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DESIGN, DEVELOPMENT AND FABRICATION OF A WATER ELECTROLYSIS SYSTEM FOR A 90-DAY MANNED TEST

Prepared Under Contract NAS1-9728

BIOTECHNOLOGY
LOCKHEED MISSILES & SPACE COMPANY
Sunnyvale, California

for

NATIONAL AERONAUTICS & SPACE ADMINISTRATION
Langley Research Center

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