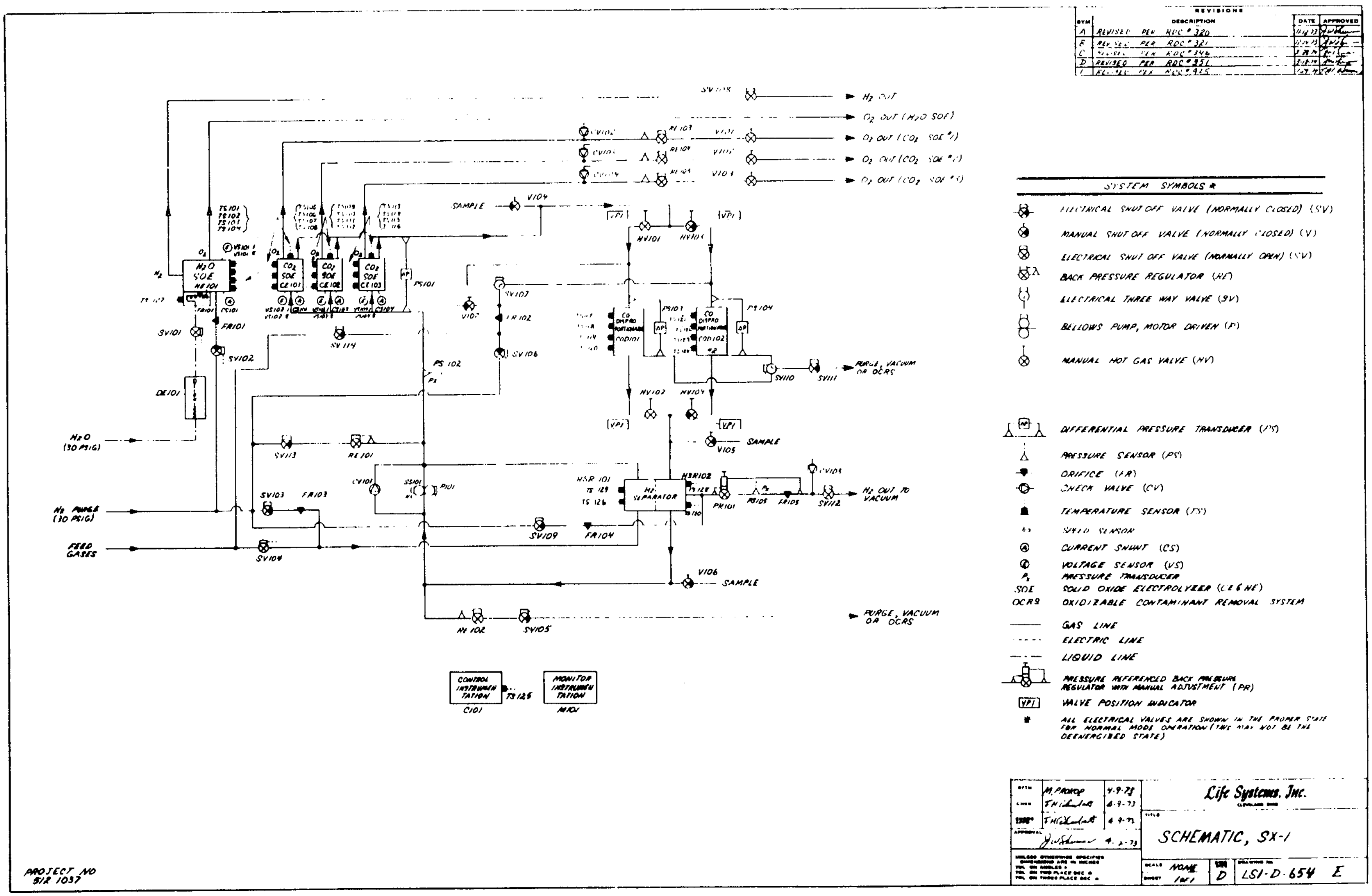


FIGURE 2 SX-1 SCHEMATIC

The water electrolyzer is designed so that the required water flow into the system is electrolyzed once through, thereby eliminating the need for a condenser/separator or a water recycle loop. From the water electrolyzer, the product O_2 is plumbed directly to the SX-1 exhaust gas interface; byproduct H_2 is plumbed through a solenoid valve, SV108, to the SX-1 exhaust gas interface.

Carbon Dioxide Electrolyzer and Recycle Loop

The feed gases are introduced through solenoid valve SV104 which remains open during normal operation. The recycle loop control technique has been designed to handle the expected fluctuations in feed gas flow from the EDC CO_2 Collection System. The CO_2 electrolyzer current will vary, dependent on recycle loop pressure as sensed by pressure transducer PS102. Increases in the flow rate of electrolyzable gases (CO_2 and water) to the system are compensated for in this manner. The gas flow is directed to the H_2 Separator, HSR101, where the excess H_2 in the feed gas is removed by selective diffusion through palladium/silver (Pd/Ag) tubes. The gas is then plumbed into the recycle loop and directed to the CO_2 Electrolyzer Modules where CO_2 and the water vapor present in the recycle loop are electrolyzed. The net reactions are

$$CO_2 = CO + \tfrac{1}{2}O_2 \qquad (5)$$

and

$$H_2O = H_2 + \tfrac{1}{2}O_2 \qquad (6)$$

It is important to maintain a minimum of 3% water vapor and/or H_2 in the CO_2 electrolyzers since the presence of water vapor in the CO_2 Electrolyzer Module acts as a catalyst for the cathode reaction.[10] Hydrogen has a similar catalytic effect; therefore, any combination of H_2 and water vapor equaling 3% of the feed gas composition to the CO_2 Electrolyzer Modules will catalyze the reaction.[11] The presence of H_2 and/or water is maintained at 3% minimum by knowing the feed gas composition and by proper sizing of the H_2 Separator, HSR101. The recycle loop gases are then plumbed into the "on line" CO Disproportionator, COD101 or COD102. Since the CO disproportionation reaction

$$2CO = CO_2 + C \qquad (7)$$

results in the formation of solid carbon which is collected in expendable CDCs, provisions are made to direct the recycle loop gas flow to alternate reactors. In this manner, the spent CDC can be removed and replaced without interrupting system operation. Hot Gas Valves HV101, HV102, HV103 and HV104 are manually operated to direct recycle loop gas flow to the desired CO Disproportionator. Since the off-line reactor will contain hazardous CO and H_2, provisions have been made to evacuate and N_2 purge the reactor prior to changing the CDC. Electrical three-way valve, SV110, is used to select the reactor to be evacuated. On signal from the Control Instrumentation, solenoid valve SV111 is opened, thereby exposing the spent CO Disproportionator to vacuum.

After evacuation is complete, solenoid valve SV111 is closed. Prior to initiating cartridge change, the evacuated reactor is then filled with N_2 by opening solenoid valve SV106 and configuring electrical three-way valve SV107.

The recycle loop gases, after passing through the "on line" CO Disproportionator, are directed to the recycle loop H_2 Separator, HSR102, where the H_2 formed by the electrolysis of water in the feed gas is removed. The recycle loop gas then flows through the loop to the Recycle Loop Bellows Pump. The Bellows Pump, P101, maintains the recycle loop flow rate at 3.08 lpm (0.11 cfm). The recycle loop gas then exits the Bellows Pump and joins with the feed gas to complete the cycle.

CO Disproportionator Feed Gas Fill

The feed gas is divided just before entering solenoid valve SV104. This line is directed to the CO Disproportionators through solenoid valve SV114 and electrical three-way valve SV107. This line allows filling of the off-line CO Disproportionator with feed gas prior to directing the recycle loop gas into it. This is done to avoid (1) a sudden drop in recycle loop pressure which would occur if the recycle loop gas flow was diverted to an evacuated CO Disproportionator, or (2) a buildup in recycle loop inerts which would occur if the CO Disproportionator is filled with N_2 after CDC replacement.

Nitrogen Purge

The system N_2 purge is divided into four flow paths:

1. Through solenoid valve SV102 and flow restrictor FR101 for purging the H_2 gas compartment and associated plumbing of the water electrolyzer

2. Through solenoid valve SV106, flow restrictor FR102 and electrical three-way valve SV107 for purging the spent CO Disproportionator prior to replacing the CDC. Three-way valve SV107 is used to direct the flow to the desired CO Disproportionator

3. Through solenoid valve SV109 and flow restrictor FR104 for purging the H_2 exit line of the H_2 Separator

4. Through solenoid valve SV103 and flow restrictor FR103 for purging the feed gas inlet line and the recycle loop

Nitrogen is supplied through solenoid valve SV113 and pressure regulator RE101 for maintaining recycle loop pressure during Standby and Shutdown operating modes. Regulator RE101 allows N_2 into the system so as to maintain recycle loop pressure above 0.17×10^4 N/m^2 (0.25 psig).

The flow orifices used in the N_2 purge lines are incorporated to establish the N_2 flow rate and to provide overpressure protection for downstream components.

Pressure regulator RE102 and solenoid valve SV105 were added to the system to perform three functions:

1. To provide recycle loop overpressure protection. When pressure transducer PS102 senses pressure greater than 1.21×10^4 N/m^2 above ambient (1.75 psig), solenoid valve SV105 is opened and pressure regulator RE102 allows the recycle loop to vent until the pressure reaches 0.689×10^4 N/m^2 above ambient (1.0 psig). At the same time, the Control Instrumentation automatically configures the system to the Standby Mode.

2. To allow recycle loop N_2 purge. In order to purge the recycle loop, the recycle loop pump is turned off and solenoid valve SV105 is opened, allowing N_2 flow throughout the loop. Pressure regulator RE102 maintains backpressure at 0.70×10^4 N/m^2 above ambient (1.0 psig).

3. To allow the SX-1 to operate when interfacing with the feed gas of the Molecular Sieve and Steam-Desorbed Solid Amine CO_2 Collection Systems. Since the gas interface from these systems contains N_2, and since N_2 does not enter into any of the loop reactions, a recycle loop pressure rise will occur as a result of the N_2 buildup in the recycle loop.

   It will be necessary to periodically vent the recycle loop when simulating the Molecular Sieve and Steam-Desorbed Solid Amine interface conditions. In order to accomplish this, solenoid valve SV105 will be periodically opened to relieve increases in recycle loop pressure due to the buildup of inerts (N_2). This sequence will be initiated manually. Pressure regulator RE102 will allow the gas to vent until the loop pressure reaches 0.70×10^4 N/m^2 above ambient (1.0 psig). At this point the system will be manually configured back to the normal operating mode.

Gas Exits and Sample Ports

The O_2 outlet lines of the Electrolyzer Subassembly are kept separate for experimental test purposes. The O_2 outlet lines from the CO_2 electrolyzers are equipped with backpressure regulators (RE103, RE104 and RE105), pressure relief check valves (CV102, CV103 and CV104) and manual shutoff valves (V101, V102 and V103). The backpressure regulators in the O_2 exit lines are included to maintain a 1.03×10^4 N/m^2 above ambient (1.5 psig) O_2 backpressure. This is required to minimize the ΔP across the electrolyzer drums and to ensure that the pressure on the electrolyzer drum is greater on the O_2 side. These provisions were incorporated due to the concern about the ability of the electrolyzer drum's precious metal seal to withstand up to a 1.2×10^4 N/m^2 above ambient (1.75 psig) internal to external ΔP. Check valves CV102, CV103 and CV104 are incorporated to provide overpressure protection in the event the pressure regulators fail closed. The check valves open at 1.38×10^4 N/m^2 above ambient (2.0 psig). The O_2 exit lines from the four electrolyzer modules are plumbed separately so that an individual CO_2 Electrolyzer Module could be isolated from the system if desired. This provides operating flexibility in the event of a cell failure in any one of the CO_2 Electrolyzer Modules. The H_2 exit from the water electrolyzer is equipped with a solenoid valve, SV108. This valve is used to seal the H_2 lines and gas cavities of the Water Electrolyzer Module when it is not in operation. Gas sampling ports are provided downstream of the CO_2 Electrolyzer Modules (V104), downstream of the CO Disproportionators (V105) and downstream of the H_2 Separator (V106).

Instrumentation

The SX-1 schematic shows the locations of all system sensors. These include thermocouples, thermistors, pressure transducers, differential pressure transducers, speed sensor, current and voltage sensors and valve position indicators. These are further discussed in the Instrumentation Section of this report.

System Operating Modes

The SX-1 has four steady-state operating modes and one semiautomatic mode (CDC Change Mode) associated with the replacement of the CDC. The four steady-state modes are Shutdown, Standby, Normal and Purge. A description of each operating mode follows.

Shutdown Mode

In the Shutdown Mode the system is not performing the function of converting CO_2 and water vapor to O_2. In addition, all system heaters for the Electrolyzer Modules, CO Disproportionator, H_2 Separators and the Water Feed Mechanism are turned off. The Electrolyzer Modules have their currents removed, valves are in their de-energized state which closes the gas supply valves to prevent the flow of supply gas and the Recycle Loop Bellows Pump is not circulating gas within the recycle loop. The output from the H_2 Separator is isolated from vacuum; however, the recycle loop is exposed to vacuum via a backpressure regulator, RE102 (see Figure 2), to ensure that, even when in the Shutdown Mode, loop pressure does not exceed 1.21×10^4 N/m^2 above ambient (1.75 psig). As insurance that the recycle loop pressure does not drop below 0.17×10^4 N/m^2 above ambient (0.25 psig), the loop is opened to the N_2 purge gas supply via another pressure regulator, RE101. From the Shutdown Mode a significant period of time must elapse before the system can be operated because the hot components have to be slowly heated to operating temperature.

Standby Mode

In the Standby Mode, as in the Shutdown Mode, the system is not performing the function of converting CO_2 and water vapor to O_2. The major difference between the two modes is that in Standby the heaters are operating, keeping the Electrolyzer Modules, CO Disproportionator, H_2 Separators and the Water Feed Mechanism at temperature and the Recycle Loop Bellows Pump is not operating. Two other variations are that the output from the H_2 Separator (SV112) is opened to vacuum and the recycle loop is isolated from vacuum (SV105) under the normal steady-state conditions of this mode. Only if the recycle loop pressure exceeds 1.21×10^4 N/m^2 above ambient (1.75 psig) will this loop be opened to vacuum via backpressure regulator RE102. All other functions hold true as outlined above in the Shutdown Mode definition. From the Standby Mode the system can be put into operation in less than five minutes.

Normal Mode

In the Normal Mode, the system is performing its intended function of converting the CO_2 and water vapor to O_2. All monitored parameters are within allowable limits.

As the system operates, carbon will build up in the CO Disproportionator that is "on line." This CO Disproportionator will have to be isolated from the recycle loop and a second CO Disproportionator put "on line." This semiautomatic CO Disproportionator exchange mode is detailed below. Also, in the Normal Mode, if the recycle loop pressure exceeds 1.21×10^4 N/m^2 above ambient (1.75 psig), the loop will be opened to vacuum via a backpressure regulator, RE102.

Purge Mode

In the Purge Mode the system is not performing the function of converting CO_2 and water vapor to O_2. All N_2 purge valves (SV113, SV102, SV103, SV109, SV107, SV106) are configured to permit a N_2 purge to all recycle loop components and the H_2 exhaust line of the Water Electrolyzer Module. Solenoid valve SV113 remains open at the conclusion of the N_2 Purge sequence and thereby allows RE101 to compensate for any underpressure situation in the recycle loop. Similarly, SV105 remains open and allows RE102 to compensate for any overpressure condition that might occur in the recycle loop.

Carbon Deposition Cartridge Change Mode

In addition to the operating modes described above, the SX-1 contains a semiautomatic CO Disproportionator Cartridge Change Mode. This mode provides for isolating a carbon-filled CO Disproportionator from the recycle loop and putting the second unfilled CO Disproportionator "on line." The operating sequence for the semiautomatic CO Disproportionator Cartridge Change is discussed later in this report as part of the Control Instrumentation Description.

SYSTEM HARDWARE DESCRIPTION

The SX-1 consists of 58 components mounted on a welded unistrut frame. Figure 3 is a front view of the assembled SX-1. Table 3 lists the SX-1 components. Six of these were designed, fabricated and assembled under the program. The remainder of the components were off-the-shelf and were selected for the application. These are solenoid valves, pressure regulators, pressure transducers, check valves, Hot Gas Valves, a Bellows Pump and flow restrictors. Following is a discussion of the six major components designed, developed, fabricated and assembled during the program.

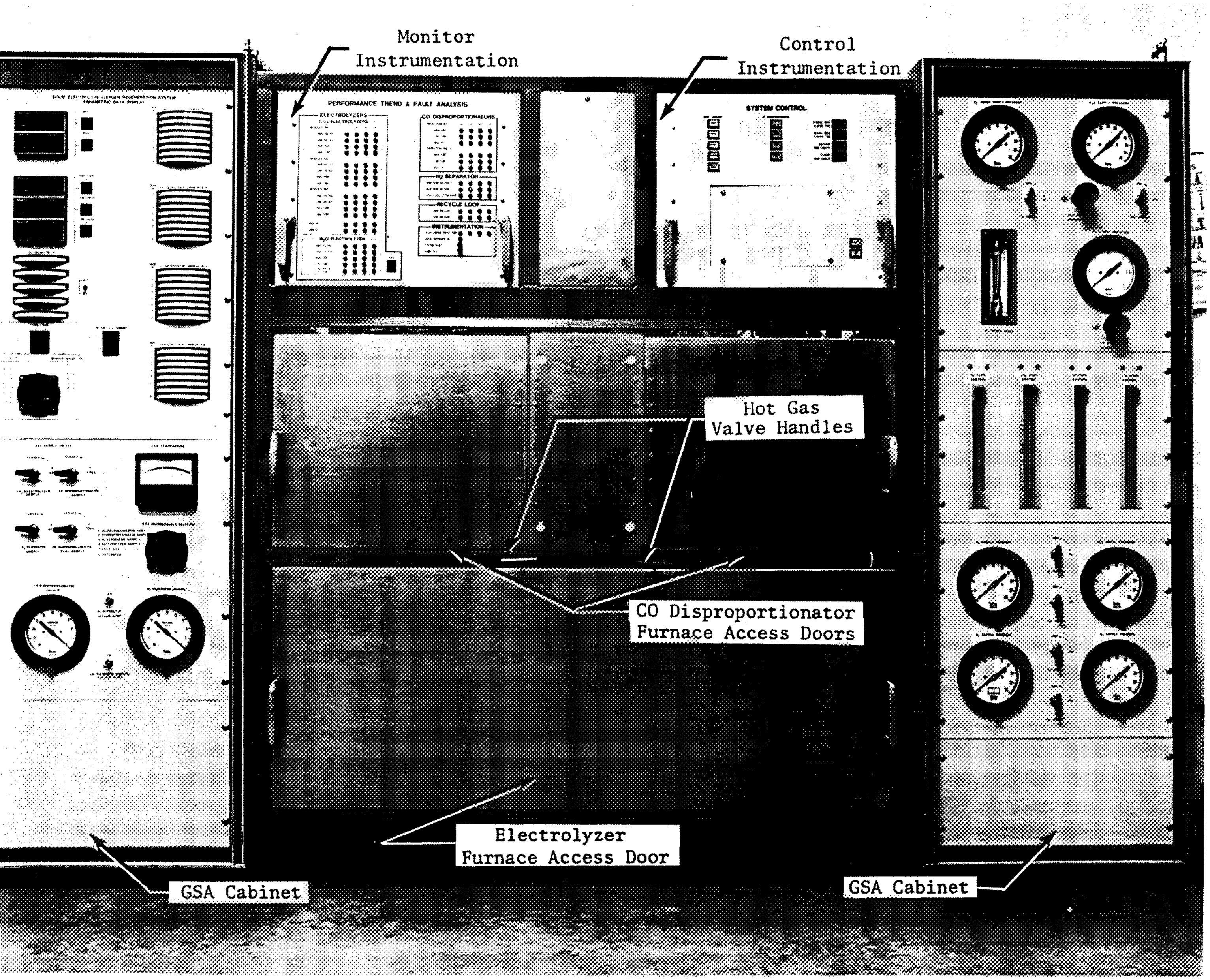


FIGURE 3 FRONT VIEW OF ASSEMBLED SX-1

TABLE 3 SX-1 COMPONENTS LIST

Item	Quantity Required	Part Number	Description/Title/Name
1	3	CE101 thru CE103	Module, Electrolyzer, CO_2
2	1	HE101	Module, Electrolyzer, Water
3	2	COD101, COD102	Disproportionator, CO
4	2	HSR101, HSR102	Separator, H_2
5	1	C101	Instrumentation, Control
6	1	M101	Instrumentation, Monitor
7	1	P101	Pump, Bellows
8	8	SV103, SV105, SV106, SV102, SV109, SV111, SV113, SV114	Valve, Shutoff, Electrical Normally Closed
9	4	SV101, SV104, SV108, SV112	Valve, Shutoff, Electrical, Normally Open
10	2	SV107, SV110	Valve, 3-Way, Electrical
11	4	HV101 thru HV104	Valve, Hot Gas
12	7	V101 thru V107	Valve, Shutoff, Manual
13	5	CV101 thru CV105	Valve, Check
14	5	RE101 thru RE105	Regulator, Pressure
15	1	PR101	Regulator, Pressure, Pressure Referenced
16	1	FB101	Mechanism, Water Feed
17	5	FR101 thru FR105	Restrictor, Flow
18	2	PS102, PS105	Transducer, Pressure
19	3	PS101, PS103, PS104	Transducer, Pressure Differential

Electrolyzer Subassembly

The electrolyzer subassembly consists of four major parts. The electrolyzer furnace, with built-in heaters and insulation; three CO_2 Electrolyzer Modules; one Water Electrolyzer Module; and the associated plumbing and wiring connections.

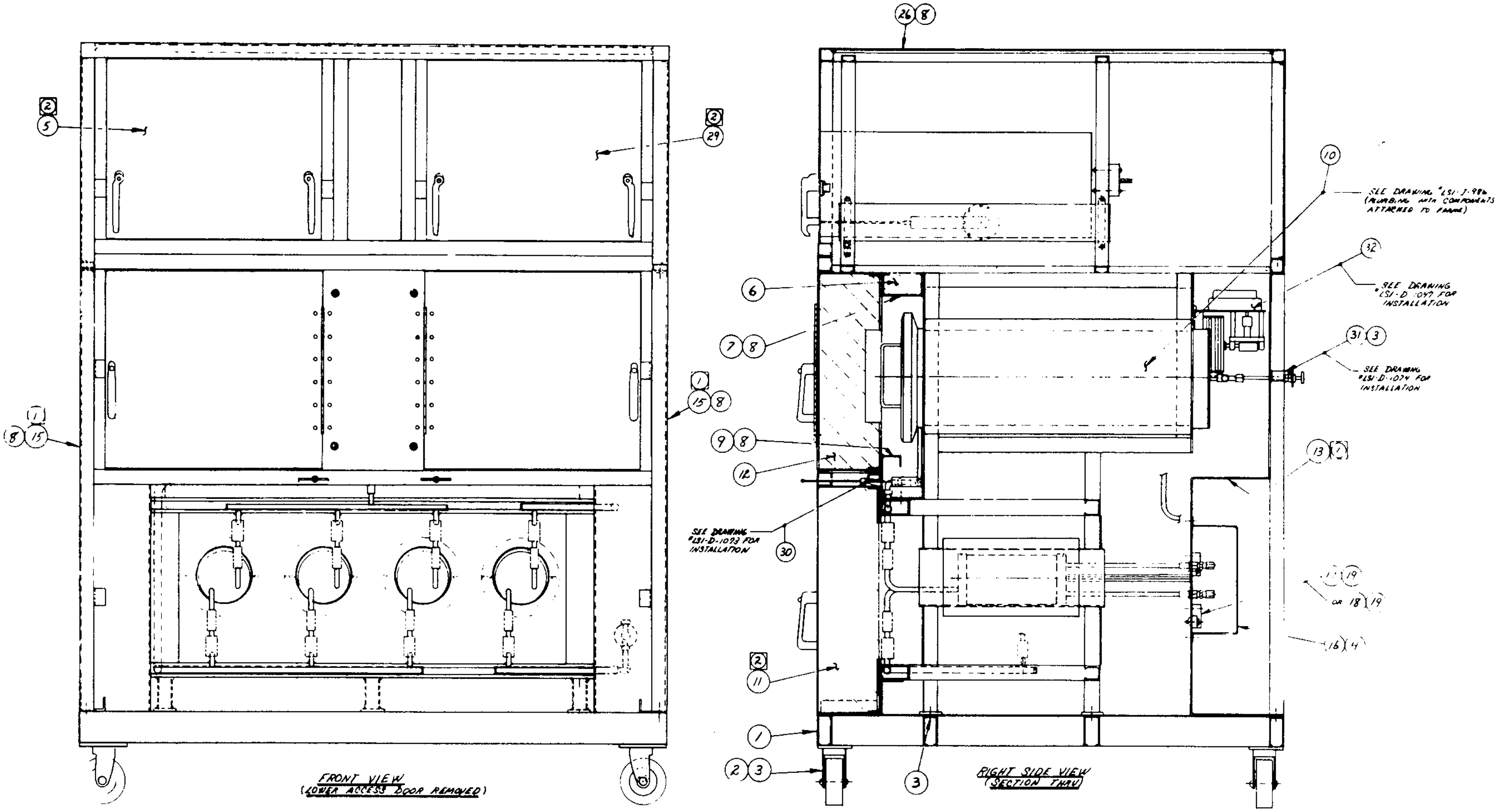
Electrolyzer Furnace

The function of the electrolyzer furnace is to heat and maintain the CO_2 and Water Electrolyzer Modules at their operating temperature. The assembly drawing showing the location of the electrolyzer furnace is shown in Figure 4. The materials of construction and operating characteristics of the electrolyzer furnace are listed in Table 4. The furnace is a self-supporting unit consisting of a welded structural frame, gas manifolding, heaters, insulation, stainless steel covers and module access doors. The frame is used to support the modules, heaters and gas manifolding. The electrolyzer modules are supported inside the Inconel muffles (horizontal tubes) with the ceramic heaters attached to the outside. The muffle support plates are welded to the 302 stainless steel unistrut channel. The process gas manifolding is welded to the frame channel with a tube fitting at each end. The tube fitting and metal bellows allow for a frame and module differential thermal expansion and simple module removal from the electrolyzer furnace. The stainless steel frame is completely enclosed with insulation for minimum heat loss. The only contact the frame has with the external covers is at the mounting pads on the bottom surface and at the flanged front face with the access doors. The insulation material is protected externally by the stainless steel covers and internally at the service area with a muffle support plate and front face flanges. The insulation thickness was selected to give an external cover operating temperature of less than 322K (120F). The insulation thickness required to achieve this outer skin temperature was calculated to be 20.3 cm (8.0 in). The furnace assembly includes Bakelite terminal blocks for power and thermocouple lead connections on the back cover.

Electrolyzer Modules

The function of the electrolyzer modules is to convert CO_2 to CO and O_2 and to convert water into H_2 and O_2.

The CO_2 and Water Electrolyzer Modules that were incorporated into the electrolyzer subassembly were based on the results of a development effort sponsored by the NASA Ames Research Center under Contracts NAS2-2870, NAS2-4843 and NAS2-6412. This work was reported to result in CO_2 electrolysis cells that provide breathable O_2 containing less than 1% impurities and that operate at 100% Faradaic current efficiency. A 12-cell (six-drum) module has demonstrated operation for 101 days.[12] The CO_2 and Water Electrolyzer Modules contain eight electlyzer drums. Each electrolyzer drum contains two electrolysis cells as shown in Figure 5. The electrolyzer drum is a cylinder with a diameter of 6.3 cm (2.48 in) and a height of 1.0 cm (0.39 in). Each cell contains two fully stabilized zirconium oxide electrolyte disks with active platinum (Pt) elec-



Explanation of numbers in circles on page 20.

continued-

FIGURE 4 COMPLETE ELECTROLYZER FURNACE ASSEMBLY

Figure 4 - continued

QT'Y REQ'D	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	REFERENCE OR NOTE	ITEM NO.
1	LSI-D-1047	ACTUATOR ASS'Y	SEE DETAIL	LSI	32
2	LSI-D-1074	SWITCH (REAR) ASS'Y	SEE DETAIL	LSI	31
2	LSI-D-1073	SWITCH (FRONT) ASS'Y	SEE DETAIL	LSI	30
1	LSI-E-1037	CASSIS ASSY	SEE DETAIL	LSI	29
20	LSI-J-990-13	LOCK WASHER, SPRING	#10 ~ S/STL	INSTOCK FASTENERS	28
12	LSI-J-990-12	NUT, HEX REG	#10-32 ~ S/STL	INSTOCK FASTENERS	27
1	LSI-D-984-1	TOP PANEL	SEE DETAIL	LSI	26
1	LSI-D-984-2	REAR PANEL (ELECT)	SEE DETAIL	LSI	25
2	LSI-D-984-4	SIDE PANEL (ELECT)	SEE DETAIL	LSI	24
1	LSI-D-984-3	FRONT PANEL (ELECT)	SEE DETAIL	LSI	23
2	LSI-J-990-10	CABLE RETRACTOR	CR-200	ZERO MFG CO	22
12	LSI-J-990-11	SCREW, RD HD MAC	#10-32 X 1.75 LG ~ S/STL	INSTOCK FASTENERS	21
AR	LSI-J-990-9	SHIM	.015 THICK ~ STEEL	LSI	20
34	LSI-J-990-8	SCREW, RD HD MAC	#10-32 X .75 LG ~ S/STL	INSTOCK FASTENERS	19
11	LSI-J-990-7	TERMINAL BOARD	# 1215-3	KULKA ELECT CO	18
6	LSI-J-990-6	TERMINAL BOARD	# 1215-2	KULKA ELECT Co	17
1	LSI-C-989	COVER, TERM BOARD	SEE DETAIL	LSI	16
2	LSI-D-984-5	PANEL, SIDE	SEE DETAIL	LSI	15
2 PAIRS	LSI-J-990-5	CABINET & CHASSIS SECTION	CTRD-224	ZERO MFG Co	14
1	LSI-D-987	INTERFACE PANEL	SEE DETAIL	LSI	13
1	LSI-D-971	H_2 SEP HINGED DOOR ASSY	SEE DETAIL	LSI	12
1	LSI-D-975	CO DIS ACCESS COVER ASSY	SEE DETAIL	LSI	11
1	LSI-J-986	FURNACE SUB-ASSY	SEE DETAIL	LSI	10
1	LSI-C-981	DOOR STOP CHANNEL	SEE DETAIL	LSI	9
36	LSI-J-990-4	SCREW, PAN HD	#10 TYPE TYPE B SELF-TAP	INSTOCK FASTENERS	8
2	LSI-C-982	DOOR STOP, UPPER	SEE DETAIL	LSI	7
2	LSI-	INSULATION	SEE DETAIL	LSI	6
1	LSI-E-1009	CHASSIS ASSY	SEE DETAIL	LSI	5
8	LSI-J-990-3	SCREW, RD HD MACH	#10-32 X .38 LG ~ S/STL	INSTOCK FASTENERS	4
26	LSI-J-990-2	SCREW, RD HD MAC	#1/4-20 X .50 LG ~ S/STL	INSTOCK FASTENERS	3
4	LSI-J-990-1	SWIVEL-PLATE CASTERS	#5X731	W.W. GRAINGER	2
1	LSI-J-813	MAIN FRAME ASSY	SEE DETAIL	LSI	1

LIST OF MATERIALS OR PARTS LIST

DFTM.	M. PROKOP	8-5-74
CHKR.	M. Prokopcak	1-8-75
ENGRG. APPD.	E. Mahake	1-8-75
APPROVAL	JW Shumar	1-9-75

Life Systems, Inc.
CLEVELAND, OHIO

TITLE ASSY, ELECTROLYZER FURNACE

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

SCALE QUARTER | SHEET 1 OF 1 | DWG. SIZE J | DRAWING No. LSI-J-990

TABLE 4 SX-1 ELECTROLYZER FURNACE
OPERATING CHARACTERISTICS AND MATERIALS

Characteristics	Description
Overall Size, cm (In)	125.9 x 59.2 x 80.8 (49.5 x 23.3 x 31.8)
Power (Heaters), V	230, 1400 W/each
Temperature, K (F)	1123 (1562)
Process Gas Tube Interfaces, cm (In)	0.950 (0.375) stainless steel tube fittings
Access Area Opening, cm (In)	87.0 x 33.0 (34.2 x 13.0)
Materials	
Frame	Standard Unistrut 302 stainless steel channel A5000 and A1000, Inconel 600 muffles
Covers, cm (In)	0.127 (0.050) 304 stainless steel
Insulation	Standard Johns-Manville Micro Quartz
Heaters	Standard Lindberg Model 50531, Type 5712-SP, Ceramic Clam Shells, eight required
Fittings, cm (In)	Standard Swagelok stainless steel, 0.950 (0.375) union tube fittings

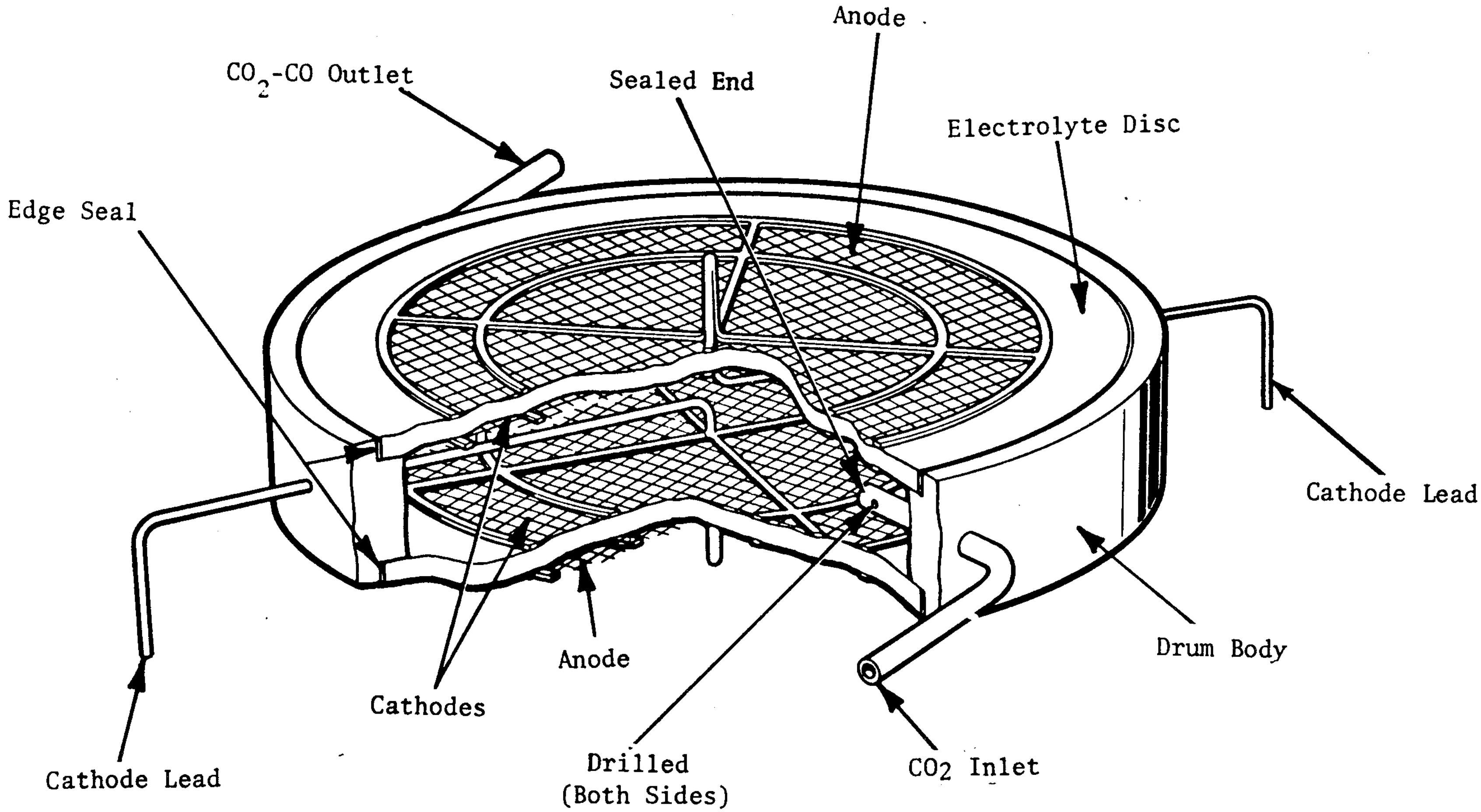


FIGURE 5 ELECTROLYZER DRUM

trodes integrally attached to both sides of each disk. The active area of each cell is 20 cm^2 (3.10 in^2). The electrolyzer subassembly contains four electrolyzer modules. Three CO_2 Electrolyzer Modules are plumbed into the recycle loop. The fourth electrolyzer module is fed separately with water vapor and is utilized to electrolyze water in a once-through fashion. The operating characteristics of the electrolyzer modules are listed in Table 5. The electrolyzer modules are packaged by enclosing a set of eight drums in a gas-tight 304 stainless steel or Inconel 600 can. The heating elements and all furnace insulation material are external to the can. This packaging tecnique has been described as the Internal Can Concept.(13)

A photo of a completed electrolyzer module is shown in Figure 6. The inlet and outlet manifold tubes shown are constructed with bellows to allow easy electrolyzer module removal and replacement within the confinement of the fixed system plumbing. They also allow for thermal deflections that occur as the system comes up to temperature. The O_2 outlet manifold tube is a branch of one of the electrical conductor support tubes described next. The nine tap wires and two current conductors come out of the modules in groups of 4, 4, and 3 in the three electrical conductor tubes indicated. They are supported and insulated from each other in the system manifolding by the use of four-hole alumina insulators. These insulators run the full length of the tube. The thermocouple wells are close-ended and spaced at the proper axial distance inside the can assembly. Since they are close-ended tubes and the thermocouples enter from outside of the module, no penetration or discontinuity in the electrolyzer module boundary exists. This feature allows for in situ maintenance of thermocouples without the need for cooling down the system and disassembling the electrolyzer modules. The major components of the module, as shown separated in Figure 6, are the module can assembly, including the O_2 manifold end cap, thermocouples, and electrical connectors and the electrolyzer drums and manifold assembly. The module can assembly seal is an Inconel O-ring seal that is held in place and compressed by the use of 12 equally spaced Inconel screws holding the cover to the module can assembly. The seal for the electrical connectors is a bulkhead seal located at the end of the electrical conductor tubes. This seal is made by use of a crushable lava spacer. The thermocouples do not require a boundary seal since they are externally inserted into the tubes that are welded to the end cap. The electrolyzer drum supports and the two alumina manifold tube supports are both made from fired lava.

The materials used in the electrolyzer module assembly were chosen for their resistance to the expected recycle loop gases (CO, CO_2, H_2 and water) at the maximum operating temperature of 1173K (1652F). Where required, electrical conductivity and thermal expansion considerations were included. Inconel 600 is used for the can assembly and the 1.27 cm (0.5 in) diameter external manifold tubes and electrical conductor support tubes. The 0.95 cm (0.375 in) diameter internal manifold tubes are made out of alumina tubing closed on one end. The tubulations used to connect the drums to the alumina manifold tubes are Pt/10% iridium (Ir) alloy. The tap wires and conductors are made of gold (Au)/3.5% Pd alloy.

TABLE 5 ELECTROLYZER SUBASSEMBLY
PERFORMANCE CHARACTERISTICS

<u>Carbon Dioxide Electrolyzer</u>	
Feed Gas Composition, kg/s (Lb/Hr), %	
CO_2	9.317×10^{-5} (0.7389), 51.60
CO	5.217×10^{-5} (0.4137), 45.40
H_2	0.010×10^{-5} (0.0019), 2.86
Water	0.010×10^{-5} (0.0008), 0.14
Feed Gas Temperature, K (F)	628 to 658 (670 to 725)
Feed Gas Pressure, N/m^2 (Psia)	10.3×10^4 to 11.0×10^4 (15 to 16)
Current (Total), Cell A	102
Current Density (48 Cells), mA/cm^2 (ASF)	106 (98.5)
Current per Module, A	2.1
Operating Temperature, K (F)	1143 to 1163 (1598 to 1634)
<u>Water Electrolyzer</u>	
Feed Gas. kg/s (Lb/Hr)	
Water Vapor	0.285×10^{-5} (0.542)
Feed Gas Temperature, K (F)	397 to 402 (255 to 264)
Feed Gas Pressure, N/m^2 (Psia)	10.1×10^4 to 11.7×10^4 (14.7 to 17)
Current (Total), Cell A	30.5
Current Density (16 Cells), mA/cm^2 (ASF)	97 (90.1)
Current per Module, A	1.9
Operating Temperature, K (F)	1143 to 1163 (1598 to 1634)

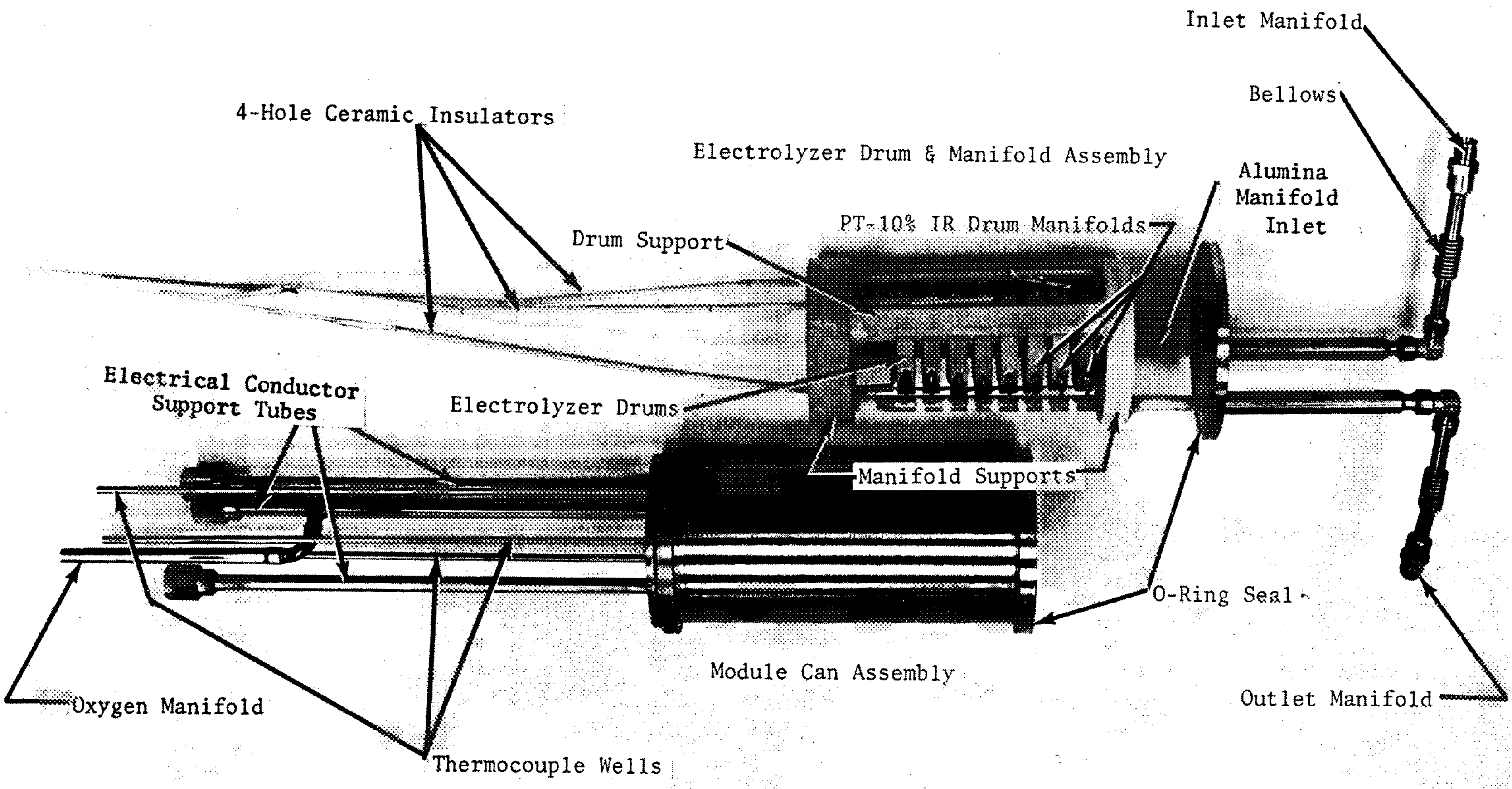


FIGURE 6 ELECTROLYZER MODULE

CO DISPROPORTIONATOR

The function of the CO Disproportionator is to convert the SX-1 system recycle loop CO gas to CO_2 and solid carbon in the presence of a carbon steel (AISI 1025) catalyst, with the addition of heat. The reaction taking place in the CO Disproportionator is

$$2CO = CO_2 + C \tag{8}$$

A disassembled CO Disproportionator is shown in Figure 7. The CO Disproportionator consists of a housing assembly and a replaceable CDC assembly. The CDC consists of a front and rear end cap filter and screen, a catalyst star, the CDC housing, and the cover assembly with handles provided for ease of CDC removal and replacement. For a cartridge change, the CDC is pulled from the housing assembly utilizing the two handles. The CDC is then disassembled and the formed carbon and remaining catalysts are disposed of. A new catalyst star is obtained and the CDC is reassembled and inserted into the housing assembly. The process gas enters the CO Disproportionator at the inlet manifold tube shown in Figure 7. It then passes through the front cartridge end cap, filter and screen, and reacts in the presence of the star-shaped catalyst. The solid carbon forms on the surface of the star catalyst with the formed CO_2 passing through the rear cartridge end cap, filter and screen, and into the recycle loop. The main CO Disproportionator seal is an O-ring seal made from copper-clad Inconel. This fits between the cover assembly and the cylindrical outer housing. When the quick-disconnect clamp is fastened around the cover and main body assembly, the seal is formed. Leakage or parallel passage of gas between the CDC and housing assembly is prevented by two wire seals placed around the ends of the CDC assembly. The other end of the CO Disproportionator housing assembly is secured by welding, thus no seals are required at this end.

A literature survey was performed to determine what materials could be used for construction of the CO Disproportionator.[8,14,15] Based on material availability, ease of fabrication and cost, electroless nickel-plated stainless steel was selected as the base construction material. As a result, all metal components other than the star catalyst have been plated with 0.0025 cm (0.001 in) thick electroless nickel to prevent the CO Disproportionation reaction from occurring on these surfaces. Table 6 lists the CO Disproportionator operating characteristics and materials.

H_2 SEPARATOR

The function of the H_2 Separator is to remove excess H_2 from the feed and recycle loop gases. Figure 8 shows a sectioned view of the completed design. The process gas enters the vertical tube and exits through the horizontal tube at the right of the assembly. A vacuum is drawn through the horizontal tube at the left side of the assembly and on the inside of the commonly manifolded Pd/Ag tubes. The Pd/Ag tubes are concentrically packed and welded into a header assembly which is metal O-ring-sealed and bolted to the external housing.

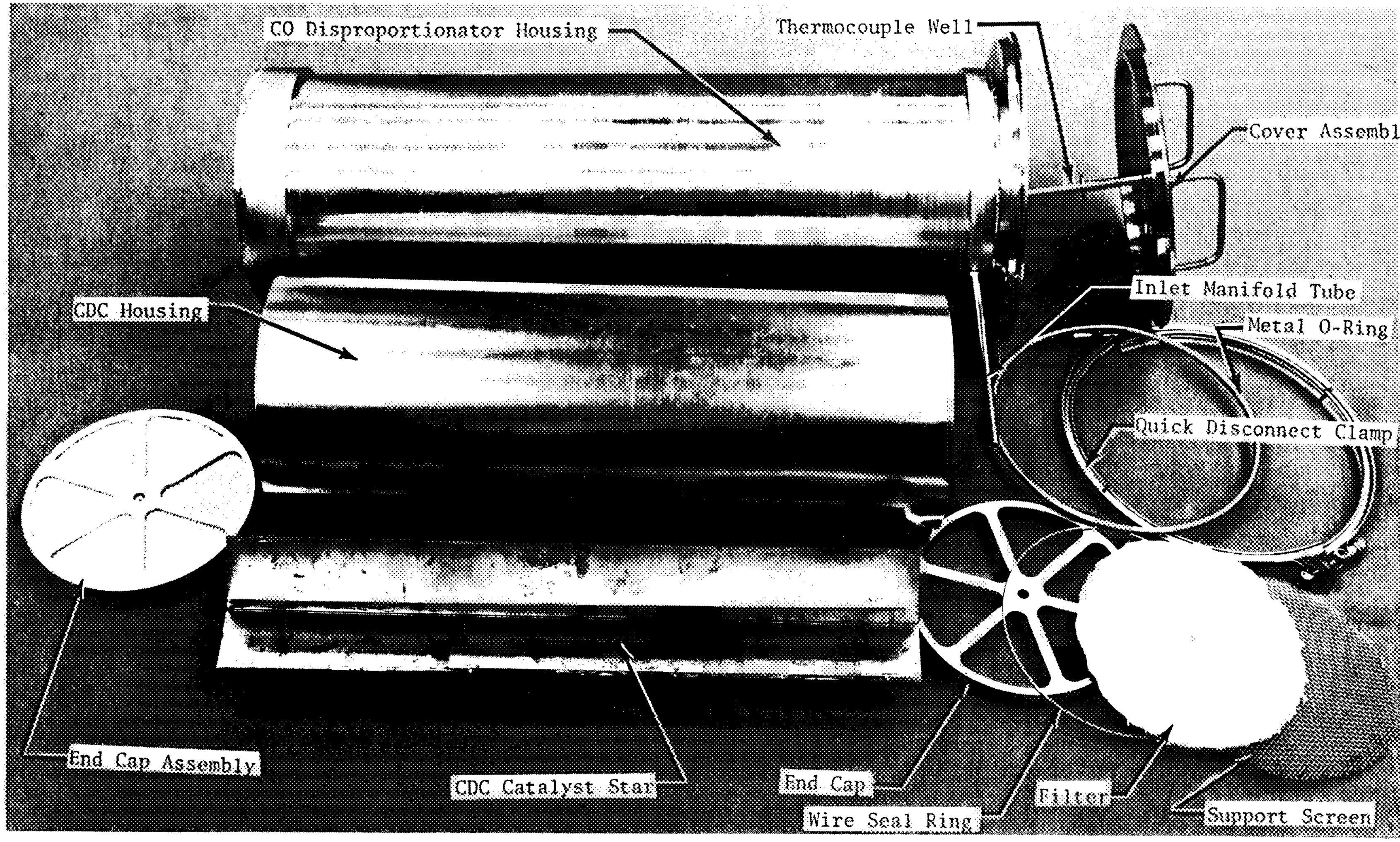


FIGURE 7 CO DISPROPORTIONATOR

TABLE 6 SX-1 CARBON MONOXIDE DISPROPORTIONATOR AND CATALYST ACTIVATION FURNACE OPERATING CHARACTERISTICS AND MATERIALS

Characteristics	Description
Overall Size, cm (In)	24.76 x 76.2 (9.75 x 30.0)
Power (Heaters), V	115, 875 W/each
Temperature, K (F)	823 (1022)
Process Gas Tube Interface, cm (In)	0.950 (0.375) stainless steel tube fitting
Materials	
Housing, cm (In)	Standard 20.3 (8.0) Schedule 40 304 stainless steel pipe, electroless nickel plated (0.0025 (0.001))
CDC Housing, cm (In)	0.150 (0.059) 316 stainless steel, electroless nickel plated (0.0025 (0.001))
CDC Catalyst, cm (In)	Standard 0.013 (0.005) A1S1 1025 sheet steel
CDC Filter	Standard Fiberfrax LO-CON ceramic fiber
CDC End Caps, cm (In)	20.3 (8.0) round 304 stainless steel, electroless nickel plated (0.0025 (0.001))
CDC Screen, cm (In)	Stainless steel 8 x 8 mesh, electroless nickle plated (0.0025 (0.001))
Heaters	Standard Lindberg Model 50821, Type 8708-SP, Ceramic Clam (1/4) Shell, twelve required
Fittings, cm (In)	Standard Swagelok union tee 600-3-316, electroless nickel plated (0.0025 (0.001))

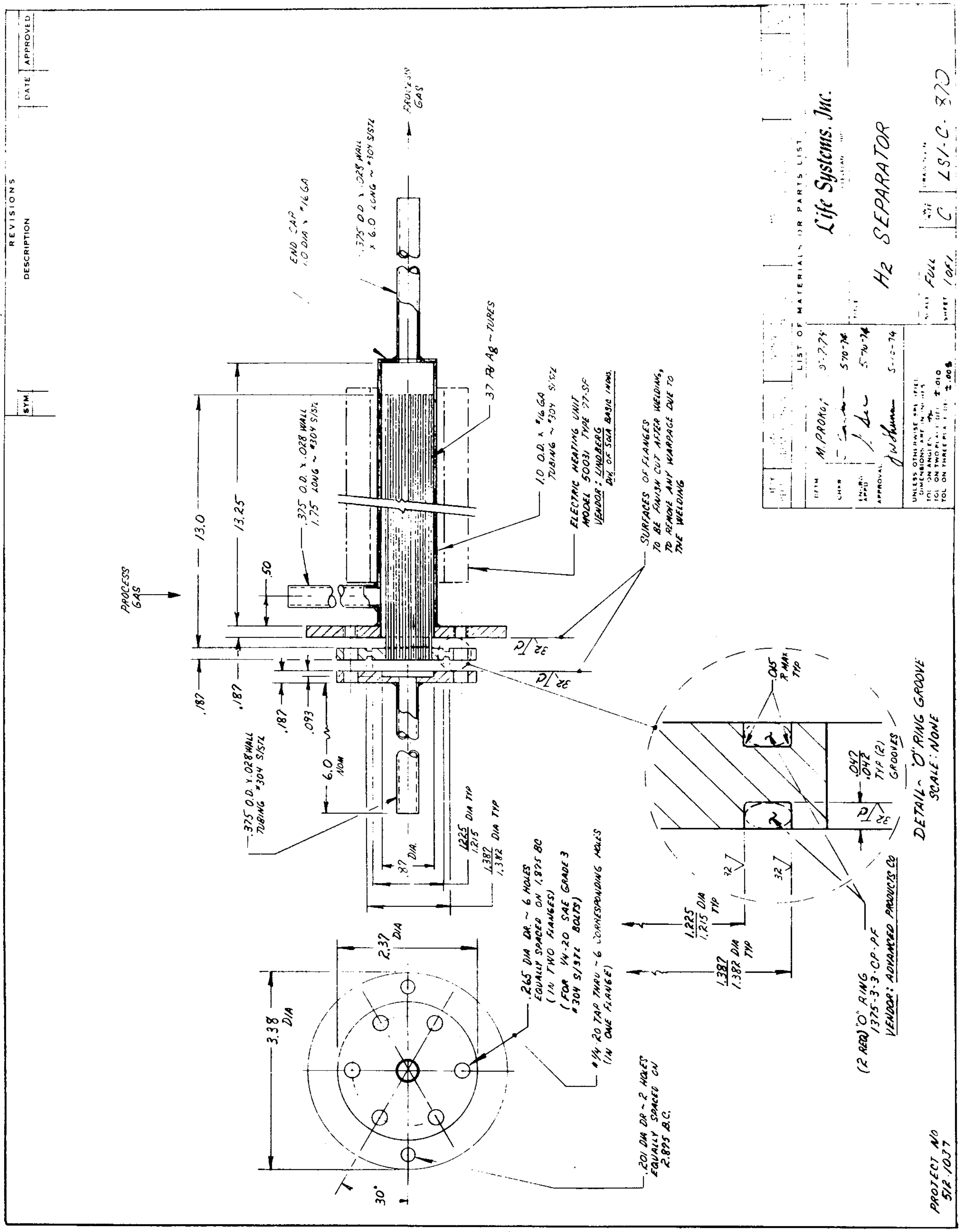


FIGURE 8 H2 SEPARATOR

Based on the theoretical expression, relating diffusion rate, Pd/Ag tube diameter, Pd/Ag tube wall thickness, and Pd/Ag tube length, it was determined that 12.19 m (40 ft) of 0.159 cm (0.062 in) diameter and 0.0076 cm (0.003 in) wall Pd/Ag tubes were required.[16] This requirement was based on a 75% Pd/25% Ag alloy and an operating temperature of 616K (650F).

One common design is used for both the recycle loop and the feed gas H_2 separators. Figure 9 is a picture of a disassembled H_2 Separator. The H_2 Separator operating characteristics and materials of construction are listed in Table 7.

WATER FEED MECHANISM

The function of the Water Feed Mechanism is to provide a stable and constant flow of super-heated steam to the Water Electrolyzer Module. The steam is required as a source of additional O_2 to make up the difference between the O_2 available from CO_2 and that metabolically required by man. The Water Feed Mechanism consists of the following major components: heater, tube, orifice, thermocouples and temperature control which is part of the Control Instrumentation. The Water Feed Mechanism consists of three specific stages: preheater, flash orifice, and a boiler. In the preheater stage, the water temperature is raised along its length to a liquid saturation temperature of 407K at 31.0 x 10^4 N/m^2 (274F at 45 psia) and maintains that level at the orifice entrance by a thermocouple and temperature control. This corresponds to Point 1 on Figure 10, which is a plot of temperature versus distance along the flash boiler tube. The super-heated water is flashed through the orifice to the low pressure, 10.3 x 10^4 N/m^2 (15 psia), side of the Water Feed Mechanism (Point 4). As the water passes through the orifice, it undergoes a phase change from liquid to vapor. However, not all the liquid is transformed into vapor at the orifice and as a result more heat energy must be applied in the boiler section to achieve a complete change to the vapor phase (Point 3). However, a large enough phase change of liquid to vapor is achieved at the orifice (90% by volume) to yield a uniform and constant steam flow mode. A drawing of the Water Feed Mechanism with callouts describing the individual components is shown in Figure 11.

CONTROL INSTRUMENTATION

The primary functions of the Control Instrumentation are to provide the logic and programming for system mode transitions, to control Normal Mode operation by automatically varying the CO_2 Electrolyzer Module's current as a function of recycle loop pressure, and to control all other parameters critical to the system operation, such as Electrolyzer Module temperature, CO Disproportionator temperature, H_2 Separator temperature, Water Feed Mechanism temperature, Water Electrolyzer Module current, and Recycle Loop Bellows Pump speed. A listing of the parameters, their controlling functions, and all internal adjustments, is presented in Table 8. The SX-1 has four steady-state operating modes and one semiautomatic mode. The latter is associated with the replacement of the CDC. The allowed mode transitions are described in Figure 12. The flow chart describing the sequencing for mode transitions is presented in Appendix 1.

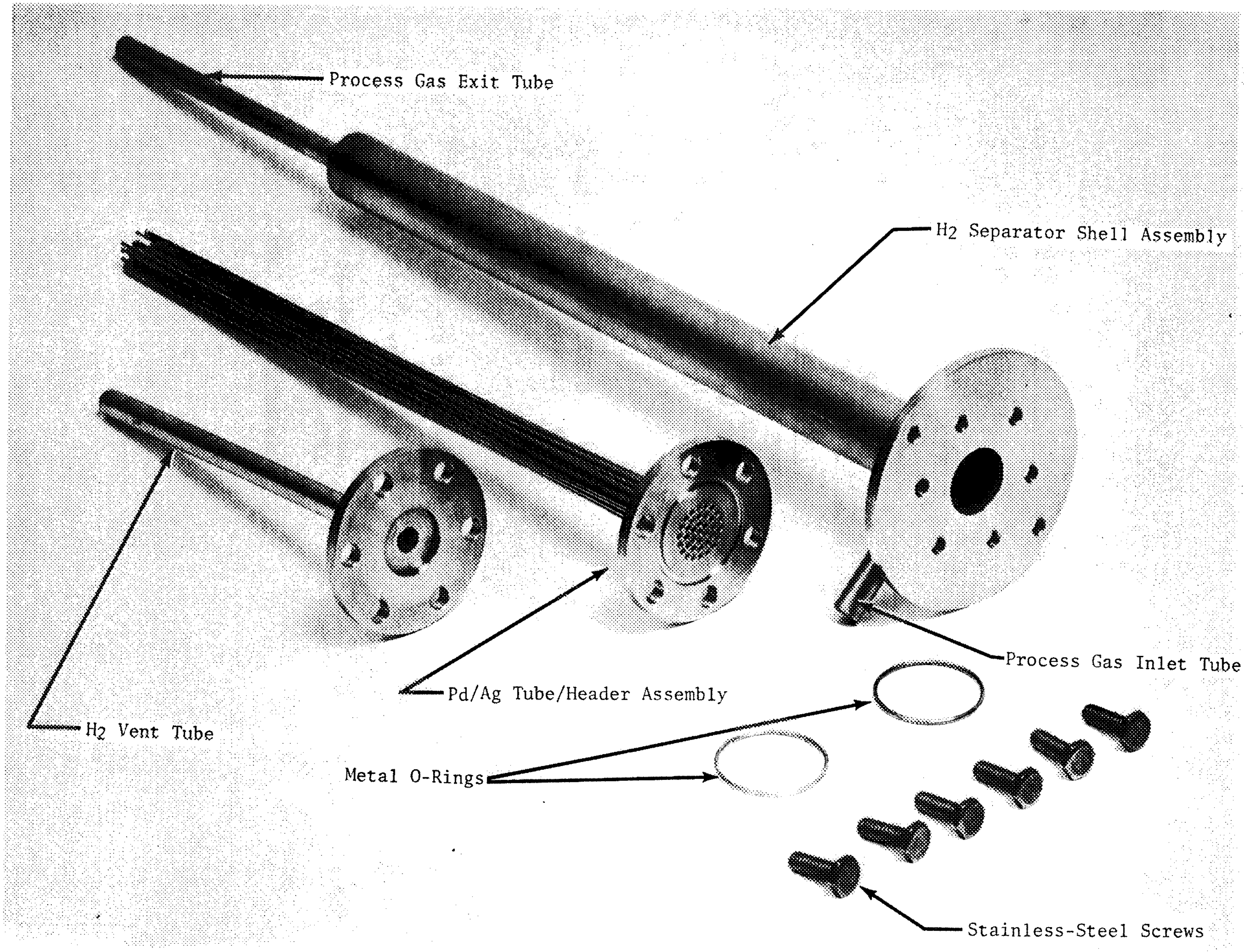


FIGURE 9 DISASSEMBLED HYDROGEN SEPARATOR

TABLE 7 SX-1 HYDROGEN SEPARATOR
OPERATING CHARACTERISTICS AND MATERIALS

Characteristics	Description	
Overall Size, cm (In)	8.6 x 63.0 (3.4 x 25.0)	
Hydrogen Diffusion Area, cm^2 (In^2)	606.0 (94.0)	
Process Gas Inlet		
Temperature, K (F)	616 (650)	
Pressure, N/m^2 (Psia)	10.3×10^4 (15)	
	Feed Gas	Recycle Gas
Flow Rate, Sccm (Scfm)/Min	505.6 (0.018)	2696.2 (0.095)
Composition, % V	75.20 CO_2 1.67 Water 23.13 H_2	32.19 CO 64.39 CO 3.42 H_2 0 Water
Power, W	175	
Tube Interface, cm (In)	0.95 (0.375) diameter stainless steel tubing	

Materials	
Housing	304 stainless steel
Separator Tubes	Pd/Ag Alloy (75/25)
O-Rings	Advanced Products Company, 1375-3-3-CP-PF
Heaters	Lindberg Model 50031, Type 77-SP

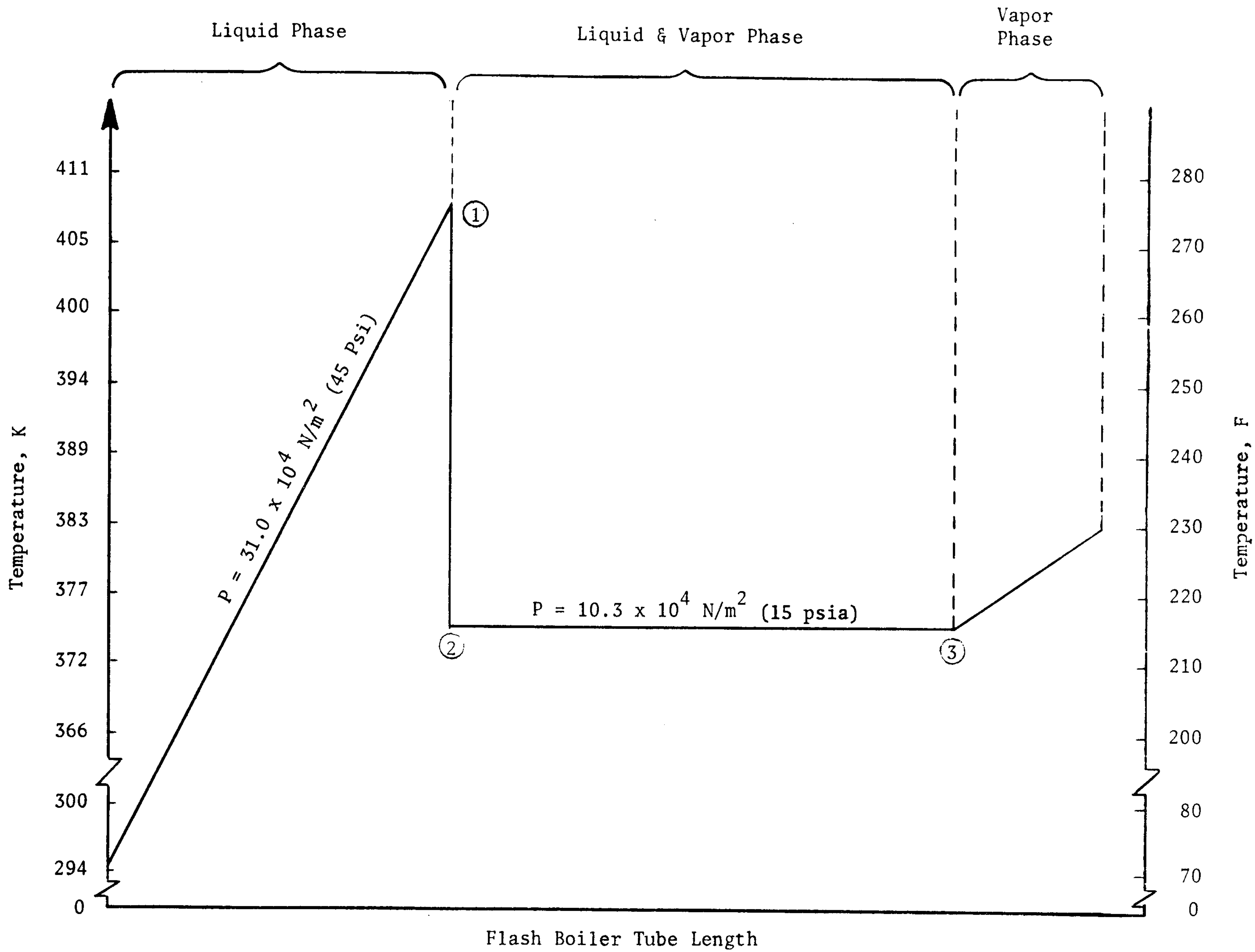
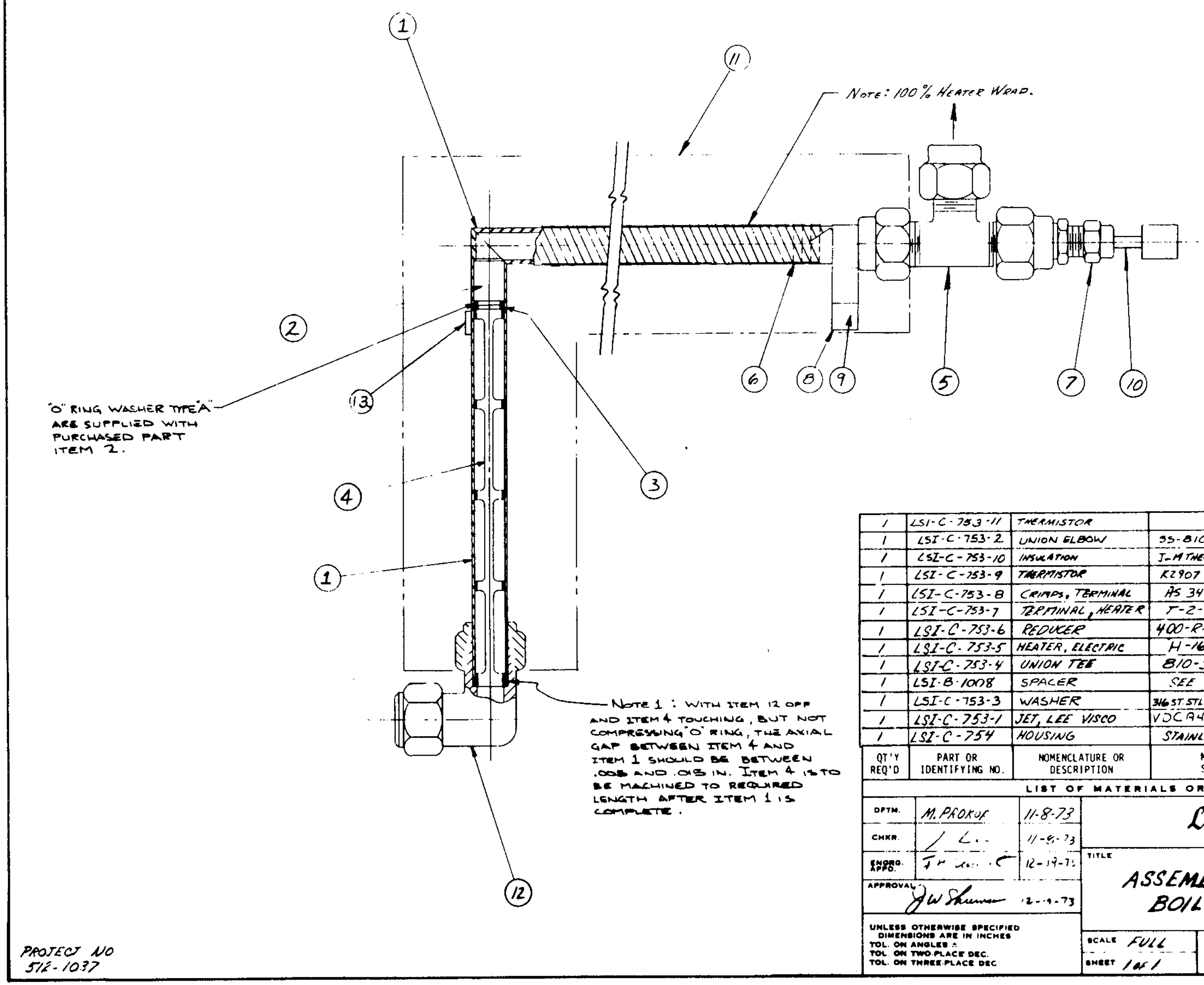


FIGURE 10 H_2O TEMPERATURE VERSUS FLASH BOILER TUBE LENGTH

REVISIONS			
SYM.	DESCRIPTION	DATE	APPROVED
A	REVISED PER RDC #332	1-14-74	
B	REVISED PER RDC #461	8-16-74	



QT'Y REQ'D	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	REFERENCE OR NOTE	ITEM NO.
1	LSI-C-753-11	THERMISTOR			13
1	LSI-C-753-2	UNION ELBOW	SS-810-9	SWAGELOK	12
1	LSI-C-753-10	INSULATION	J-M THERMO-12	JOHNS-MANVILLE	11
1	LSI-C-753-9	THERMISTOR	KZ907	FENWAL	10
1	LSI-C-753-8	CRIMPS, TERMINAL	AS 345	CLAYBORN LABS	9
1	LSI-C-753-7	TERMINAL, HEATER	T-2-L	CLAYBORN LABS	8
1	LSI-C-753-6	REDUCER	400-R-8-BT	CRAWFORD FITTING	7
1	LSI-C-753-5	HEATER, ELECTRIC	H-16-2H	CLAYBORN LABS	6
1	LSI-C-753-4	UNION TEE	810-3-316	CRAWFORD FITTINGS	5
1	LSI-B-1008	SPACER	SEE DETAIL	LSI	4
1	LSI-C-753-3	WASHER	316 ST. STL. 3/16 O.D. x 1/8 I.D. x 1/16 THK	LSI	3
1	LSI-C-753-1	JET, LEE VISCO	VDCA4315220T	THE LEE CO	2
1	LSI-C-754	HOUSING	STAINLESS STEEL #316	LSI	1

LIST OF MATERIALS OR PARTS LIST

DFTM.	M. PROKOF	11-8-73
CHKR.		11-9-73
ENGRG. APPD.		12-19-73
APPROVAL	J W Shumar	12-19-73

Life Systems, Inc.
CLEVELAND OHIO

TITLE: ASSEMBLY, FLASH BOILER

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

SCALE: FULL | SHEET: 1 of 1 | DWG SIZE: C | DRAWING No: LSI-C-753 B

FIGURE 11 WATER FEED MECHANISM

TABLE 8 SX-1 STEADY STATE CONTROLLED PARAMETERS

Controlled Parameter	Controlling Function	Adjustments
1. FB101[a] Flash Boiler Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermistor TS 127. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure.
2. HE101 Water Electrolyzer Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermocouple TS 101. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure. Each of the four electrolyzers has a separate set point adjustment.
3. CE101 CO_2 Electrolyzer Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermocouple TS 105. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure. Each of the four electrolyzers has a separate set point adjustment.
4. CE102 CO_2 Electrolyzer Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermocouple TS 109. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure. Each of the four electrolyzers has a separate set point adjustment.

(a) See Figure 2, page 10, for sensor locations.

continued-

SX-1 STEADY STATE CONTROLLED PARAMETERS

Controlled Parameter	Controlling Function	Adjustments
5. CE103 CO_2 Electrolyzer Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermocouple TS 113. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure. Each of the four electrolyzers has a separate set point adjustment.
6. COD101 CO Disproportionator No. 1 Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermocouple TS 117. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure. Each of the two disproportionators has a separate set point adjustment.
7. COD102 CO Disproportionator No. 2 Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermocouple TS 121. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure. Each of the two disproportionators has a separate set point adjustment.
8. HSR101 H_2 Separator Temperature	Error signal representing the difference between the desired set point temperature and the true temperature as measured by thermocouple TS 126. Proportional Control.	Desired set point temperature is a potentiometer setting inside the system control instrumentation enclosure. The feedback temperature measurement may come from either TS 126 or TS 128.

continued-

SX-1 STEADY STATE CONTROLLED PARAMETERS

Controlled Parameter	Controlling Function	Adjustments
9. HE101 Water Electrolyzer Voltage/Current	Manual set point for desired applied voltage. Manual set point for desired max. current limit.	Desired module applied voltage is a potentiometer setting within the control instrumentation enclosure. Desired module max. current limit is a potentiometer setting within the control instrumentation enclosure.
10. CE101 CO_2 Electrolyzer Voltage/Current	Manual set point for desired max. voltage limit. Current controlled by recycle loop pressure in the automatic mode, by a manual set point in the manual mode. Proportional Control.	Desired module max voltage limit is a potentiometer setting within the control instrumentation enclosure. In the automatic mode, there are potentiometer settings to adjust the steady state current/pressure operating point, the current vs pressure loop gain, and the desired max. current limit. All these adjustments are within the control instrumentation enclosure. In the manual mode, there is a potentiometer setting for the desired electrolyzer current. This too is within the control instrumentation enclosure.

continued-

SX-1 STEADY STATE CONTROLLED PARAMETERS

Controlled Parameter	Controlling Function	Adjustments
11. CE102 CO_2 Electrolyzer Voltage/Current	Manual set point for desired max. voltage limit. Current controlled by recycle loop pressure in the automatic mode, by a manual set point in the manual mode. Proportional Control	Desired module max. voltage limit is a potentiometer setting within the control instrumentation enclosure. In the automatic mode, there are potentiometer settings to adjust the steady state current/pressure operating point, the current vs pressure loop gain, and the desired max current limit. All these adjustments are within the control instrumentation enclosure. In the manual mode, there is a potentiometer setting for the desired electrolyzer current. This too is within the control instrumentation enclosure.
12. CE103 CO_2 Electrolyzer Voltage/Current	Manual set point for desired max. voltage limit. Current controlled by recycle loop pressure in the automatic mode, by a manual set point in the manual mode. Proportional Control.	Desired module max. voltage limit is a potentiometer setting within the control instrumentation enclosure. In the automatic mode, there are potentiometer settings to adjust the steady state current/pressure operating point, the current vs pressure loop gain, and the desired max current limit. All these adjustments are within the control instrumentation enclosure. In the manual mode, there is a potentiometer setting for the desired electrolyzer current. This too is within the control instrumentation enclosure.

continued-

Table 8 - continued

SX-1 STEADY STATE CONTROLLED PARAMETERS

Controlled Parameter	Controlling Function	Adjustments
13. P101 Recycle Loop Pump Speed	Error signal representing the difference between the desired set point pump speed and the true pump speed as measured by speed sensor SS 101.	Desired set point pump speed is a potentiometer setting inside the system control instrumentation enclosure.
14. P102 Recycle Loop Pump Speed	Error signal representing the difference between the desired set point pump speed and the true pump speed as measured by speed sensor SS 102.	Desired set point pump speed is a potentiometer setting inside the system control instrumentation enclosure.

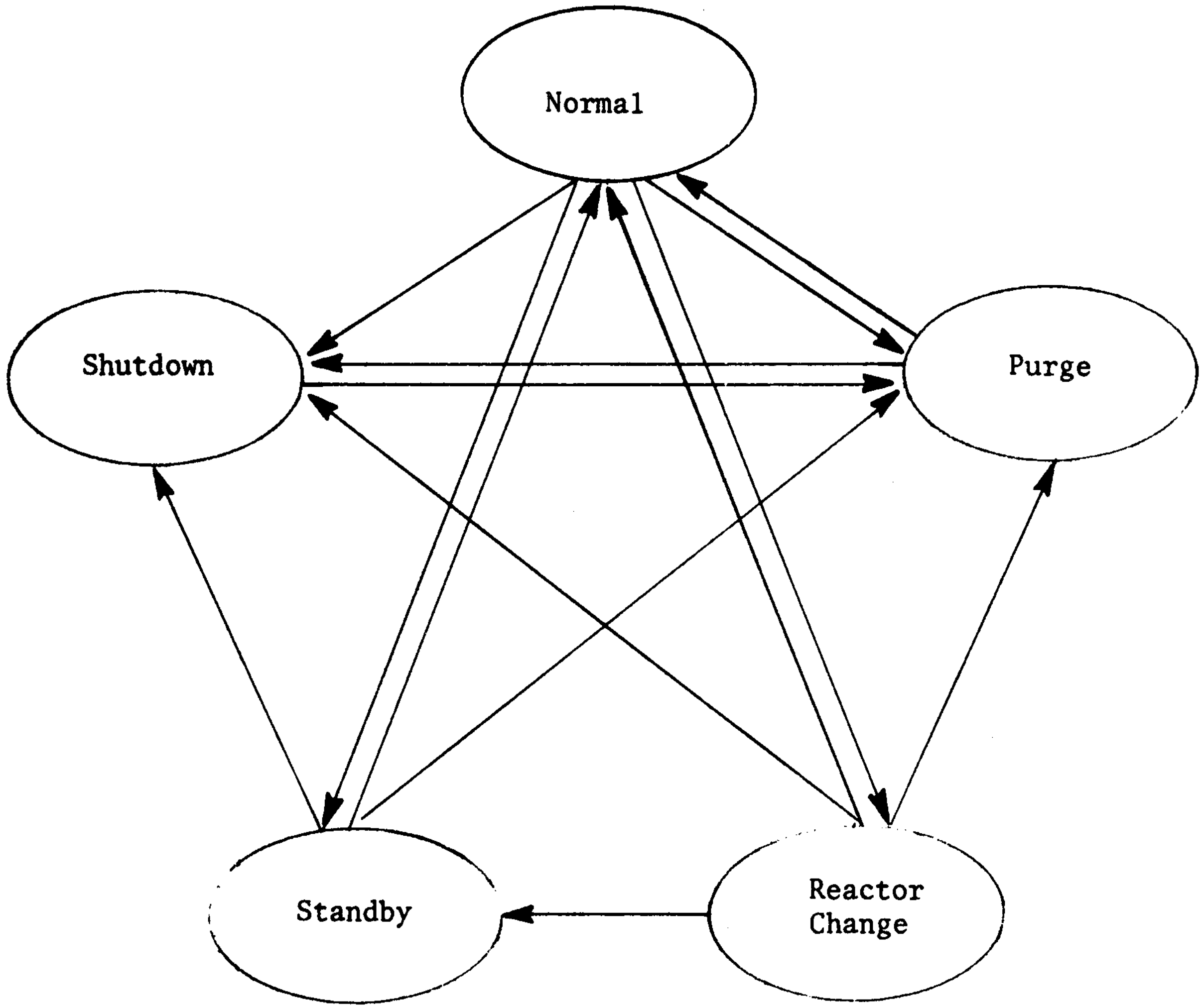


FIGURE 12 SX-1 ALLOWED MODE TRANSITIONS

The flow chart consists of the main program which calls upon five separate subroutines describing the Purge, Normal, Reactor Change, Standby, and Shutdown sequences. In order to follow the flow chart it is necessary to refer to the system schematic which is included as Figure A1-1. The operations described in the flow chart are completely automatic with the exception of the Reactor Change Mode and system startup. In these two cases manual intervention is required. For the Reactor Change Mode, manual intervention is required to configure the Hot Gas Valves in the recycle loop to allow CO_2 Disproportionator switchover and servicing. The manual operations are described in detail in Appendix 1.

To start the system, the operator first depresses the Purge Pushbutton and then the Normal Pushbutton which initiates the automatic sequence as described in Appendix 1. The pushbuttons are shown in Figure 13 which is a picture of the completed Control Instrumentation. The Control Instrumentation is contained in a pull-out drawer mounted within the framework of the SX-1. The system control panel is the front of the drawer. The Control Instrumentation contains 20 printed circuit (PC) cards and these are described in Table 9. The Control Instrumentation also contains four power supplies, 28 photo isolated power relays, 19 manual override switch assemblies, a shutdown counter and an elapsed time meter, and four electrical connectors. The Control Instrumentation's front panel is pictured in Figure 14. This photograph shows the recessed panel with the safety cover removed, revealing a cluster of manual override switches and current control potentiometers and the pump speed control potentiometer. Also indicated on the front panel are the Mode Command Pushbuttons, the CO Disproportionator status indicator and pushbuttons, and the elapsed time meter and event counters. Also present is an override indicator which is used to indicate that any one of the system prime movers are in a manual override condition and a Lamp Test Pushbutton to verify the operation of the lamps in the indicators.

MONITOR INSTRUMENTATION

The SX-1 Monitor Instrumentation functionally provides for three things: (1) the display of Trend and Fault Analysis information, (2) the protection of the system by automatic shutdown or standby, and (3) the conditioning of system sensor signals prior to their being sent to ground support equipment for display in engineering units. In the first of these functions, the Monitor Instrumentation collects signals from the important system sensors, conditions these sensor signals and displays the results with illuminated indicators on the Performance Trend and Fault Analysis Panel. The Performance Trend and Fault Analysis Panel is shown in Figure 15, which is a picture of the Monitor Instrumentation package. The indicators on the Performance Trend and Fault Analysis Panel provide the following information:

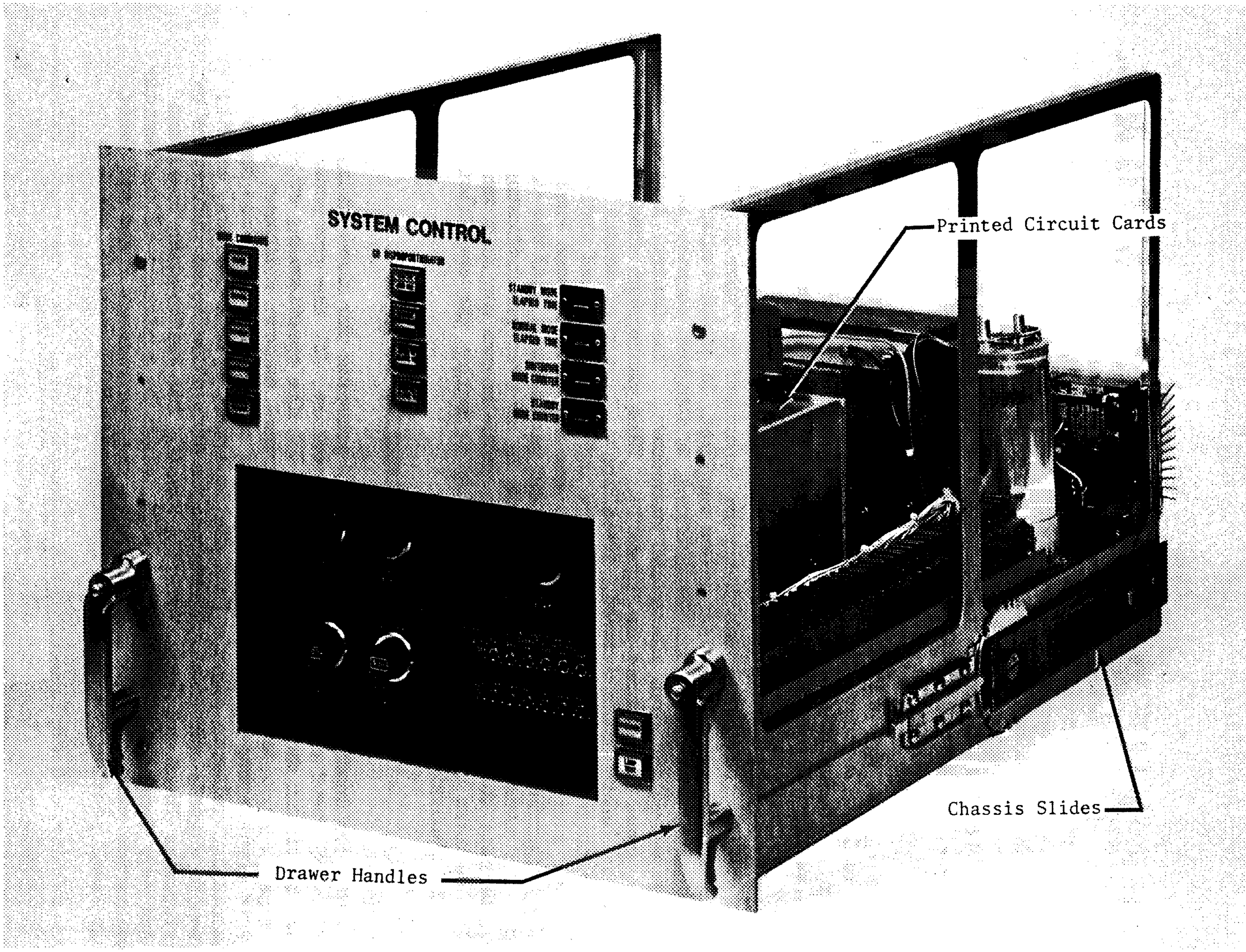


FIGURE 13 CONTROL INSTRUMENTATION

TABLE 9 CONTROL INSTRUMENTATION PC CARD LIST

Qty.	Card No.	Title	Functions
4	A13	Current/Voltage Control (Electrolyzer Modules)	Controls current in electrolyzer cells.
1	AC17	Automatic Slew Control	Generates 276K (37.4F)/Min ramp for Electrolyzer Module temp. control.
4	AC18-1	Temperature Control (Electrolyzer Modules)	Controls Electrolyzer Module temp.
1	AC18-2	Temperature Control (Flash Boiler)	Controls Flash Boiler temperature.
4	AC18-3	Temperature Control (CO Disproportionators and H_2 Separator)	Controls CO Disproportionator and H_2 Separator Temperatures.
1	AC19	Power Switch/Latch	Power driver stage and enable/disable logic electrolyzer module current controllers.
1	AC20	Pump Speed Control	Controls the speed of the recycle loop pump motor.
1	AC21	Main Sequencer "A" (Input Multiplexer)	Multiplexes and latches input signals for sequence generator.
1	AC23	Main Sequencer "C" (Sequence Generator)	Generates sequential control of system.
1	AC24	Main Sequencer "D" (System Clocks & Timers)	Generates system clock and required timeouts.
1	AC25	Main Sequencer "E" (Output Decoder/Driver)	Decodes inputs from sequence generator and drives required output.

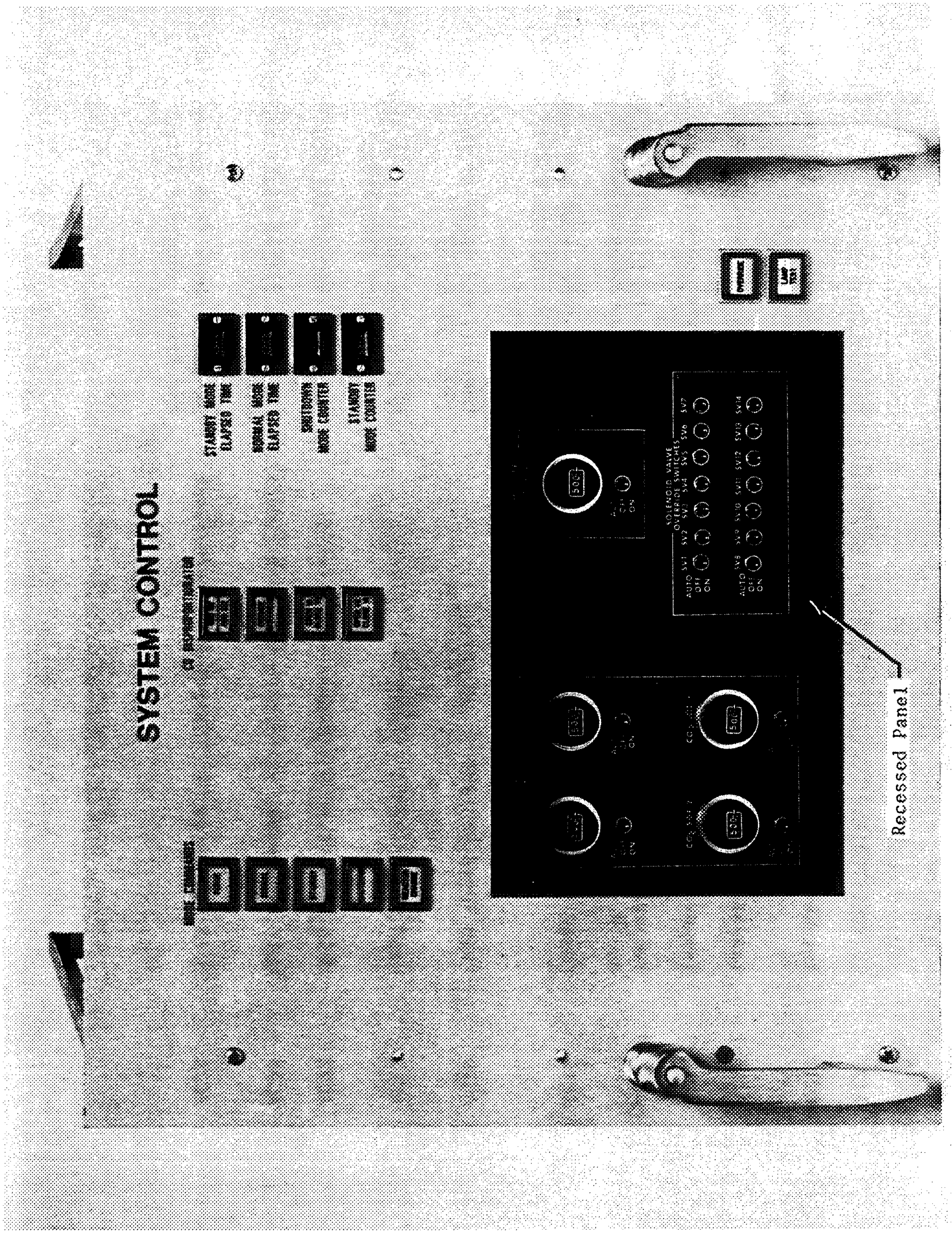


FIGURE 14 CONTROL INSTRUMENTATION FRONT PANEL

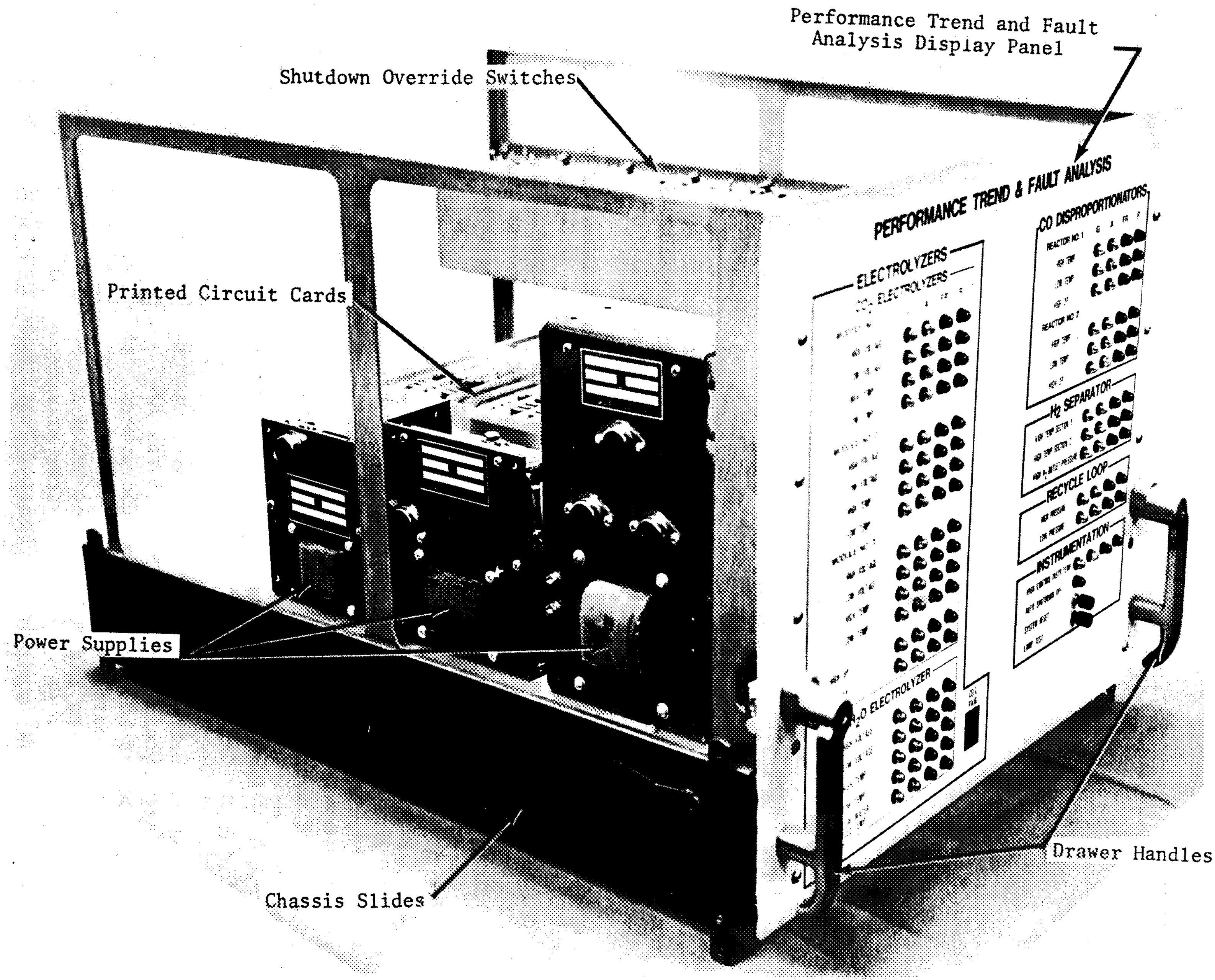


FIGURE 15 MONITOR INSTRUMENTATION

Condition	Color	Response
Normal	Green	No response needed.
Caution	Amber	Condition developing that could result in a hazardous situation; predetermined response necessary but not necessarily time critical.
Warning	Flashing Red	Hazardous condition developing in which urgent action is required by the operator (crew) to avoid an alarm or other serious situation. Predetermined action by operator required, but by direction of lead engineer rather than by automatic reaction.
Alarm	Red	Condition exists causing automatic system shutdown. If a shutdown does not occur, emergency response by the operator is required and predetermined reaction is necessary.

The Performance Trend and Fault Analysis Panel provides the operator of the system with an advanced warning of a parameter moving out of its acceptable operating range and thus allows for the operator to modify system operation to correct for this parameter deviation. The panel further aids detecting and isolating faults in the system when problems do occur.

In the second of these functions, the Monitor Instrumentation provides for automatic system shutdown or standby when a parameter or group of parameters deviate from safe ranges and when such deviations can potentially cause personnel injury or equipment damage. Table 10 lists the SX-1 shutdown causes, possible malfunctions that can cause such shutdowns, shutdown trip levels and the final mode in which the system is automatically placed.

The final function of the Monitor Instrumentation is to condition sensor signals for the ground support display. This conditioning consists of amplification, attenuation, filtering, and scaling of sensor information so that the ground support data can be displayed in engineering units. Table 11 shows the parameters monitored during SX-1 operation, and whether these parameters are monitored on the Performance Trend and Fault Analysis Panel or the Ground Support Panel. The component and sensor identification numbers listed in Table 11 refer to the system schematic which is presented in Figure 2.

The Monitor Instrumentation electronics is contained in a pull-out drawer which is mounted within the framework of the SX-1. The Performance Trend and Fault Analysis Panel is the front of the drawer. Contained within the drawer are all required PC cards, all bias power supplies, all Monitor Instrumentation input/output connectors and 25 switches which allow the system operator to individually inhibit each of the 25 system shutdown protections. Table 12 lists the types of PC cards in the Monitor Instrumentation electronics, the quantity of each type, and their monitor functions.

TABLE 10 SX-1 SHUTDOWN PROTECTION

Shutdown Cause	Possible Malfunctions	Trip Level	Final Mode
1) High HE101 water electrolyzer temperature	Controller failure, sensor failure	1133 K(1580F)	Shutdown
2) Low HE101 water electrolyzer temperature	Controller failure, sensor failure, heater failure	1113 K(1544F)	Standby
3) High CE101 CO_2 electrolyzer temperature	Controller failure, sensor failure	1133 K(1580F)	Shutdown
4) Low CE101 CO_2 electrolyzer temperature	Controller failure, sensor failure, heater failure	1113 K(1544F)	Standby
5) High CE102 CO_2 electrolyzer temperature	Controller failure, sensor failure	1133 K(1580F)	Shutdown
6) Low CE102 CO_2 electrolyzer temperature	Controller failure, sensor failure, heater failure	1113 K(1544F)	Standby
7) High CE103 CO_2 electrolyzer temperature	Controller failure, sensor failure	1133 K(1580F)	Shutdown
8) Low CE103 CO_2 electrolyzer temperature	Controller failure, sensor failure, heater failure	1113 K(1544F)	Standby
9) High COD101 CO disproportionator temperature	Controller failure, sensor failure	848 K(1067F)	Shutdown
10) Low COD101 CO disproportionator temperature	Controller failure, sensor failure, heater failure	798 K(977F)	Standby

continued-

Table 10 - continued

Shutdown Cause	Possible Malfunctions	Trip Level	Final Mode
11) High COD102 CO disproportionator temperature	Controller failure, sensor failure	848 K(1067F)	Shutdown
12) Low COD102 CO disproportionator temperature	Controller failure, sensor failure, heater failure	798 K(977F)	Standby
13) High HSR101 H_2 separator temperature	Controller failure, sensor failure	693 K(788F)	Shutdown
14) High HSR102 H_2 separator temperature	Controller failure, sensor failure	658 K(725F)	Shutdown
15) High C101 control instrumentation temperature	Controller failure, sensor failure	338 K(149F)	Standby
16) Low FB101 flash boiler temperature	Controller failure, sensor failure, heater failure	383 K(230F)	Standby
17) High drum voltage in HE101, CE101, CE102 or CE103	Electrolyzer drum failure	4.4 VDC	Standby
18) High ΔP across CE101, CE102 and CE103	Blockage in electrolyzer module	$2.49 \times 10^3 N/m^2$ (10 in of H_2O)	Standby
19) Low ΔP across CE101, CE102 and CE103	Leak in the electrolyzer module, low flow through the modules due to a system blockage	$2.49 \times 10^2 N/m^2$ (1 in of H_2O)	

continued-

Table 10 - continued

	Shutdown Cause	Possible Malfunctions	Trip Level	Final Mode
20)	High recycle loop pressure	System blockage, build up of non-electrolyzable gas in the loop, electrolyzer malfunction, H_2 separator failure	$1.21 \times 10^4 N/m^2$ above ambient (1.75 Psig)	Standby
21)	Low recycle loop pressure	Leak in the system, controller failure, H_2 separator failure	$1.72 \times 10^3 N/m^2$ above ambient (0.25 Psig)	Standby
22)	High Δ P across COD101 when it is "on line"	Blockage in the CO disproportionator	TBD	Standby
23)	High Δ P across COD102 when it is "on line"	Blockage in the CO disproportionator	TBD	Standby
24)	High HSR101 output pressure	H_2 separator failure, H_2 line blockage, ground support vacuum pump failure	$3.45 \times 10^3 N/m^2$ (0.5 Psia)	Standby
25)	Low drum voltage in HE101, CE101, CE102, or CE103	Electrolyzer drum failure	2.0 VDC	Standby

TABLE 11 SX-1 MONITORED PARAMETERS

Monitored Parameter	SX-1 Trend and Fault Analysis Panel		SX-1 Ground Support Panel	
	Type of Display	Comments	Type of Display	Comments
1) HE101[a] water electrolyzer oven temperature			Digital panel meter temperature readout	From TS101 via control instru mentation
2) HE101 water electrolyzer module temperature	Two sets of four level trend and fault indicators, one each for high and low temperature	From TS102	Digital panel meter temperature readout	From TS102 via monitor instru mentation
			Thermocouple test points	From TS103 and TS104
3) CE101 CO_2 electrolyzer oven temperature			Digital panel meter temperature readout	From TS105 via control instru mentation
4) CE101 CO_2 electrolyzer module temperature	Two sets of four level trend and fault indicators, one each for high and low temperature	From TS106	Digital panel meter temperature readout	From TS106 via monitor instru mentation
			Thermocouple test points	From TS107 and TS108
5) CE102 CO_2 electrolyzer oven temperature			Digital panel meter temperature readout	From TS109 via control instru mentation
6) CE102 CO_2 electrolyzer module temperature	Two sets of four level trend and fault indicators, one each for high and low temperature	From TS110	Digital panel meter temperature readout	From TS110 via monitor instru mentation

(a) All functional item numbers are referenced to Figure 2, page 10

continued-

Table 11 - continued

Monitored Parameter	SX-1 Trend and Fault Analysis Panel		SX-1 Ground Support Panel	
	Type of Display	Comments	Type of Display	Comments
7) CE103 CO_2 electrolyzer oven temperature			Digital panel meter temperature readout	From TS113 via control instrumentation
8) CE103 CO_2 electrolyzer module temperature	Two sets of four level trend and fault indicators, one each for high and low temperature	From TS114	Digital panel meter temperature readout	From TS114 via monitor instrumentation
			Thermocouple test points	From TS115 and TS116
9) COD101 CO disproportionator oven temperature			Digital panel meter temperature readout	From TS117 via control instrumentation
10) COD101 CO disproportionator internal temperature	Two sets of four level trend and fault indicators, one each for high and low temperature	From TS118	Digital panel meter temperature readout	From TS118 via monitor instrumentation
			Thermocouple test points	From TS119 and TS120
11) COD 102 CO disproportionator oven temperature			Digital panel meter temperature readout	From TS121 via control instrumentation
12) COD102 CO disproportionator internal temperature	Two sets of four level trend and fault indicators, one each for high and low temperature	From TS122	Digital panel meter temperature readout	From TS122 via monitor instrumentation
			Thermocouple test points	From TS123 and TS124

continued-

Table 11 - continued

Monitored Parameter	SX-1 Trend and Fault Analysis Panel		SX-1 Ground Support Panel	
	Type of Display	Comments	Type of Display	Comments
13) C101 control instrumentation temperature	A set of four level trend and fault indicators for high temperature	From TS125		
14) HSR101 H_2 separator oven temperature			Digital panel meter temperature readout	From TS126 via control instrumentation
15) HSR101 H_2 separator internal temperature	A set of four level trend and fault indicators for high temperature	From TS129	Digital panel meter temperature readout	From TS129 via monitor instrumentation
16) HSR102 H_2 separator oven temperature			Digital panel meter temperature readout	From TS128 via control instrumentation
17) HSR102 H_2 separator internal temperature	A set of four level trend and fault indicators for high temperature	From TS130	Digital panel meter temperature readout	From TS130 via monitor instrumentation
18) FB101 flash boiler temperature	A set of four level trend and fault indicators for low temperature	From TS127 via control instrumentation	Analog panel meter temperature readout	From TS127 via control instrumentation
19) HE101 water electrolyzer individual drum voltages (8)	Two sets of four level trend and fault indicators, one each for high and low drum voltage. The eight individual drums are scanned by a multiplexer.	From voltage taps VS-101-1 through VS-101-8.	Analog panel meter voltage readouts for each drum	From voltage taps VS-101-1 through VS-101-8 via monitor instrumentation

continued -

Table 11 - continued

Monitored Parameter	SX-1 Trend and Fault Analysis Panel		SX-1 Ground Support Panel	
	Type of Display	Comments	Type of Display	Comments
20) CE101 CO_2 electrolyzer individual drum voltages (8)	Two sets of four level trend and fault indicators, one each for high and low drum voltage. The eight individual drums are scanned by a multiplexer.	From voltage taps VS-102-1 through VS-102-8	Analog panel meter voltage readouts for each drum	From voltage taps VS-102-1 through VS-102-8 via monitor instrumentation
21) CE102 CO_2 electrolyzer individual drum voltages (8)	Two sets of four level trend and fault indicators, one each for high and low drum voltage. The eight individual drums are scanned by a multiplexer.	From voltage taps VS-103-1 through VS-103-8.	Analog panel meter voltage readouts for each drum	From voltage taps VS-103-1 through VS-103-8 via monitor instrumentation
22) CE103 CO_2 electrolyzer individual drum voltages (8)	Two sets of four level trend and fault indicators, one each for high and low drum voltage. The eight individual drums are scanned by a multiplexer.	From voltage taps VS-104-1 through VS-104-8	Analog panel meter voltage readouts for each drum	From voltage taps VS-1-4-1 through VS-104-8 via monitor instrumentation
23) HE101 water electrolyzer module voltage			Digital panel meter voltage readout	From VS101 via control instrumentation
24) CE101 CO_2 electrolyzer module voltage			Digital panel meter voltage readout	From VS102 via control instrumentation
25) CE102 CO_2 electrolyzer module voltage			Digital panel meter voltage readout	From VS103 via control instrumentation

continued-

Table 11 - continued

Monitored Parameter	SX-1 Trend and Fault Analysis Panel		SX-1 Ground Support Panel	
	Type of Display	Comments	Type of Display	Comments
26) CE103 CO_2 electrolyzer module voltage			Digital panel meter voltage readout	From VS104 via control instrumentation
27) HE101 water electrolyzer module current			Digital panel meter current readout	From CS101 via control instrumentation
28) CE101 CO_2 electrolyzer module current			Digital panel meter current readout	From CS102 via control instrumentation
29) CE102 CO_2 electrolyzer module current			Digital panel meter current readout	From CS103 via control instrumentation
30) CE103 CO_2 electrolyzer module current			Digital panel meter current readout	From CS104 via control instrumentation
31) ΔP across CE101 through CE103 CO_2 electrolyzers	Two sets of four level trend and fault indicators, one each for high and low ΔP	From PS101	Analog panel meter ΔP readout	From PS101 via monitor instrumentation
32) Recirculation loop pressure	Two sets of four level trend and fault indicators, one each for high and low pressure	From PS102	Analog panel meter pressure readout	From PS102 via monitor instrumentation
33) ΔP across COD101 CO disproportionator	A set of four level trend and fault indicators for high ΔP	From PS103	Analog panel meter pressure readout	From PS103 via monitor instrumentation

continued-

Table 11 - continued

Monitored Parameter	SX-1 Trend and Fault Analysis Panel		SX-1 Ground-Support Panel	
	Type of Display	Comments	Type of Display	Comments
34) ΔP across COD102 CO disproportionator	A set of four level trend and fault indicators for high ΔP	From PS104	Analog panel meter pressure readout	From PS104 via monitor instrumentation
35) Vacuum pressure of HSR101 and HSR102 H_2 separators	A set of four level trend and fault indicators for high vacuum pressure	From PS105		
36) P101 bellows pump drive motor speed			Analog panel meter speed readout	From SS101 via control instrumentation

TABLE 12 MONITOR INSTRUMENTATION
PRINTED CIRCUIT CARD LIST

Qty.	Card No.	Title	Monitor Function(s)
1	B2	Thermistor Temperature Monitor	High instrumentation temperature
14	B6	0 to 5 VDC Monitor	Low electrolyzer, disproportionator and flash boiler temperatures, high and low CO_2 electrolyzer ΔP, high and low recycle loop pressure, high disproportionator ΔP and high H_2 separator vacuum pressure.
8	B7	Voltage Level Monitor	High and low electrolyzer drum voltages
4	BC14	Multiplexer Switches	Scan of electrolyzer drum voltages
1	BC15	Multiplexer Timing	Scan of electrolyzer drum voltages
8	BC16	Thermocouple Temperature Monitor	High electrolyzer, disproportionator and H_2 separator temperatures
1	I1	Logic Interface	Input/output interface
37	Total Monitor Printed Circuit Cards		

GROUND SUPPORT ACCESSORIES

Various items of support equipment are required to simulate the actual spacecraft interfaces of the SX-1. These GSA, shown in Figure 16, are needed to compensate for the absence of spacecraft cabin resources (power, water, space vacuum and N_2 purge) to synthesize the exhaust gas from the various CO_2 collection subsystems over the operating ranges required during the subsystem parametric testing, and to monitor subsystem operation throughout the test program. Four distinct GSA were provided: (1) Ground Checkout Unit (GCU), (2) Fluid Supply Unit (FSU), (3) Space Vacuum Simulator (SVS), and (4) Gas Products Monitor (GPM).

Ground Checkout Unit

The GCU provides for the analog readout of parameters necessary to monitor the performance of the subsystem during the program test phase. Since the SX-1 does not require the GCU instrumentation to perform its intended function, the GCU has been designed only to read out important parametric test data. The front panel of the GCU, shown in Figure 17 is called the Parametric Data Display Panel. It contains five digital panel meters which display Electrolyzer Module voltage, Electrolyzer Module current, Electrolyzer Module temperature, CO Disproportionator temperature and H_2 Separator temperature. Adjacent to the digital panel meters are thumbwheel switches which allow data from each of the various system components to be individually displayed. The GCU also contains 37 edge-type analog panel meters. Thirty-two of these meters are used to monitor individual electrolyzer drum voltages (eight drums in each of the four electrolyzer modules). The remaining five meters are used to monitor CO_2 Electrolyzer differential pressure, recycle loop pressure, CO Disproportionator differential pressure, Recycle Loop Bellows Pump speed and Water Feed Mechanism temperature.

Also provided on the Parametric Data Display Panel is a temperature output terminal and corresponding selector switch which provides thermocouple connectors to allow monitoring of the system's auxiliary temperature sensors. The auxiliary temperature sensors are mounted at various places in the Electrolyzer Modules and CO Disproportionators. Since these signals are not processed by the Control or Monitor Instrumentation, the sensor information must be monitored by an external instrument. The temperature selector shown on the GCU front panel chooses which sensor information is presented at the output connectors.

The final data display on the GCU is the subsystem's status summary. This display provides information summarizing the status (shutdown, alarm, warning, caution or normal) of the parameters monitored by the Monitor Instrumentation. An operator can quickly check on qualitative system operation by observing the system status summary display.

Fluid Supply Unit

The FSU is designed to simulate the feed gas mixtures from any of the three CO_2 collection subsystems, the EDC, the molecular sieve and the steam desorbed

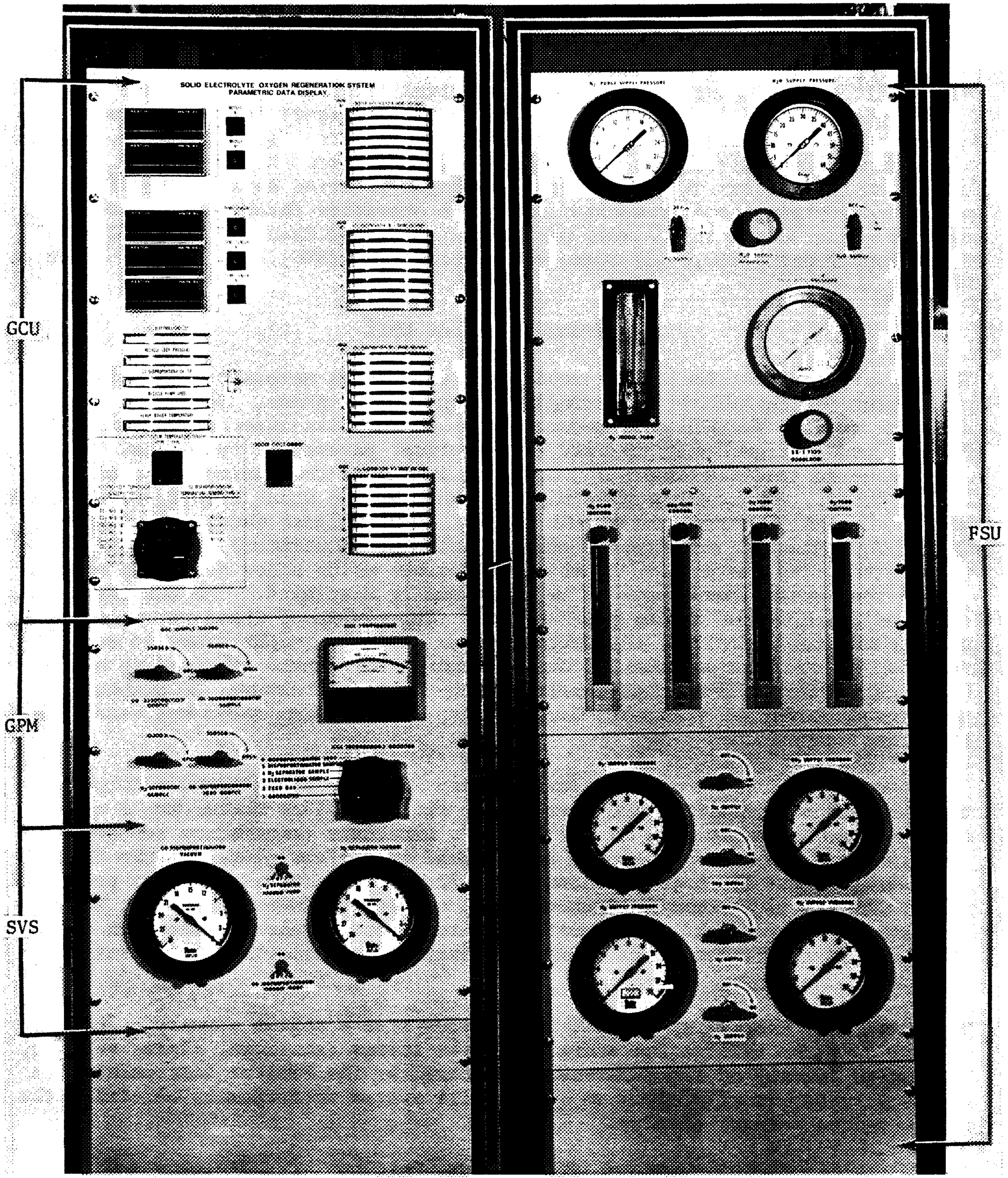


FIGURE 16 SX-1 GROUND SUPPORT ACCESSORIES

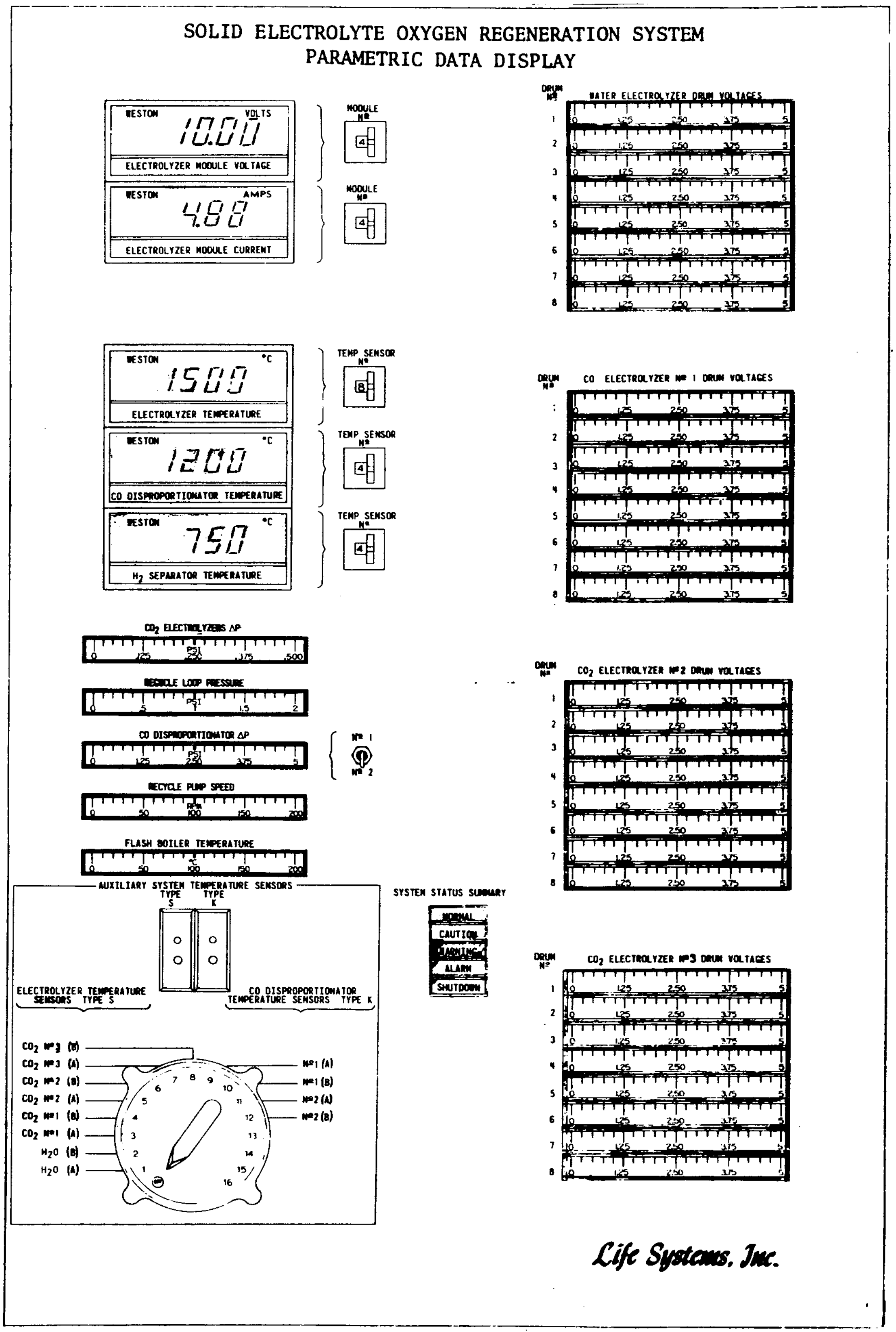


FIGURE 17 GROUND CHECKOUT UNIT PANEL

solid amine, which could interface with the SX-1. The unit consists of mass flow controllers, mass flowmeters, deionized water accumulator, a gas humidifier, pressure regulators and various sensors, fittings and tubing. A schematic of the FSU is presented in Figure 18. Hydrogen, N_2, CO_2 and O_2 are supplied to the FSU where they are regulated to simulate the exhaust from any CO_2 collection subsystem. Check valves in the H_2 and O_2 lines insure that no upstream mixing can occur in case of mechanical failure. The gases are mixed and humidified to a selected water vapor content and then flow through a moisture trap, dew point sensor and into the SX-1. The feed gas delivery pressure can be varied between 101 and 136 kN/m^2 above ambient (0 and 5 psig).

Distilled water is supplied to the SX-1 Water Feed Mechanism by filling an accumulator and then pressurizing it with air. This allows the water to be delivered to the Water Feed Mechanism at a preset flow rate without entrapped air. Provisions have been included to allow for the refilling of both the feed gas humidifier and distilled water accumulator. The FSU supplies the SX-1 with 308 kN/m^2 above ambient (30 psig) N_2 for startup, CDC replacement and shutdown. In addition, if the SX-1 experiences a total power failure, the FSU contains a battery-powered emergency purge unit which will supply N_2 to the subsystem for two minutes.

Space Vacuum Simulator

A SVS was designed to furnish the SX-1 with the vacuum normally encountered when the system is venting to space. The SVS consists of two mechanical type vacuum pumps, two vacuum gauges, and associated tubing and fittings. One pump maintains a vacuum on the H_2 Separator which remains constant and unaffected by pressure fluctuations during subsystem operation. The other pump is used to evacuate the CO Disproportionator prior to cartridge replacement. The CO Disproportionator is first evacuated then refilled with N_2, thereby eliminating the possibility of toxic gases escaping during the maintenance activities.

Gas Products Monitor

The GPM allows the exhaust gases from the SX-1 to be monitored and sampled. The H_2 and O_2 exhaust lines from the Water Electrolyzer Module and the O_2 lines from the CO_2 Electrolyzer Modules are plumbed into the GPM so that they can either be vented or fed directly into a gas chromatograph for analysis; thereby allowing the product gases to be sampled without affecting the operation of the subsystem. Ports are also provided to sample the recycle loop gases at the CO Disproportionator, the CO Electrolyzer and H_2 Separator, and the CO Disproportionator vent gas. Provisions to monitor gas temperatures at these locations are also included. The feed gas humidifier and feed gas delivery temperatures in the FSU, the recycle loop samples and the CO Disproportionator vent temperatures can be displayed. Hydrogen and CO sensors were placed near the system to insure personnel and equipment safety.

PRODUCT ASSURANCE PROGRAM

The Product Assurance Program encompassed the activities associated with Quality Assurance, Reliability, Safety and Maintainability.

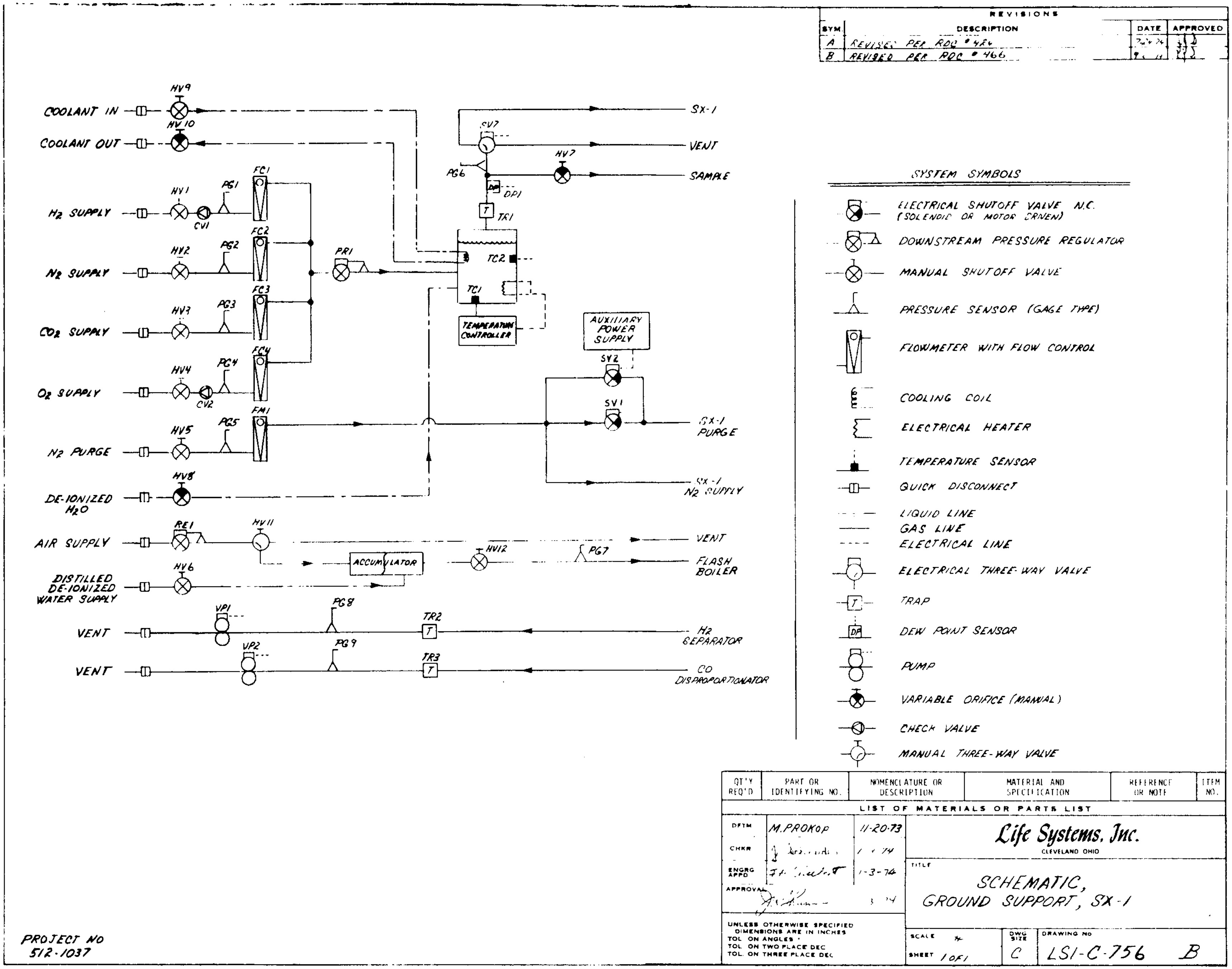


FIGURE 18 SX-1 FSU SCHEMATIC

ORIGINAL PAGE IS OF POOR QUALITY

Quality Assurance

The Quality Assurance activities for the SX-1 consisted of the following:

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

2. Participation in the design phase of the SX-1 program to insure the incorporation of Quality Assurance considerations in component and system design.

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

4. Monitor of all SX-1 testing.

5. Preparation and maintenance of system and component specifications.

6. Preparation of a failure reporting procedure which was to be utilized during the SX-1 Endurance Testing.

Reliability

The Reliability activities carried out during the SX-1 development program consisted of performing a Failure Mode Effects and Criticality Analysis (FMECA) and participation in component and system design to insure that concepts such as overdesign, derating and redundancy were incorporated.

For the FMECA that was performed on the SX-1 system, each component, as shown on the system schematic, was analyzed with regard to its failure modes, the failure effect on component/functional assembly, the failure effect on the system, the failure detection method, and crew action required. A criticality level was assigned to each failure mode as described below:

<u>Criticality</u>

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 revealed that the SX-1 contains criticality IIa failure modes. These failure modes are the external leakage failure mode of all components which carry H_2 or CO. If these failure modes are allowed to persist, dangerous levels of H_2 or CO could be attained in the cabin atmosphere. The next associated failure which could cause loss of personnel would be the failure of a detector whose function would be to detect the leak and initiate system shutdown and N_2 purge. For flight applications, this hazard would be reduced by incorporating redundant H_2 and CO level detectors. An example of a FMECA is presented in Figure 19.

Safety

A major effort was made during the design phase of the SX-1 to include those safety features which would minimize danger to personnel. Consideration was given to the operational functions of the system and to all maintenance functions that must be performed. In addition, equipment protection features were incorporated in the safety design criteria to insure that off-design system operation would not result in damage to system components. Fail-safe characteristics, safety interlocks and system shutdown instrumentation were included in the system design to insure safety.

The safety design criteria utilized during the design, fabrication, assembly and testing of the SX-1 is divided into three sections: System Design Guidelines, Mechanical Design Guidelines, and Electrical Design Guidelines.

System Design Guidelines

1. Personnel safety will not be compromised in meeting system performance requirements.

2. A single failure in one component will not cause successive failures in other components.

3. A single failure of any component will not expose personnel to the possibility of injury.

4. All hazardous failure modes that are identified in the FMECA will be eliminated by incorporation of safety interlocks, instrumentation and/or system shutdown.

5. The system will be designed so that all maintenance can be accomplished without hazard to personnel.

6. Service points for the fluids and gases involved will be designed with positive protection by location, connector size or type to prevent connection to incorrect fluid and gas service lines.

7. All components that require protective devices will be interconnected in such a way that failure of a single element will not fail both devices.

Life Systems, Inc. CLEVELAND, OHIO 44122	FAILURE MODE, EFFECTS & CRITICALITY ANALYSIS	PAGE 1 OF 2	REVISION LTR.
			DATE

TITLE H_2 SEPARATOR, ITEM NO. HSR101 and HSR102 — ☐ SUBSYSTEM ☐ LOOP ☒ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
HSR-101 and HSR-102	N/A	H_2 Separator	To remove H_2 from the SX-1 feed gas and recycle loop gas.

FAILURE MODE AND CAUSE:	CRITICALITY
a. Control or monitor temperature sensor fails low, caused by open couple or electronic malfunction.	a. III
b. Control or monitor temperature sensor fails high, caused by shorted couple or electronic malfunction.	b. III
c. Heater fails.	c. III
d. Internal leakage-recycle loop gases to H_2 vent, caused by O-ring leak, weld degradation or Pd/Ag tube rupture. (continued on page 2)	d. III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

a. If the control sensor fails low the instrumentation, upon receiving a low temperature signal will increase heater current, if the monitor sensor fails low there will be no effect except that if the control sensor also fails low (double failure) the separator would continue to heat without any provisions for shutdown.

b. If the controls sensor fails high, the control instrumentation will decrease heater current, if the monitor sensor fails high, an automatic system shutdown will be caused.

c. The heater will no longer maintain the separator temperature.

d. It will be more difficult to maintain H_2 vent vacuum.

e. Recycle loop gas will be admitted to the cabin.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

a. If the control sensor fails low, a system shutdown will ensue initiated by the monitor temperature sensor. If the monitor temperature sensor fails low, then the system will lose its shutdown capability for high H_2 separator temperature and, in the event of the control temperature sensor also failing low (double failure), there will be no means for shutdown and the H_2 separator would be damaged by exposure to high temperature.

b. If the control sensor fails high, the temperature of the H_2 separator will decrease, its H_2 removal capability will decrease and eventually a subsystem shutdown,

(continued on page 2)

FAILURE DETECTION METHOD:

a, b, c. Redundant temperature sensor.
d. Recycle loop and separator exhaust pressure sensor.
e. CO and combustible.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
a, b, c, d, e. Replacement of separator. (a) After system cool-down	0.2 Hr[a]	N/A

continued-

FIGURE 19 FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

Figure 19 - continued

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

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
HSR-101 and HSR-102	N/A	H_2 Separator	To remove H_2 from the SX-1 feed gas and recycle loop gas.

FAILURE MODE AND CAUSE:	CRITICALITY
e. External leakage.	e. IIa

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

caused by high recycle loop pressure, will occur. If the monitor temperature sensor fails high, a subsystem shutdown would occur.

c. Temperature of H_2 separator will decrease, H_2 removal capacity will also decrease. Eventual system shutdown will occur because of high recycle loop pressure.

d. Loss of feed gas and recycle loop pressure, a low pressure shutdown would ensue.

e. The recycle loop gases (H_2, CO, CO_2) would be admitted to the cabin atmosphere. System shutdown initiated by ambient CO or H_2 level detectors will occur.

FAILURE DETECTION METHOD:

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.

8. Mounting and connections will be designed so that the component or its connections cannot be inadvertently reversed.

9. Manual override techniques will be provided for critical automatic functions to permit safe operation to shut down during an emergency.

10. Since the system will contain hazardous and toxic gases (H_2 and CO) a N_2 purge will be incorporated so that a system purge can be performed prior to startup, after shutdown and prior to performing maintenance activities.

11. Hydrogen and CO gas monitors will be installed near the system in strategic locations to sense for leakage of these hazardous gases. The units will alarm and the system will be shut down when H_2 and/or CO concentration reaches dangerous levels.

12. The system will be designed so that components that are susceptible to pressure damage are protected. Protection can be by incorporation of pressure relief valves or system shutdown followed by venting and N_2 purge.

13. Overtemperature protection by automatic shutdown will be incorporated for those components that are susceptible to high temperature damage.

14. A caution and warning system will be incorporated into the instrumentation design to provide an indication prior to occurrence of a dangerous situation. This will consist of Life Systems' Trend and Fault Analysis instrumentation.

15. All known possibilities of human error in system operation will be eliminated. Accidental activation of system components of the system itself, which might cause damage, will be given special consideration to minimize or eliminate the possibility of accidental actuation. Noncritical controls will be located in areas where accidental actuation is improbable, critical controls will be protected by a physical guard. Where sequence of operations is critical, an interlock system which prevents out-of-order manipulation of controls will be used. All such sequential operations will be designed so that operation is automatic upon issuing the command to start up, shut down or to change operating mode. In an override condition, labels and warnings will be posted to prevent out-of-sequence operation.

16. Human engineering consideration will be given to both operation and maintenance of the SX-1. Special attention will be given to the handling provisions, visual displays, illumination, and labels. The company's safety program includes analysis to determine where human error during operation and maintenance could cause a safety hazard. This information will be incorporated into the final design to minimize the chance of human error causing a safety hazard.

17. Provisions will be included in the system design to insure that the product O_2 gas meets NASA purity requirements. Product O_2 purity will be monitored throughout system testing.

18. The automatic system shutdowns that are projected for inclusion in the design of the SX-1 are listed in Table 10.

Mechanical Design Guidelines

1. All high temperature components will be insulated so that the surface temperature during operation is less than 323K (120F). In the event this is not practical, then warning signs and a protective standoff will be incorporated to protect personnel.

2. Carbon formation in the recycle loop will be prevented by screening components for unacceptable materials and replacing materials where required. Electroless nickel plated stainless steel, Inconel, Monel and copper are materials which will not catalyze the carbon formation reaction and will be acceptable for use in the recycle loop.

3. All moving parts will be shielded to prevent accidental contact with personnel.

4. Application of factors of safety typical for aerospace hardware will be incorporated into the design of structural components and parts.

5. Sharp edges and corners will be eliminated or will be adequately covered with a protective cushion to prevent injuries.

6. In order to avoid fatigue failures, the following guidelines will be adhered to:

    a. Parts will be designed such that residual stress and surface defects are minimized.

    b. Fillet radii will be made as generous as possible.

    c. Sharp edges will be broken.

    d. Corrosion protection of metals will be considered to avoid corrosion fatigue problems.

7. A procedure for describing the safe handling of the hazardous gases in the system will be prepared and implemented during the operation of the system and testing of the various components.

Electrical Design Guidelines

1. All electrical equipment will be enclosed in vented containers.

2. The power supplies utilized in the system will be designed to accept peak and transients which may occur.

3. Circuit breakers will be incorporated in the ground support to protect electrical equipment from unexpected high current. All DC supplies in the system will have current limits to prevent component damage.

4. All electronic enclosures will be grounded.

5. Electrical equipment which could contact personnel or other conductive equipment that could contact personnel will be equipped with current limiting devices which prevents an injurious current from passing through the human body. Limiting currents will be as defined in NASA CR-1205, "Compendium of Human Responses to the Aerospace Environment," Vol. 1, Section 5.

6. Electrical connectors, plugs and receptacles will be positively keyed to prevent incorrect mating with other accessible connectors, plugs, or receptacles.

7. Wherever practical, the "hot" (live) electrical connectors will be the (female) socket.

8. Electrical circuits will not be routed through adjacent pins of an electrical connector if a short between them will constitute a failure that could cause a serious disaster.

9. Warning labels will be provided on all access panels leading to high voltages.

Maintainability

The Maintainability features designed and incorporated into the SX-1 follow:

1. The SX-1 components were overdesigned where possible to preclude failure of components resulting from operation at or near their maximum operational tolerance.

2. Automatic control was incorporated into the SX-1 to vary CO_2 Electrolyzer Module current to compensate for variable CO_2 feed rates and to provide the controlled sequencing of components when changing from one operating mode to another.

3. Performance trend and fault analysis instrumentation was included in the SX-1 to provide advance warning of out-of-specification operating conditions. This serves to avoid system shutdowns by alerting test engineers of problems before they degrade system performance.

4. Equipment protection features were included in the system design to increase the operating life of the SX-1. These include the incorporation of safety shutdowns for out-of-tolerance temperatures and pressures.

5. The only identified servicing are the activities associated with the Reactor Change operating mode and monitoring of the System Status Summary on the Parametric Data Display Panel. The system was designed such that the Reactor Changeover does not interrupt system operation.

6. The SX-1 was packaged for ease of accessiblity to all components with the exception of the Electrolyzer Module and CO Disproportionator heaters. A failure of one of these heaters would involve a significant maintenance activity involving the removal and replacement of insulation.

7. A Standby Mode was incorporated in the design to prevent unnecessary temperature cycling of the SX-1 components, in particular, the Electrolyzer Modules. The Standby Mode is similar to the Shutdown Mode except all system heaters remain on and the temperatures of all components are controlled at their normal operation set points.

PROGRAM TESTING

The SX-1 testing activity was to consist of a five part effort:

1. Component Checkout and Calibration Tests
2. Major component DVT
3. SX-1 Checkout and Shakedown Tests
4. SX-1 Parametric Tests
5. SX-1 Endurance Tests

Due to the occurrence of electrolyzer drum leakage, the DVT of the Electrolyzer Modules and the system checkout, shakedown, parametric and endurance testing were not performed. The component DVTs that were performed are discussed below.

Electrolyzer Drum Leak Tests

The Electrolyzer Drums used in the electrolyzer modules were fabricated, assembled and tested under Contract NAS2-6412. They were to be made available as Government-Furnished Property (GFP) for assembly into the SX-1 Electrolyzer Modules. Twenty-nine electrolyzer drums were reported as acceptable at the conclusion of NAS2-6412.[17] Upon receipt of the GFP electrolyzer drums, they were leak-tested using a $\Delta t/\Delta P$ leak test procedure. This procedure involves pressurizing the electrolyzer drums to 15.2 cm (6.0 in) of water, isolating the drum being tested and monitoring the time required for the pressure inside the drum to drop from 15.2 cm (6.0 in) of water to 12.7 cm (5.0 in). Electrolyzer drums taking less than two minutes for the pressure to decrease from 15.2 cm to 12.7 cm (6.0 to 5.0 in) of water are rejected. The electrolyzer drums are baked at 423K (302F) prior to the test to insure that condensation is removed from any microporosity that might be present. If the moisture is not removed, false high $\Delta t/\Delta P$ data can be obtained. The results of the $\Delta t/\Delta P$ test are presented in Table 13. Thirty-one drums were tested: 6 were acceptable, 2 were marginally acceptable and 23 did not meet the requirements of the $\Delta t/\Delta P$ test. Since the subject Electrolyzer Drums were previously tested at the conclusion of NAS2-6412 (approximately 28 months prior to the test reported here), it appears that either the electrolyzer drum seals are subject to degradation with time, or at some time during their storage, since the conclusion of NAS2-6412, they were inadvertently exposed to an excessive thermal gradient which deteriorated the precious metal/ceramic seals.

Attempts were made to reseal the electrolyzer drums by placing the drums in a resealing fixture and then heating them to the brazing temperature, 1353K (1976F), at a rate not exceeding 3K (5.4F) per minute. Only five of the leaky Electrolyzer Drums resealed.

It was postulated that if the seal failure was at a metal-to-metal joint, then the reseal procedure would be successful. However, if the seal failure was at a precious metal-to-ceramic joint, the reseal furnace run would do no good as the molten gold braze material would not wet the ceramic.

Hydrogen Separator DVT

The H_2 Separators are used within the SX-1 recycle loop and the feed gas line to remove excess H_2 from the respective gas flows. A picture of one of the H_2 Separators is shown in Figure 9. A DVT was performed on the H_2 Separators which verified that both separators were leak-tight and that the performance of each separator exceeded the design requirement by more than 25%. The design requirement is a H_2 separation rate of 0.322 cm^3/s (0.68×10^{-3} scfm) when operating at 645K (702F). Summary data is provided in Table 14.

CO Disproportionator DVT

The CO Disproportionator is required in the SX-1 to convert the CO formed by the CO_2 Electrolyzer Modules into carbon and CO_2 for eventual recycling into the Electrolyzer Modules. The CO Disproportionator is shown in Figure 7. It was determined during the DVT of the CO Disproportionator that carbon was formed in areas other than the CDC. That is, disproportionation was taking place within the inlet tube and the inlet chamber of the CO Disproportionator prior to full disproportionation within the CDC assembly as planned. These areas had been electroless nickel plated to prevent carbon formation as reported previously in the description of the CO Disproportionator. As indicated, the electroless nickel was selected based on results reported in the literature in which this coating was used as a protective coating for preventing carbon formation during the Bosch reaction, which is:

$$CO_2 + 2H_2 = 2H_2O + C \qquad (9)$$

TABLE 13 ELECTROLYZER DRUM $\Delta t/\Delta P$ TEST RESULTS

Drum No.	Initial $\Delta t/\Delta P$ Test Result[a]	$\Delta t/\Delta P$ Test After 423K (302F) Bake[a]	Disposition[b]
F-285	< 10 sec		
-297	< 10 sec		
-288	< 10 sec		
-287	>120 sec (2 min)	81 sec	Marginal
-278	< 10 sec		
-279	< 10 sec		
-271	< 10 sec		
-292	< 10 sec		
-291	>120 sec (2 min)	>120 sec (2 min)	Acceptable
-302	>120 sec (2 min)	>120 sec (2 min)	Marginal
-277R	< 10 sec		
-283	< 10 sec		
-265	< 10 sec		
-298	< 10 sec		
-269Z	< 10 sec		
-303	< 10 sec		
-307	>120 sec (2 min)	30 sec	
-286	>120 sec (2 min)	>120 sec (2 min)	Acceptable
-264	< 10 sec		
-308	>120 sec (2 min)	>120 sec (2 min)	Acceptable
-289	< 10 sec		
-293	>120 sec (2 min)	>120 sec (2 min)	Acceptable
-284	< 10 sec		
-282	>120 sec (2 min)	>120 sec (2 min)	Acceptable
-295	< 10 sec		
-301	< 10 sec		
-294	< 10 sec		
-266	< 10 sec		
-268	< 10 sec		
-281	< 10 sec		
-273	>120 sec (2 min)	>120 sec (2 min)	Acceptable

(a) Time for pressure inside drum to drop from 15.2 cm (6 in) water to 12.7 cm (5 in) water.
(b) All those not marked are unacceptable.

TABLE 14A HYDROGEN SEPARATOR TEST RESULTS SUMMARY (METRIC UNITS)

Data Point No.	Module No.	Module Temp., K	Product H_2 Vacuum, mm Hg	H_2 Separator Feed Gas Flow, cm^3/s	H_2 Separator Exit Gas Flow, cm^3/s	H_2 Removal Rate, cm^3/s	% Overcapacity[a]
1	1	645-650	0.50	45.89	45.32	0.56	75
2	1	645-650	0.50	45.80	45.32	0.52	62
3	1	655-661	0.54	45.87	45.16	0.68	112
4	1	655-661	0.54	45.88	45.10	0.72	125
5	1	665-678	0.55	45.92	45.20	0.69	115
6	1	665-678	0.55	45.84	45.20	0.65	100
7	1	617-625	0.38	48.32	47.76	0.49	53
8	1	611-617	0.38	48.23	47.60	0.53	65
9	2	645-650	NA	45.89	45.48	0.41	28
10	2	645-650	0.35	45.55	45.10	0.42	31
11	2	645-650	0.35	45.57	45.15	0.41	28
12	2	665-672	NA	49.97	49.30	0.67	109
13	2	665-678	NA	50.17	49.35	0.82	156
14	2	665-672	0.33	51.81	51.20	0.50	56
15	2	665-672	0.33	51.73	51.12	0.50	56

(a) $\% \text{ Overcapacity} = \dfrac{H_2 \text{ Removal Rate} - \text{Design } H_2 \text{ Removal Rate } (0.322 \ cm^3/s)}{\text{Design } H_2 \text{ Removal Rate } (0.322 \ cm^3/s)} \times 100$

TABLE 14B HYDROGEN SEPARATOR TEST RESULTS SUMMARY (ENGLIGH UNITS)

Data Point No.	Module No.	Module Temp., F	Product H_2 Vacuum, In Water	H_2 Separator Feed Gas Scfm x 10^2	H_2 Separator Exit Gas Scfm x 10^2	H_2 Removal Rate, Scfm x 10^3	% Overcapacity[a]
1	1	700-710	0.268	9.723	9.600	1.195	75
2	1	700-710	0.268	9.704	9.601	1.098	62
3	1	720-730	0.289	9.718	9.569	1.439	112
4	1	720-730	0.289	9.721	9.554	1.526	125
5	1	740-760	0.294	9.729	9.576	1.470	115
6	1	740-760	0.294	9.711	9.575	1.383	100
7	1	650-665	0.203	10.237	10.119	1.034	53
8	1	640-650	0.203	10.219	10.085	1.113	65
9	2	700-710	NA	9.722	9.636	0.855	28
10	2	700-710	0.187	9.650	9.555	0.886	31
11	2	700-710	0.187	9.654	9.565	0.856	28
12	2	740-750	NA	10.587	10.445	1.423	109
13	2	740-760	NA	10.629	10.455	1.741	156
14	2	740-750	0.177	10.977	10.846	1.065	56
15	2	740-750	0.177	10.959	10.830	1.054	56

(a) $\% \text{ Overcapacity} = \dfrac{H_2 \text{ Removal Rate} - \text{Design } H_2 \text{ Removal Rate } (0.68 \times 10^{-3} \text{ cfm})}{\text{Design } H_2 \text{ Removal Rate } (0.68 \times 10^{-3} \text{ cfm})} \times 100$

Since the reaction mechanism of the Bosch and CO Disproportionator reactors are different, a material that retards carbon formation for one reactor may not for the other. However, it was later established that researchers working with Bosch reactors were also experiencing carbon formation on electroless nickel surfaces.[18] The problem was attributed to variations in plating parameters that were difficult to control.

It was decided that a redesign or a material study would not be implemented due to the following two reasons: (1) the problem could be adequately handled by manual removal of carbon during the required carbon change cycles and (2) work was being done by other NASA contractors on material studies relating to the Bosch process and other carbon reduction processes.[19] Thus it was felt that in the SX-1 program, carbon formation on the electroless nickel was not a problem that required immediate attention.

As shown in Figure 20, the conversion efficiency at an inlet gas flow rate of 3080 sccm (0.1088 scfm) ranged between 40 and 45% over a temperature range of 773 to 843K (932 to 1058F). This exceeded the reactor conversion efficiency design goal of 36% which was previously demonstrated.[20] Data obtained during testing of the CO Disproportionator for integrated operational testing is provided in Table 15.

Water Feed Mechanism DVT

The Water Feed Mechanism is used in the SX-1 to supply a constant flow of super-heated steam to the Water Electrolyzer Module. The steam is required as a source of additional O_2 to make up the difference between the O_2 available from CO_2 and that metabolically required by a man. A photo of the Water Feed Mechanism test stand is shown in Figure 21. As was noted in the Fourth Quarterly Report,[21] problems were incurred which resulted in certain design changes in the Water Feed Mechanism. The design changes were required to correct the effect of off-gassing in a 1 g environment to provide for a testing capability on the ground. Bubbles collected on the water side of the Water Feed Mechanism, thereby affecting the heat transfer area and causing erratic flow fluctuations. With the design changes and the orientation where the water side of the Water Feed Mechanism is pointed vertically up toward the water to steam orifice, the gas that is formed during normal operation is ejected through the orifice and out into the steam line. In this orientation, it causes no problems to the overall system operation. The temperature gradients and flow fluctuations that were being caused by erratic flow or expulsion of the accumulated gas no longer existed, and thus, a more stable system operation was achieved.

The DVT was completed after the modifications. All the steam flow rate data collected for the DVT were within the Water Feed Mechanism design range of 2.85 to 5.70 x 10^{-6} kg/s (0.544 to 1.09 lb/day). Long term data was consistent as evidenced by Figure 22 which is a plot of Water Feed Mechanism steam flow rate versus time.

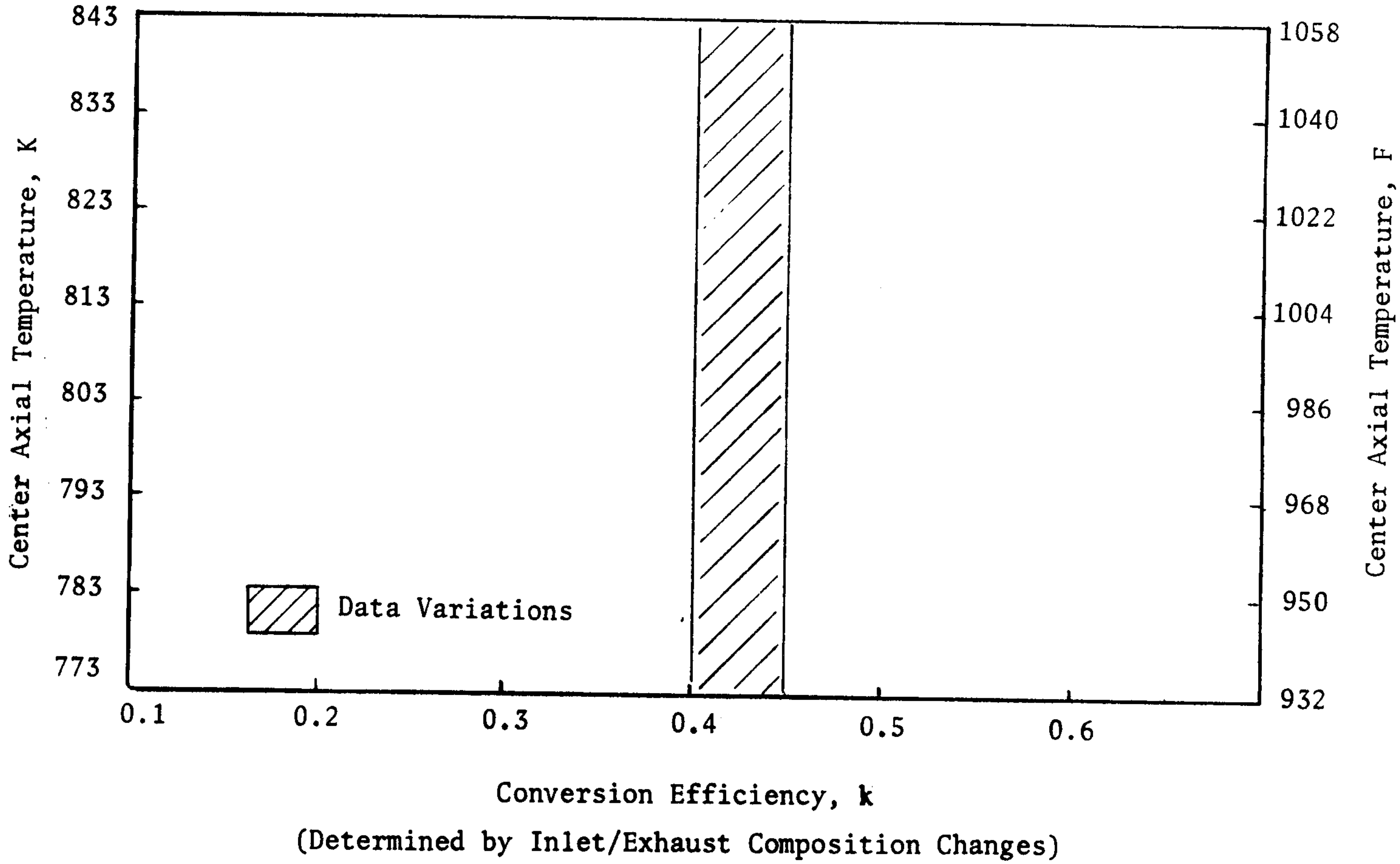


FIGURE 20 CO DISPROPORTIONATOR CONVERSION EFFICIENCY VERSUS TEMPERATURE

TABLE 15A CO DISPROPORTIONATOR TEST RESULTS (METRIC UNITS)

Temperatures, K							Conversion Efficiency Data				
Internal			External			Exhaust					
TC1	TC2	TC3	TC4	TC5	TC6	TC7	Exhaust Flow Rate, Sccm	Inlet Flow Rate, Sccm	% CO In Exhaust	Conversion Efficiency, %	Pressure Drop Across COD, N/m^2
293	293	293	293	293	293	293					
775	803	800	577	833	633		2910	3080		43[a]	0
788	811	805	575	833	648	713	2730	3080		43	49.82
807	833	825	577	855	672	738	2730	3080		43	49.82
803	843	835	604	853	674	736	2730	8030		43	49.82
802	831	824	591	843	658	736	2730	3080		43	49.82
773	838	831	590	853	676	739	2750	3080		40.4	74.73
799	833	826	584	853	676	739	2750	3080	35.7	50	74.73
800	831	833	583	851	676	733	2780	3080		37	124.55
804	839	833	584	852	698	743	2860	3080		27	174.37
Exhaust Vent Plugged With Ice At Approximately 2:00 AM, 12/18/74											
737	837	829	583	848	693		2750	3080		40.4	1295.32
745	826	828	583	843	692	734	2780	3080			1494.6
Shutdown											
External Thermal Couples (TC4-TC6) Moved											
Start Heating											
840	837	791	603	793	771	743	2650	3080			24.91
System Has Less Than 5% Nitrogen Remaining											
773	849	863	(b)	793	790	791	2650	3080	35	41.4	24.91
780	848	863		793	789	792	2630	2950	35	41.4	24.91
Adjust to Lower Flow and High Temperature											
784	850	865		774	781	788	2325	2640	33.1	45.3	24.91
747	826	814		778	795	765	2380	2670	35.1	41.2	24.91
750	837	833		775	772	758	2380	2660	35.8	39.8	24.91
768	831	852		788	777	775					24.91
Adjust Flow To						3500 Sccm					
789	846	841		783	775	778	3300	3670	36.6	38.4	24.91

(a) Determined from inlet/exhaust flow rate
(b) TC4 failed

-continued-

Table 15A - continued

Temperatures, K							Conversion Efficiency Data				
Internal			External			Exhaust					
TC1	TC2	TC3	TC4	TC5	TC6	TC7	Exhaust Flow Rate, Sccm	Inlet Flow Rate, Sccm	% CO In Exhaust	Conversion Efficiency, %	Pressure Drop Accross COD, N/m^2
768	841	843		783	773	781	3300	3670	36.9	37.8	24.91
778	837	850		783	775	783	3300	3670	36.7	38.2	24.91
Adjust Flow To Approximately 700 Sccm											
Adjust To Recycle Loop Flow Rate											
740	823	821		773	776	759	2750	3060	36.6	38.4	24.91
733	790	770		753	736	713	2750	3040	37.8	36.0	24.91
698	773	759		768	751	698	2750	3070	35.8	39.8	24.91
690	780	773		773	753	695	2780	3110	35.5	40.6	24.91
673	770	761		768	741	693	2750	3100	34.3	42.9	24.91
678	785	778		773	755	693	2750	3090	35.2	41.1	24.91
693	782	773		773	751	693			34	43.4	24.91
Adjust Flow To Approximately 750 Sccm											
Adjust To Recycle Loop Flow Rate											
727	775	759		773	745	689	2610	2950	34.2	43.1	49.82
712	772	758		773	737	690	2650	3000	33.7	44	49.82
Purged With Nitrogen and Placed In Standby Mode											
Recycle Gas Flow Resumed											
689	774	776		793	753	693	2630	2960	34.7	42	124.55
702	785	768		775	746	693	2630	2970	34.2	43.1	124.55
Purged With Nitrogen and Placed In Standby Mode											
Recycle Loop Gas Flow Resumed											
697	791	761		783	755	698	2630	2980	33.3	44.8	149.46
711	845	850		785	775	769	2680	2970	37.6	36.6	149.46
Purged With Nitrogen and Placed In Standby Mode											
Recycle Loop Gas Flow Resumed											
707	801	792		811	768	705	2650	2980	35	41.4	1569.33
713	791	777		803	769	706	2650	2980	34.6	42.3	1619.15
Purged With Nitrogen and Placed in Standby Mode											
Recycle Loop Gas Flow Resumed											
696	849	853		791	783	779					2466.09
Recycle Loop Gas Composition Changed to 19.6% Hydrogen, 8.04% CO											
Test Stopped											

TABLE 15B CO DISPROPORTIONATOR TEST RESULTS (ENGLISH UNITS)

Temperatures, F							Conversion Efficiency Data				
Internal			External			Exhaust					
TC1	TC2	TC3	TC4	TC5	TC6	TC7	Exhaust Flow Rate, Ft^3/Min	Inlet Flow Rate, Ft^3/Min	% CO In Exhaust	Conversion Efficiency,%	Pressure Drop Across COD,In Wate
Amb	Amb	Amb	Amb	Amb	Amb	Amb					
936	986	981	579	1040	680		0.1028	0.1088		43	0
959	1000	990	576	1040	707	824	0.0964	0.1088		43	0.2
993	1040	1026	579	1080	750	869	0.0964	0.1088		43	0.2
986	1058	1044	628	1076	754	865	0.0964	0.1088		43	0.2
984	1036	1024	604	1058	743	865	0.0964	0.1088		43	0.2
932	1049	1036	603	1076	757	871	0.0971	0.1088		40.4	0.3
979	1040	1027	590	1076	757	871	0.0971	0.1088	35.7	40	0.3
981	1036	1040	590	1072	757	860	0.0982	0.1088		37	0.5
988	1051	1040	590	1074	797	878	0.0946	0.1088		27	0.7
Exhaust Vent Plugged With Ice at Approximately 2:00 AM, December 18, 1975											
867	1047	1033	590	1067	788		0.0971	0.1088		40.4	5.2
882	1027	1031	590	1058	786	862	0.0982	0.1088			6.0
Shut Down											
External Thermal Couples (TC4-TC6) Moved.											
Start Heating											
1053	1047	964	626	908	928	878	0.0936	0.1088			0.1
System has less than 5% Nitrogen Remaining.											
932	1069	1094	(b)	968	963	964	0.0936	0.1088	35	41.4	0.1
945	1067	1094		968	961	966	0.0929	0.1042	35	41.4	0.1
Adjust to Lower Flow and High Temperature											
952	1071	1098		934	946	959	0.0821	0.0932	33.1	45.3	0.1
885	1027	1006		941	972	918	0.0840	0.0943	35.1	41.2	0.1
891	1047	1040		936	930	905	0.0840	0.0939	35.8	39.8	0.1
923	1036	1074		959	939	936					0.1
Adjust Flow to Approximately 0.1236 Ft^3/Min.											
961	1063	1054		950	936	941	0.1165	0.1298	36.6	38.4	0.1
923	1054	1058		950	932	946	0.1165	0.1298	36.9	37.8	0.1
941	1047	1071		950	936	950	0.1165	0.1298	36.7	38.2	0.1
Adjust Flow to Approximately 0.0247 Ft^3/Min.											

(a) Determined from inlet/exhaust flow rate.
(b) TC4 failed.

-continued-

Table 15B - continued

Temperatures, F							Conversion Efficiency Data				
Internal			External			Exhaust					
TC1	TC2	TC3	TC4	TC5	TC6	TC7	Exhaust Flow Rate, Ft^3/Min	Inlet Flow Rate, Ft^3/Min	% CO In Exhaust	Conversion Efficiency,%	Pressure Drop Across COD,In Water
Adjust to Recycle Loop Flow Rate.											
873	1022	1018		932	937	907	0.0971	0.1081	36.6	38.4	0.1
860	963	927		896	865	824	0.0971	0.1074	37.8	36.0	0.1
797	932	907		923	892	497	0.0971	0.1084	35.8	39.8	0.1
783	945	932		932	896	422	0.0981	0.1098	35.5	40.6	0.1
752	927	910		923	874	788	0.0971	0.1095	34.3	42.9	0.1
761	954	941		932	900	788	0.0971	0.1091	35.2	41.4	0.1
788	948	932		932	892	788			34.0	43.4	0.1
Adjust Flow to Approximately 0.0265 Ft^3/Min.											
Adjust to Recycle Loop Flow Rate.											
849	936	907		932	882	781	0.0922	0.1042	34.2	43.1	0.2
822	930	905		932	867	783	0.0936	0.1059	33.7	44.0	0.2
Purged With Nitrogen and Placed in Standby Mode.											
Recycle Gas Flow Resumed.											
781	934	937		968	896	788	0.0929	0.1045	34.7	42.0	0.5
804	954	928		936	883	788	0.0929	0.1049	34.2	43.1	0.5
Purged With Nitrogen and Placed in Standby Mode.											
Recycle Loop Gas Flow Resumed.											
795	964	910		950	900	797	0.0929	0.1052	33.3	44.8	0.6
820	1062	1071		954	936	925	0.0946	0.1049	37.6	36.6	0.6
Purged With Nitrogen and Placed in Standby Mode.											
Recycle Loop Gas Flow Resumed.											
813	982	966		1000	923	810	0.0936	0.1052	35.0	41.4	6.3
824	964	939		986	925	811	0.0936	0.1052	34.6	42.3	6.5
Purged With Nitrogen and Placed in Standby Mode.											
Recycle Loop Gas Flow Resumed.											
793	1069	1076		964	950	943					9.9
Recycle Loop Gas Composition Changed to 19.6% Hydrogen, 8.04% CO.											
Test Stopped											10.9

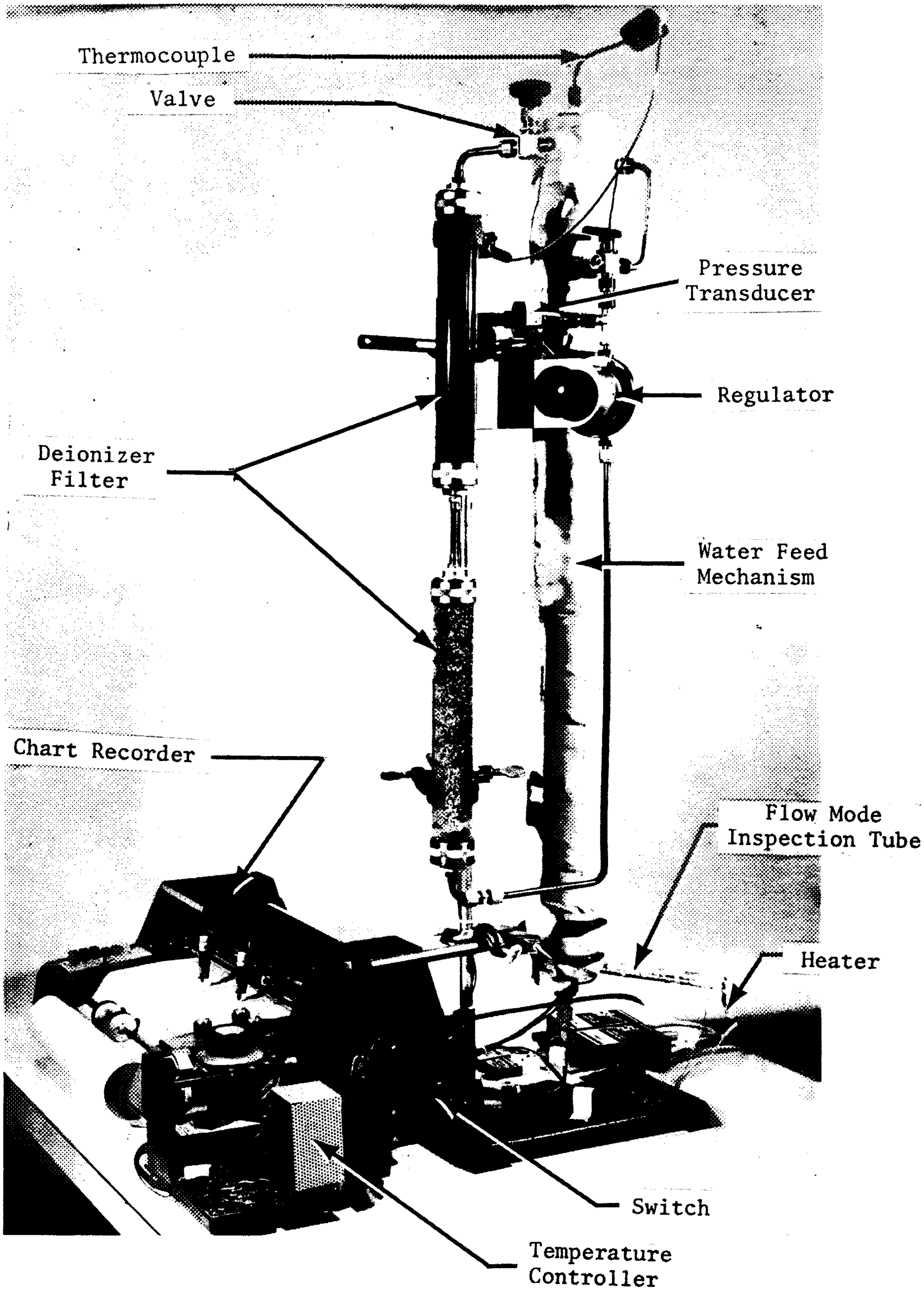


FIGURE 21 WATER FEED MECHANISM TEST STAND

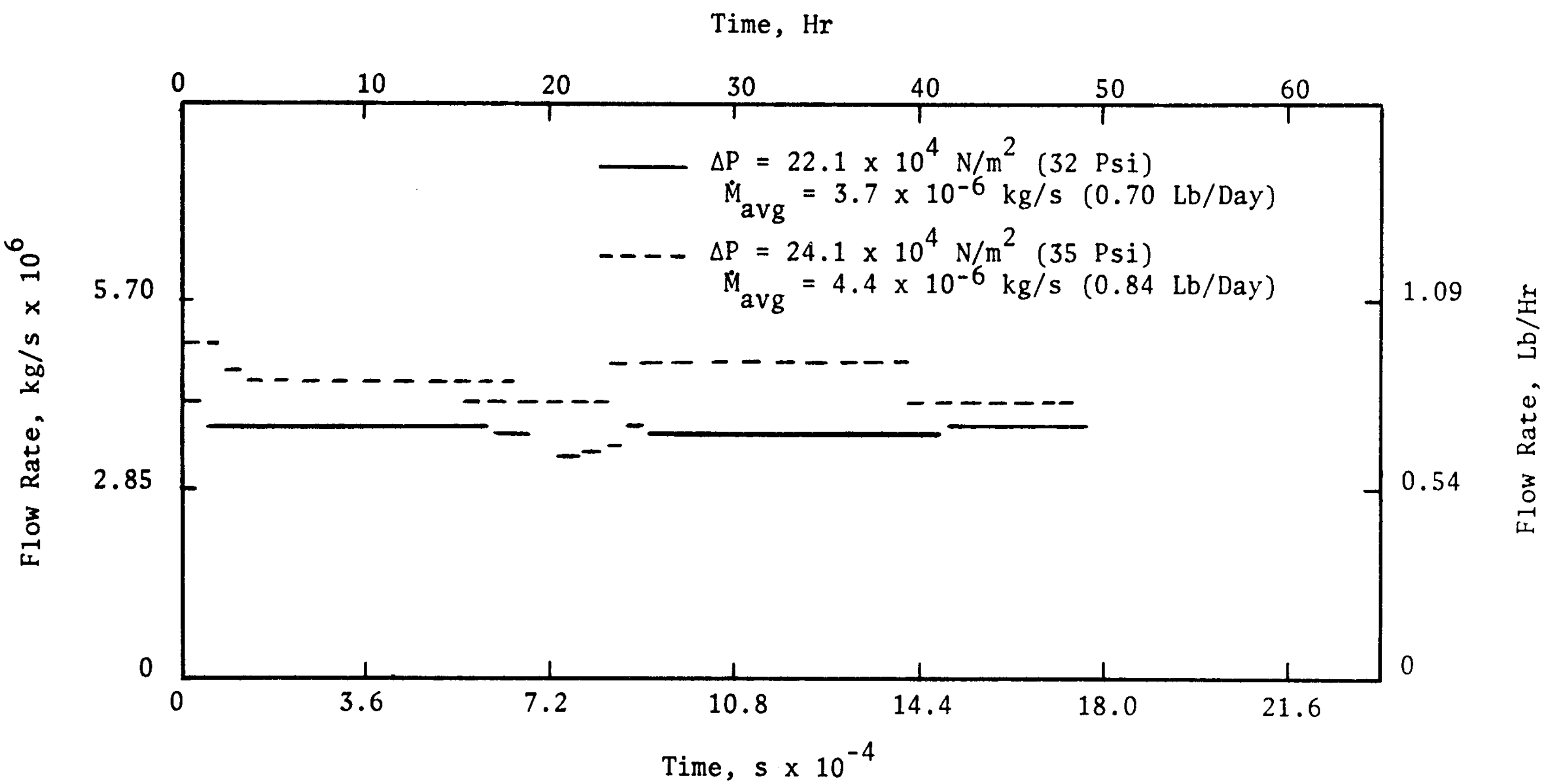


FIGURE 22 WATER FEED MECHANISM FLOW RATE VERSUS TIME

Control and Monitor Instrumentation DVT

The Control and Monitor Instrumentation is used in the SX-1 for control of all heaters, current controls and sequence controls and to monitor the trends of the system, respectively.

All control PC cards were individually calibrated and checked out on the Life Systems' special PC card tester. The list of Control Instrumentation PC cards was presented in Table 9. The control points were set by using simulated input signals. Next, a wiring continuity check on the Control Instrumentation backplane and a check of all Control Instrumentation power supplies was performed. Printed circuit cards were then inserted into the Control Instrumentation package, one function at a time, to determine that the particular function, independent of the remainder of the Control Instrumentation, was operating properly. The CO Disproportionator temperature control cards were set up to functionally operate the proper heaters. The resulting control characteristics of temperature versus time can be found in Figure 23. In a like manner, the electrolyzer module temperature control cards and temperature ramp cards were checked out and the results are presented in Figure 24. The purpose of the temperature ramp card is to ensure that the electrolyzer module heat-up rate is 3K (5.4F)/min. This is necessary to prevent damage to the ceramic parts of the electrolyzer drums and modules.

The main sequence cards were checked out on the Life Systems special PC card tester. The memory addresses were simulated with input switches and the memory outputs were connected to light-emitting diodes (LEDs). A pulse generator was used to step through the sequence one state at a time. For a given memory address, the output LEDs were checked for proper ones and zeros according to the required bit pattern. The sequence was checked out for proper operation of all devices in the Purge, Normal, Standby, Reactor Change and Shutdown Modes.

The last step of the Control Instrumentation DVT included checking out the Control Instrumentation/SX-1 interface, including all sensor inputs, actuators, heater outputs and interfaces with the GSA and Monitor Instrumentation.

A wiring continuity check was performed on the Monitor Instrumentation backplane. All monitor PC cards were individually calibrated and checked out on the Life Systems' special PC card tester. A list of the Monitor Instrumentation PC cards was presented in Table 12. The Monitor Instrumentation trip points were set on the individual cards in accordance with Table 16. This was done by applying simulated input signals and adjusting the appropriate potentiometers accordingly. All normal, caution, warning and alarm indicaters were checked for proper operation at the levels indicated in Table 16. Table 17 lists the value in engineering limits that correspond to the voltage trip points. The final step in the Monitor Instrumentation test included checking out the integration of the Monitor Instrumentation with the remainder of the SX-1 system.

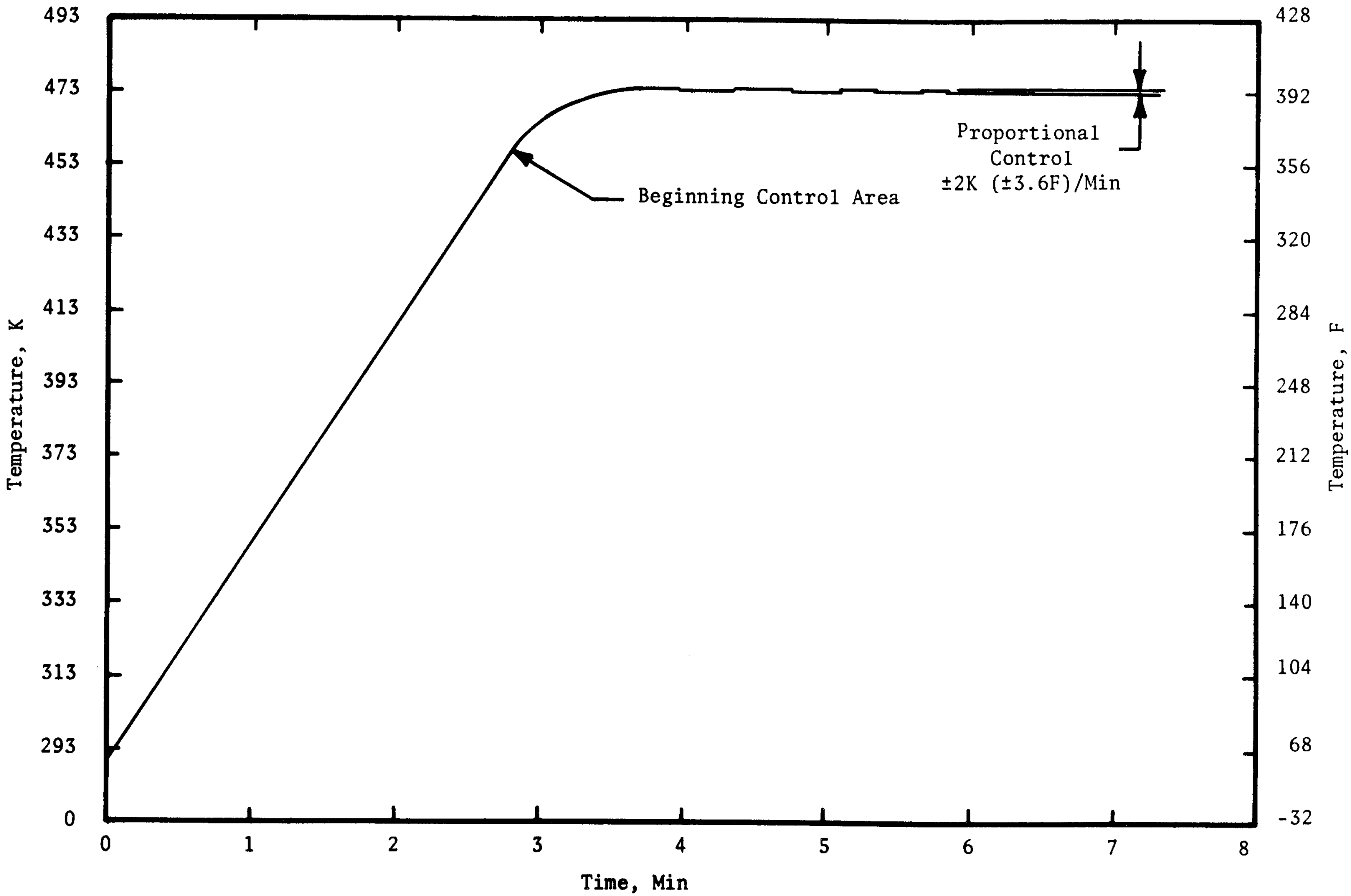


FIGURE 23 CO DISPROPORTIONATOR TEMPERATURE CONTROL CHARACTERISTICS

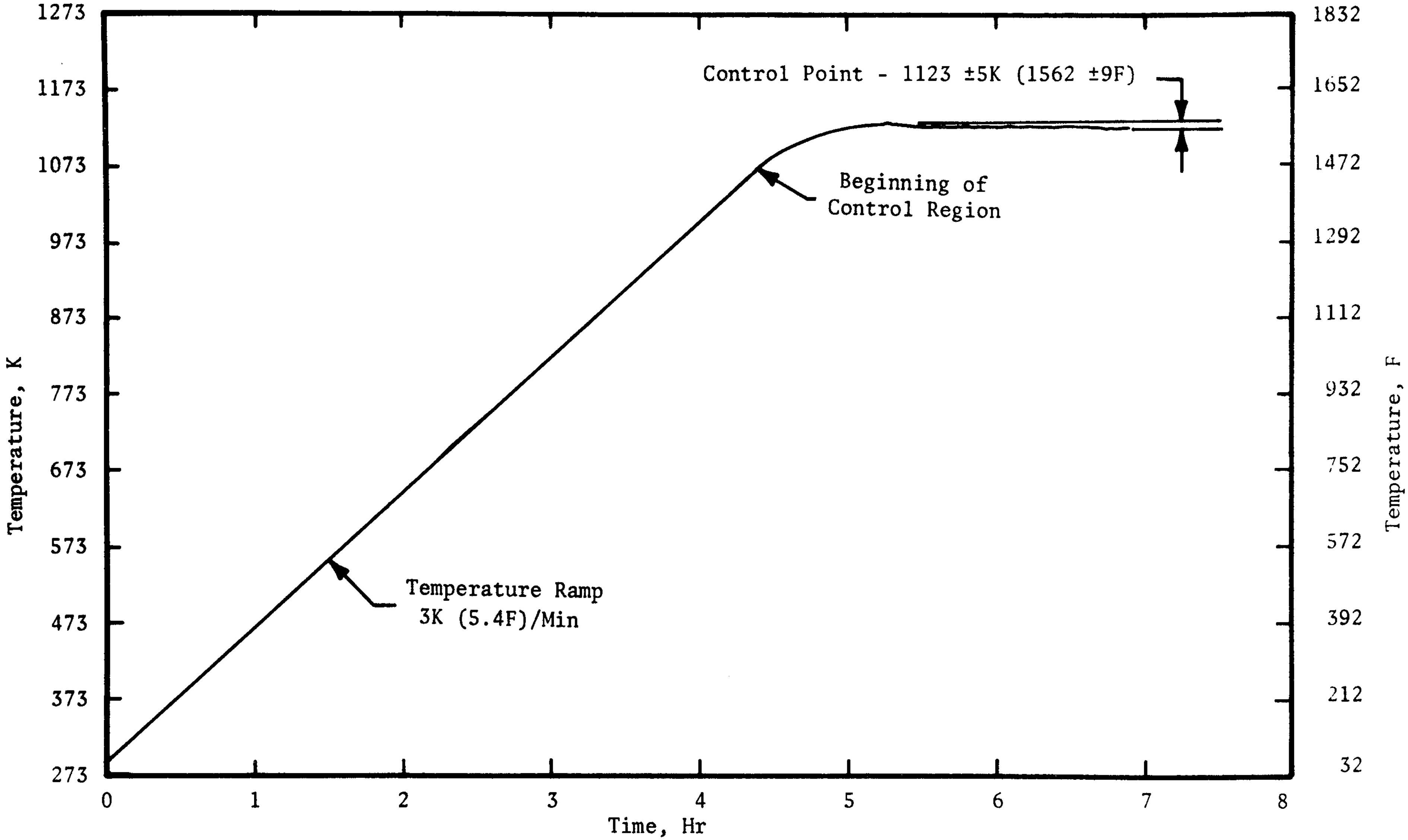


FIGURE 24 ELECTROLYZER MODULE TEMPERATURE CONTROL CHARACTERISTICS

TABLE 16 MONITOR INSTRUMENTATION VOLTAGE TRIP POINTS

Carbon Dioxide Electrolyzer	Caution	Warning	Alarm
Module 1			
High Voltage	3.600	4.000	4.400
Low Voltage	3.000	2.500	2.000
High Temperature	4.300	4.350	4.375
Low Temperature	4.200	4.150	4.125
Module 2			
High Voltage	3.600	4.000	4.400
Low Voltage	3.000	2.500	2.000
High Temperature	4.300	4.350	4.375
Low Temperature	4.200	4.150	4.125
Module 3			
High Voltage	3.600	4.000	4.400
Low Voltage	3.000	2.500	2.000
High Temperature	4.300	4.350	4.375
Low Temperature	4.200	4.150	4.125
High ΔP	1.250	2.000	2.500
Low ΔP	0.500	0.475	0.125
Water Electrolyzer			
High Voltage	3.600	4.000	4.400
Low Voltage	3.000	2.500	2.000
High Temperature	4.300	4.350	4.375
Low Temperature	4.200	4.150	4.125
Low Water Feed Temperature	0.877	0.700	0.550
CO Disproportionator			
Reactor 1			
High Temperature	3.730	3.799	3.833
Low Temperature	3.533	3.433	3.333
High ΔP	0.500	0.750	1.500
Reactor 2			
High Temperature	3.730	3.799	3.833
Low Temperature	3.533	3.433	3.333
High ΔP	0.500	0.750	1.500

continued-

Table 16 - continued

Hydrogen Separator	Caution	Warning	Alarm
Section 1			
High Temperature	2.630	2.730	2.800
Section 2			
High Temperature	2.630	2.730	2.800
High H_2 Outlet Pressure	1.500	2.000	2.500
Recycle Loop			
High Pressure	1.200	1.400	1.500
Low Pressure	0.750	0.500	0.250
Instrumentation			
High Control Temperature	3.540	3.700	3.868

TABLE 17A MONITOR INSTRUMENTATION TRIP POINTS (METRIC UNITS)

Carbon Dioxide Electrolyzer	Caution	Warning	Alarm
Module 1			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, K	1133	1143	1148
Low Temperature, K	1133	1103	1098
Module 2			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, K	1133	1143	1148
Low Temperature, K	1113	1103	1098
Module 3			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, K	1133	1143	1148
Low Temperature, K	1133	1103	1098
High ΔP, N/m^2	1245	1990	2490
Low ΔP, N/m^2	498	473	374
Water Electrolyzer			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, K	1133	1143	1148
Low Temperature, K	1113	1103	1098
Low Water Feed Temperature, K	396	389	383
CO Disproportionator			
Reactor 1			
High Temperature, K	833	843	848
Low Temperature, K	803	788	773
High ΔP, N/m^2	498	747	1475
Reactor 2			
High Temperature, K	833	843	848
Low Temperature, K	803	788	773
High ΔP, N/m^2	498	747	1475

continued-

Table 17A - continued

Hydrogen Separator	Caution	Warning	Alarm
Section 1			
High Temperature, K	668	683	693
Section 2			
High Temperature, K	668	683	693
High H_2 Outlet Pressure, N/m^2	2070	2760	3450
Recycle Loop			
High Pressure, N/m^2	8270	9650	10300
Low Pressure, N/m^2	5170	3450	1720
Instrumentation			
High Control Temperature, K	325	331	338

TABLE 17B MONITOR INSTRUMENTATION TRIP POINTS (ENGLISH UNITS)

Carbon Dioxide Electrolyzer	Caution	Warning	Alarm
Module 1			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, F	1580	1598	1607
Low Temperature, F	1544	1526	1517
Module 2			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, F	1580	1598	1607
Low Temperature, F	1544	1526	1517
Module 3			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, F	1580	1598	1607
Low Temperature, F	1544	1526	1517
High ΔP, In of Water	5.0	8.0	10.0
Low ΔP, In of Water	2.0	1.9	1.5
Water Electrolyzer			
High Voltage, V	3.6	4.0	4.4
Low Voltage, V	3.0	2.5	2.0
High Temperature, F	1580	1598	1607
Low Temperature, F	1544	1526	1517
Low Water Feed Temperature, F	253	241	230
CO Disproportionator			
Reactor 1			
High Temperature, F	1040	1058	1067
Low Temperature, F	986	959	932
High ΔP, In of Water	2.0	3.0	6.0
Reactor 2			
High Temperature, F	1040	1058	1067
Low Temperature, F	986	959	932
High ΔP, In of Water	2	3	6

continued-

Table 17B - continued

Hydrogen Separator	Caution	Warning	Alarm
Section 1			
High Temperature, F	743	770	788
Section 2			
High Temperature, F	743	770	788
High H_2 Outlet Pressure, Psi	0.30	0.40	0.50
Recycle Loop			
High Pressure, Psi	1.20	1.40	1.50
Low Pressure, Psi	0.75	0.50	0.25
Instrumentation			
High Control Temperature, F	125.6	136	149

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this program, the following conclusions and recommendations are made:

1. A one-man SX-1 is designed, fabricated and assembled. Operation of the following major components was successfully demonstrated.

    a. CO Disproportionator
    b. H_2 Separator
    c. Water Feed Mechanism
    d. Control Instrumentation
    e. Monitor Instrumentation

2. Electrolyzer drum and module technology existing at the inception of the current program was not adequate to produce a leak-free electrolyzer subassembly with 32 electrolyzer drums (64 electrolyzer cells). The design of the electrolyzer modules required 340 high temperature metal-to-metal and metal-to-ceramic seals. Testing performed throughout the program revealed that the reliability of the precious metals/ceramic seals is poor. The erratic occurrence of electrolyzer drum leakage prevented the performance of integrated SX-1 testing.

3. It is recommended that further development on the Electrolyzer Cell drum and Electrolyzer Module design be carried out before the solid electrolyte concept for O_2 regeneration is further evaluated. The emphasis on this task would be to minimize the number of high temperature, precious metal/ceramic seals.

4. Upon completion of the electrolyzer cell development task described above, it is recommended that the modules required for the one-man system be fabricated, integrated into the SX-1 and SX-1 shakedown, parametric and endurance testing be completed.

5. Although the dual reactor concept is an effective means of removing carbon from the system, a continuous carbon removal technique would provide several benefits. It is recommended that a study be conducted aimed at defining a continuous carbon removal technique. This study would involve the identification of alternative techniques for collecting the carbon formed during CO_2 reduction processes. The goal of this study would be to identify possible techniques which would allow the solid carbon to be collected in a continuous manner. Such a technique would enable a decrease in the size of the reactor with a resulting decrease in weight, volume and heat loss and would eliminate the need for frequent cartridge changes, thus reducing the need for expendables. Upon completion of this study, it is recommended that the fabrication and testing of the selected continuous carbon collection technique be completed.

2

6. The DVT performed on the CO Disproportionator revealed that there was a materials problem in that the electroless nickel failed to prevent carbon formation on designated areas of the CO Disproportionator. It is recommended that a thorough materials evaluation task be performed, with the objective of establishing a material and/or a coating which will prevent carbon formation when exposed to the operating temperature and environment of the CO Disproportionator.

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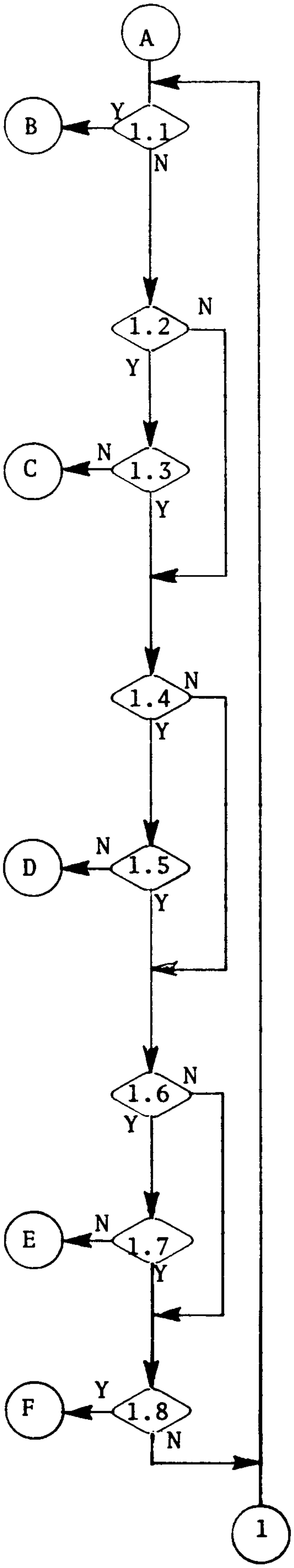


APPENDIX 1 SX-1 SEQUENCING FLOW CHART

1.0 SX-1 MAIN FLOW CHART

PURGE Requested? If PURGE has been depressed the answer to this question will be yes and the main program will go to B where B is the PURGE subroutine noted as 2.0. The PURGE subroutine will be carried out and the sequence will return to the main program at point A. If the answer to this question is no, the sequence will drop down to the next decision point.

NORMAL Requested? If NORMAL has been depressed, the answer to this will be yes and flow will drop down to the next decision point. If the answer to this is no, the next decision point will be bypassed.

Previous Mode SHUTDOWN? This decision point asks whether or not the system was previously in a SHUTDOWN mode. If it has been, the answer to this is yes and we go on to the main flow. If the answer is no, we go to C which is the NORMAL subroutine. NORMAL subroutine 3.0 is then carried out and returned to point A. This is in the system to prevent going directly from the SHUTDOWN mode to the NORMAL mode.

REACTOR CHANGE Requested? The REACTOR CHANGE is requested either by the pushbutton or automatically by a signal from the CO disproportionator monitor. If the answer is yes, we go to the next decision point. If the answer is no, we bypass the next decision point.

Previous Mode PURGE, STANDBY, or SHUTDOWN? This decision point is incorporated to prevent going to REACTOR CHANGE mode if the system was previously in PURGE, STANDBY, or SHUTDOWN. If the system was in any of these modes, we would go immediately to the next step, if not, we go to the REACTOR CHANGE subroutine (4.0). After the subroutine is completed, we return to the main flow at point A.

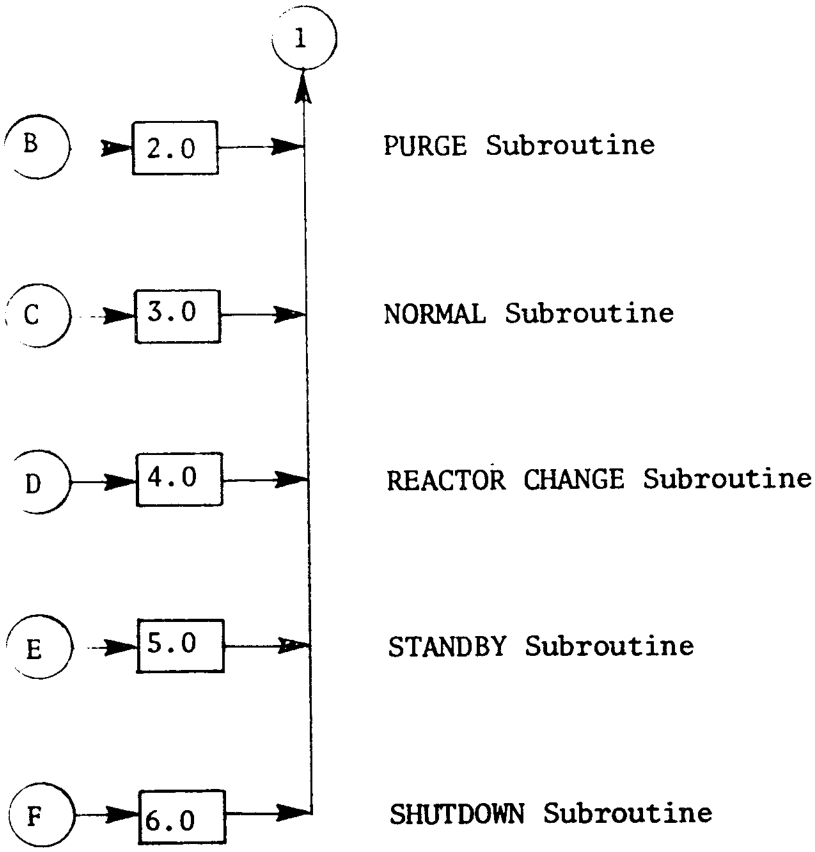
STANDBY Requested? STANDBY is requested either manually by front panel pushbutton or is automatically requested from the monitor. If STANDBY is requested, we go to the next step, if not, we bypass the next step.

Previous Mode PURGE or SHUTDOWN? If the previous mode was PURGE or SHUTDOWN, the STANDBY mode is prohibited and we go to the next step. If not, we go to the STANDBY subroutine (5.0). When this is completed the main program is again put into effect at point A.

SHUTDOWN Requested? If SHUTDOWN is detected either from pushbutton or system monitor, we go immediately to the SHUTDOWN subroutine (6.0). If not, we cycle back to the start of the main program at point A.

continued-

1.0 SX-1 MAIN FLOW CHART - continued



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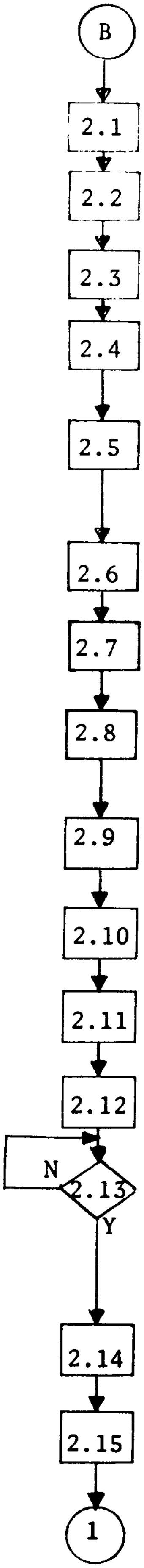


2.0 PURGE SUBROUTINE

System Reset. All logic is reset and initialized.

Energize PURGE Indicator. The PURGE indicator is energized to notify the operator that the system is in the PURGE mode.

Open SV-112 (Energize). This opens the H_2 separator to vacuum.

Open SV-113 (De-energize). This is open to the N_2 purge and allows RE-101 to control any underpressure situation across the solid oxide electrolyte (SOE) cells.

Open SV-105 (De-energize). This valve is opened to the vacuum which allows RE-102 to control any overpressure condition across the SOE cells.

Open SV-102 (De-energize). This valve opens the purge to the HE-101 water SOE cell.

Open SV-103 (De-energize). This is the main N_2 purge line; N_2 is introduced to recycle loop.

Open SV-109 (De-energize). The opening of this valve allows the N_2 purge to clear the H_2 out of the H_2 separator outlet line.

Energize SV-107 (COD-101 Direction). This action allows the COD-101 to be on line to the N_2 purge.

Open SV-106 (Energize). This valve opens the N_2 purge to clear out the lines to the COD-101.

Start P-101 Motor. The bellows pump will now pump the N_2 purge gases around the recycle loops to clear out all the lines.

Start Timer (Two Minutes). This function starts a two-minute purge cycle time.

Time Out? This decision point allows the N_2 purge to take place for two minutes. If the answer to the question is no, we just sit it in a loop waiting for the timer to time out. When the answer is yes, we fall through to the next process block.

Close SV-102 (Energize). This valve closure shuts off HE-101 to the N_2 purge.

Close SV-103 (Energize). This valve closure stops the main N_2 supply to the recycle loop.

continued-

1

2.0 PURGE SUBROUTINE - continued

2.16 Stop P-101 Motor. The recycle loop pump is stopped.

2.17 Close SV-106 (De-energize). The N_2 purge supply is cut off to COD-101.

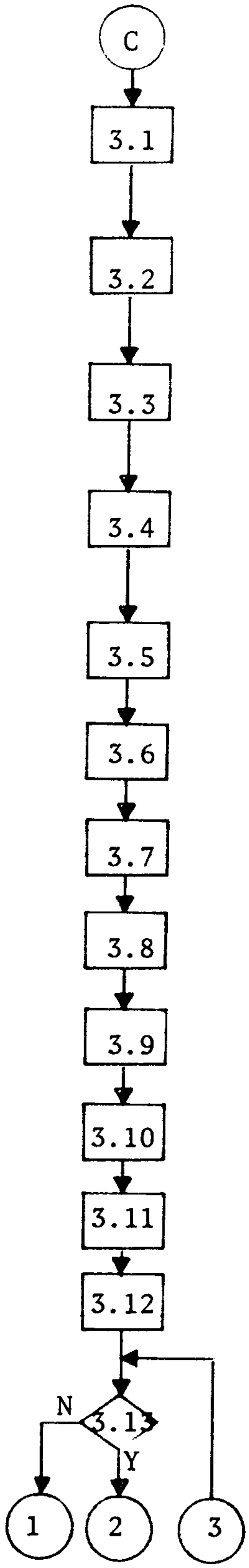
2.18 Close SV-109 (Energize). The N_2 purge is shut off to the H_2 separator outlet.

2.19 De-energize SV-107. This places the valve in the proper position for COD-101 on-line operation.

2.20 Inhibit PURGE Indicator and Reset Purge Flipflop. The PURGE indicator on the front panel is turned off, thus telling the operator the purge cycle has been completed.

A Purge complete, return to main program.

continued-



3.0 NORMAL MODE SUBROUTINE

<u>Energize NORMAL Indicator</u>. The NORMAL indicator on the front panel is energized to notify the operator that the system is now going into the NORMAL model.

<u>Flash NORMAL Indicator</u>. The NORMAL indicator is flashed telling the operator that the system is in a transition state and is heading toward the normal mode of operation.

<u>Inhibit STANDBY and PURGE Indicators and Reset Flops</u>. This is a housekeeping function in order to be sure that only one indicator is on at a time.

<u>Inhibit the STANDBY Elapsed Time Meter</u>. If the system had previously been in the STANDBY mode, the STANDBY time meter would have been stopped at this point.

<u>Enable HE-101 Temperature Control</u>. Power is applied to the HE-101 heater.

<u>Enable CE-101 Temperature Control</u>. Power is applied to the CE-101 heaters.

<u>Enable CE-102 Temperature Control</u>. Power is applied to the CE-102 heaters.

<u>Enable CE-103 Temperature Control</u>. Power is applied to the CE-103 heaters.

<u>Enable HSR-101 and HSR-102 Temperature Controls</u>. Power is applied to the HSR-101 and HSR-102 heaters.

<u>Enable FB-101 Temperature Control</u>. Power is applied to the FB-101 heaters.

<u>Enable P-101 Motor Control</u>. The recycle loop pump is started.

<u>Enable HE-101, CE-101, -102, -103 Current Controls</u>. Current is now supplied to the SOE cells which controls the amount of O_2 that is converted from the feed gas supply.

<u>COD-101 On Line?</u> At this point, one of the CO disproportionators must be on line. To determine which one is on line and if one is on line, the control logic interrogates the four limit switches which are attached to the high temperature valves. These limit switches indicate which COD is on line. If COD-101 is not on line, the program jumps to Step 3.17. If COD-101 is on line, the program goes to Step 3.14.

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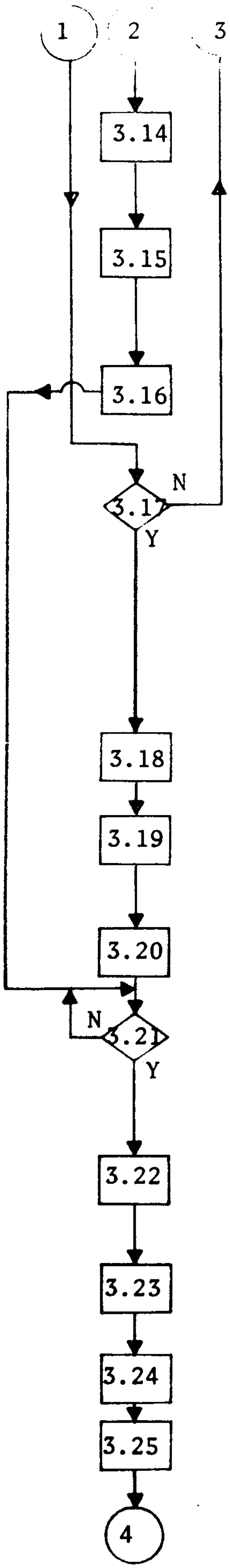

3.0 NORMAL MODE SUBROUTINE - continued

Energize COD-101 On Line Indicator. This indicator is illuminated to notify the system operator that COD-101 is now on line.

Enable COD-101 Temperature Control, Inhibit COD-102 Temperature Control. The COD-101 heaters are now enabled and the COD-102 heaters are disabled. This insures that only the disproportionator that is on line will heat up.

Inhibit COD-102 On Line Indicator. Since the COD-102 is not on line, the indicator is turned off. The sequence goes to Step 3.21 of the flow.

COD-102 On Line? If COD-101 is not on line, this decision point is reached in the program. If the COD-102 is not on line, the loop cycles back and asks if COD-101 is on line. The program sits in this loop until either COD-101 or COD-102 is on line. The normal operation cannot proceed until one of these disproportionators is on line. The operator must place either COD-101 or COD-102 on line for sequence to get out of this loop.

Energize COD-102 On Line Indicator. The COD-102 disproportionator is on line so the indicator is illuminated.

Enable COD-102 Temperature Control, Inhibit COD-101 Temperature Control. The power is applied to the COD-102 heaters and the power is disabled from the COD-101 heaters.

Inhibit COD-101 On Line Indicator. Since COD-101 is no longer on line, the indicator is turned off.

FB-101, COD-101, HSR-101, -102, HE-101, CE-101, -102, -103 At Control Point Temperature? The program sits at this point in the flow until proper operating temperatures have been reached.

Close SV-105 (Energize). At this point in the program, all system components are at their normal operating temperature. SV-105 is closed, isolating the recycle loop from vacuum.

Inhibit Flasher to NORMAL Indicator. The system is now in a normal mode and the NORMAL indicator is held steady.

Enable NORMAL Mode Elapsed Time Meter.

Open SV-101 (Energize). This valve opens the water feed to the flash boiler.

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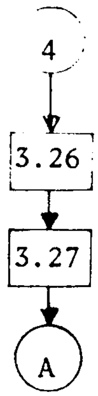


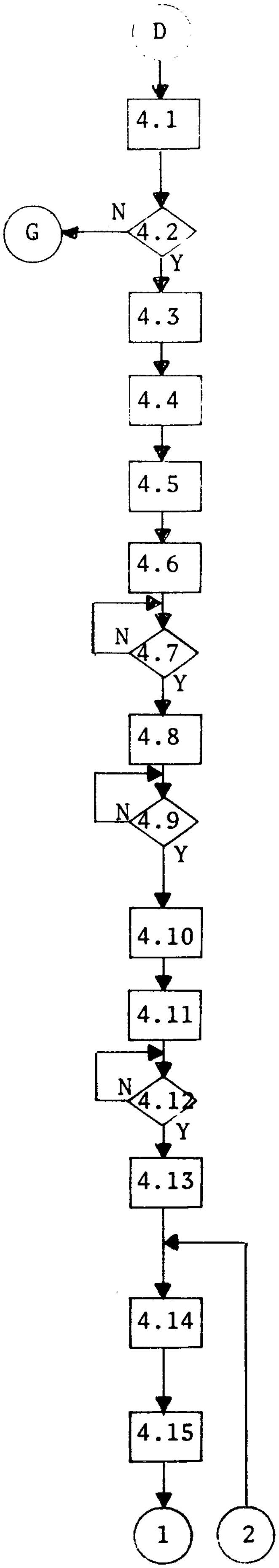
3.0 NORMAL MODE SUBROUTINE - continued

Open SV-104 (Energize). This valve allows the feed gas into the system.

Close SV-113 (Energize). The N_2 supply is now isolated from the recycle loop.

NORMAL mode in operation, return to main program.

continued-



4.0 CARTRIDGE CHANGE MODE SUBROUTINE

Energize REACTOR CHANGE Mode Indicator. This indicator is illuminated, notifying the operator that the system is going towards the REACTOR CHANGE mode.

COD-101 On Line? If COD-101 is not on line, we go to Step 4.32. If COD-101 is on line, then we go the next step.

De-energize SV-107 and SV-110. This configures valve SV-107 and SV-110 such that COD-102 is ready for servicing.

Open SV-111 (Energize). Opening this valve allows COD-102 to be evacuated.

Enable COD-102 Temperature Control. Power is now applied to the COD-102 heaters.

Start Timer (Ten Minutes). A timer is started that will allow COD-102 to be evacuated for a period of ten minutes.

Time Out? The sequence now allows evacuation to take place for ten minutes.

Close SV-111 (De-energize). Evacuation of COD-102 is now complete.

COD-102 At Control Point? The sequence at this point is waiting for the temperature of COD-102 to get to its normal operating point.

Open SV-114 (Energize). Opening this valve allows COD-102 to be filled with feed gas.

Start Timer (Two Minutes). The timer is started for purging COD-102 with fill gas for two minutes.

Time Out? The feed gas is allowed to purge COD-102 for two minutes. The system sits at this point until this occurs.

Close SV-114 (De-energize). Fill gas is now isolated from COD-102. At this point in the sequence, manual intervention is required. The high temperature valves must be configured to place COD-102 on line and COD-101 off line.

Energize OPEN V-2/CLOSE V-1 Indicator. This indicator is illuminated to notify the operator that he should open HV-103 and HV-104 and close HV-102 and HV-101.

Flash Indicator. The indicator is flashed to gain the operator's attention.

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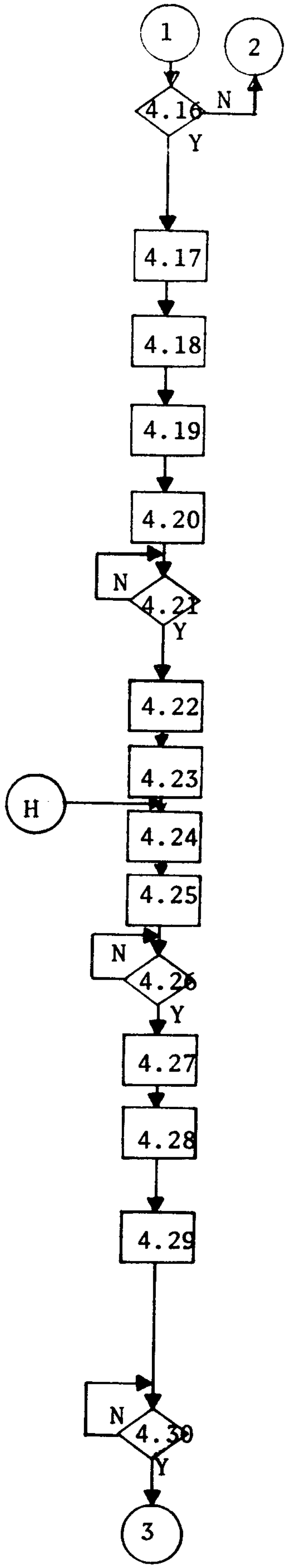

4.0 CARTRIDGE CHANGE MODE SUBROUTINE - continued

Cod-102 On Line? If the answer to this is no, the sequence sits in this loop until COD-102 is on line. When this occurs, we go to Step 4.17. This may take some time since the manual operation of opening and closing valves must take place.

Inhibit COD-101 Temperature Control. Since COD-101 is off line, it is now allowed to cool down.

Inhibit OPEN V-2/CLOSE V-1 Indicator. Since COD-102 is now on line, this indicator can be turned off.

Inhibit COD-101 On Line Indicator. Since COD-101 is no longer on line, this indicator is turned off.

Energize COD-102 On Line Indicator. Since COD-102 is now on line, this indicator is illuminated.

COD-101 At Low Temperature? Another manual operation is now necessary. COD-101 is allowed to cool down to its low temperature. When this occurs, we fall through to Step 4.22.

Energize SV-110. This allows COD-101 to be evacuated.

Energize SV-107. This valve allows COD-101 to be serviced.

Open SV-111 (Energize). COD-101 is now open to the vacuum.

Start Timer (Ten Minutes). This timer allows COD-101 to be evacuated for ten minuts.

Time Out? The sequence sits in this loop for ten minutes until COD-101 has been evacuated.

Close SV-111 (De-energize). Evacuation is now complete.

Energize CHANGE CARTRIDGE Indicator. The CHANGE CARTRIDGE indicator is illuminated to notify the operator that he can now remove COD-101.

Flash CHANGE CARTRIDGE Indicator. CHANGE CARTRIDGE indicator is flashed in order to gain the operator's attention. At this time, manual intervention in the automatic sequence is required. The operator must manually open valve V-107 in order to let air into COD-101 chamber. Once this is done, the operator can then pull the cartridge out and replace it with a new one.

CHANGE CARTRIDGE Button Depressed? The sequence rests in this loop until the operator manually depresses the CHANGE CARTRIDGE button. This notifies the sequence that the cartridge change has been completed. The operator must depress this button for normal operation to continue.

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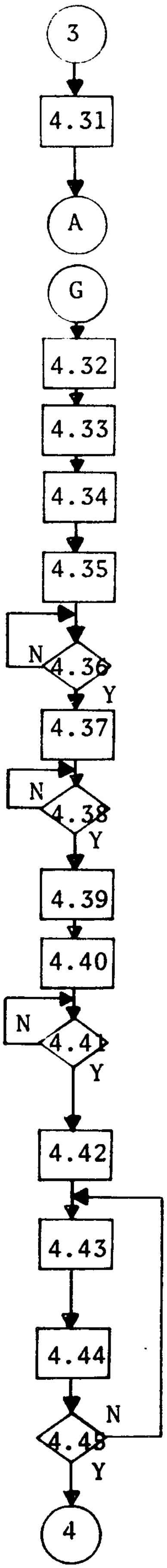
4.0 CARTRIDGE CHANGE MODE SUBROUTINE - continued



Inhibit CHANGE CARTRIDGE and REACTOR CHANGE Indicators and Reset REACTOR CHANGE Flipflop. The REACTOR CHANGE mode has been completed, therefore, the indicators are turned off.

Change mode complete, return to main program.

Energize SV-107 and SV-110. These valves are put in a position to service COD-101.

Open SV-111 (Energize). COD-101 is now open to vacuum.

Enable COD-101 Temperature Control. Power is applied to the heaters and COD-101 is allowed to heat up during evacuation.

Start Timer (Ten Minutes). A ten-minute timer is started to allow for the evacuation to take place.

Time Out? COD-101 is evacuated for ten minutes. At the end of this time the sequence continues.

Close SV-111, (De-energize). Evacuation has been completed.

COD-101 At Control Point. The sequence sits in this loop waiting for COD-101 to reach its normal operating temperature.

Open SV-114 (Energize). Feed gas is now fed into COD-101.

Start Timer (Two Minutes). The two minute timer is started for purging COD-101 with feed gas.

Time Out? The system sits in this loop for two minutes until the feed gas purge is complete.

Close SV-114 (De-energize). COD-101 has been filled with feed gas and the supply is now shut off.

Energize OPEN V-1/CLOSE V-2 Indicator. This indicator is illuminated in order to tell the operator that he can now place COD-101 on line and take COD-102 off the line.

Flash Indicator. The indicator is flashed to gain the operator's attention.

COD-101 On Line? Sequence sits in this loop waiting for the manual operation to be completed.

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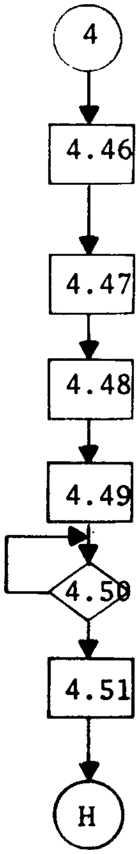

4.0 CARTRIDGE CHANGE MODE SUBROUTINE - continued

Inhibit COD-102 Temperature Control. Since COD-102 is now off line, power can be removed from its heaters and allowed to cool down.

Inhibit OPEN V-1/CLOSE V-2 Indicator. Since COD-101 is now on line, this indicator can be turned off.

Inhibit COD-102 On Line Indicator. Since COD-102 is no longer on line, this indicator is turned off.

Energize COD-101 On Line Indicator. Since COD-101 is now on line, we illuminate the indicator.

COD-102 At Low Temperature? The system waits in this loop until COD-102 has reached its low temperature.

De-energize SV-107 and SV-110. These valves are placed in a position so that COD-102 can be serviced and made ready for removal.

At this point, the removal sequence is identical to Steps 4.24 through 4.31, thus the program is returned to point H in the program which appears above process block 4.24 in the flow chart.

continued-

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5.0 STANDBY MODE SUBROUTINE

5.1 Enable STANDBY Mode Elapsed Time Meter. Since we are starting into the STANDBY mode, we enable the elapsed time meter.

5.2 Energize STANDBY Indicator. The STANDBY indicator is illuminated to notify the operator that we are now going into the STANDBY mode.

5.3 Open SV-112 (Energize). This places the H_2 separator outlet on line to vacuum.

5.4 Increment STANDBY Mode Counter. The STANDBY mode counter is incremented. This keeps track of the number of times the system has gone into the STANDBY mode.

5.5 Inhibit SHUTDOWN Indicator. This is a housekeeping function. Shut off the SHUTDOWN indicator in case the system had been in the SHUTDOWN mode prior to coming into the STANDBY mode.

I

5.6 Open SV-105 (De-energize). This allows regulator RE-102 to regulate for overpressure conditions on the SOE cells.

5.7 Close SV-102 (Energize). This is a housekeeping chore to prohibit the purge to the HE-101 SOE cell.

5.8 Close SV-106 (De-energize). This is a housekeeping chore to prohibit the purge to the CO disproportionators.

5.9 Close SV-109 (Energize). This is a housekeeping chore to prohibit purge to the H_2 separator outlet.

5.10 Open SV-113 (De-energize). This allows RE-101 to regulate for underpressure conditions with the N_2 supply to the SOE cells.

5.11 Close SV-111 (Energize). This is a housekeeping chore in case the system had previously been in a REACTOR CHANGE mode. This prohibits evacuation of the CO disproportionators.

5.12 Close SV-101 (De-energize). This shuts off the water supply to the flash boiler.

5.13 Close SV-114 (De-energize). This is a housekeeping chore in case the system had been in the REACTOR CHANGE mode. This shuts off the feed gas to the CO disproportionators.

5.14 Close SV-103 (Energize). This is a housekeeping chore. It shuts off the N_2 supply to the recycle loop.

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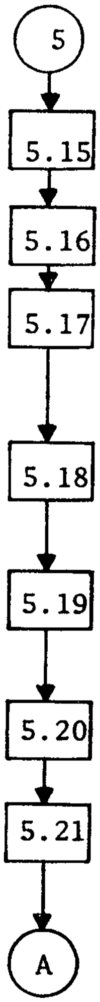


5.0 STANDBY MODE SUBROUTINE - continued

Inhibit P-101 Motor Control. The pump is stopped, thus preventing gas flow in the recycle loop.

Close SV-104 (De-energize). The feed gas supply is shut off.

Inhibit NORMAL Mode Elapsed Time Meter. Since we are now in a STANDBY mode, the NORMAL mode elapsed time meter is disabled in case we have come from a NORMAL mode into a STANDBY mode.

Inhibit REACTOR CHANGE Indicator. A housekeeping chore in case we have come from the REACTOR CHANGE mode into the STANDBY mode.

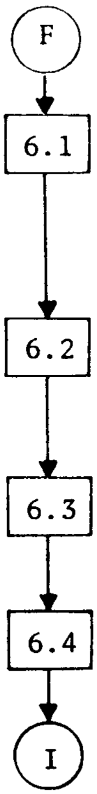
Inhibit NORMAL Indicator. This shuts off NORMAL mode indicator in case we have been in a NORMAL mode prior to entering the STANDBY mode.

Inhibit PURGE Indicator. This turns off the PURGE indicator in case we have been in a PURGE mode prior to STANDBY.

Inhibit HE-101, CE-101, -102, -103 Current Controls. This shuts off the current supply to the SOE cells thus preventing O_2 generation.

STANDBY or SHUTDOWN in effect, return to main program.

continued-



6.0 SHUTDOWN MODE SUBROUTINE

Increment SHUTDOWN Mode Counter and Energize SHUTDOWN Indicator. The SHUTDOWN mode counter is incremented in order to keep track of the number of times the system has been in a SHUTDOWN mode. The SHUTDOWN mode indicator is illuminated to notify the operator that he is now in the SHUTDOWN mode.

Inhibit STANDBY Mode Elapsed Time Meter and STANDBY Indicator. STANDBY mode elapsed time meter is inhibited in case we had been in the STANDBY mode prior to entering the SHUTDOWN mode. The STANDBY mode indicator is also extinguished at this point.

Inhibit FB-101, HSR-101, HSR-102, COD-101, -102, HE-101, CE-101, -102, -103 Temperature Controls. Power is removed from all the heaters and the system is allowed to cool down.

Close SV-112 (De-energize). The H_2 separator is sealed from vacuum.

At this point in the sequence, the SHUTDOWN mode process steps are identical to the STANDBY Mode process steps, so we return to the STANDBY mode subroutine at point I which is Step 5.6. The sequence continues through Step 5.21 and the system will stabilize in the SHUTDOWN mode. The main program will be entered again at point A and cycling will occur looking for the next request.

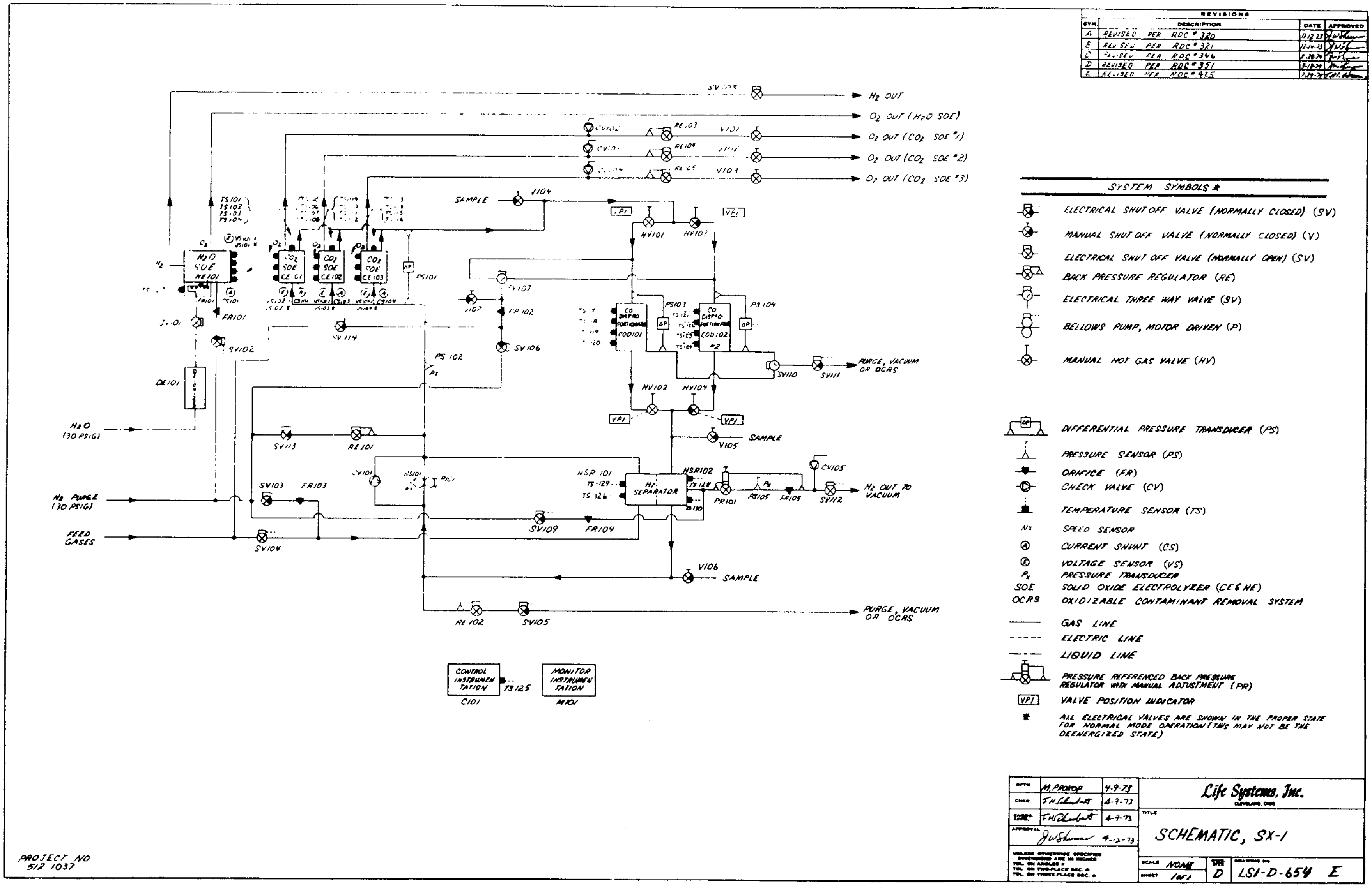


FIGURE A1-1 SX-1 SCHEMATIC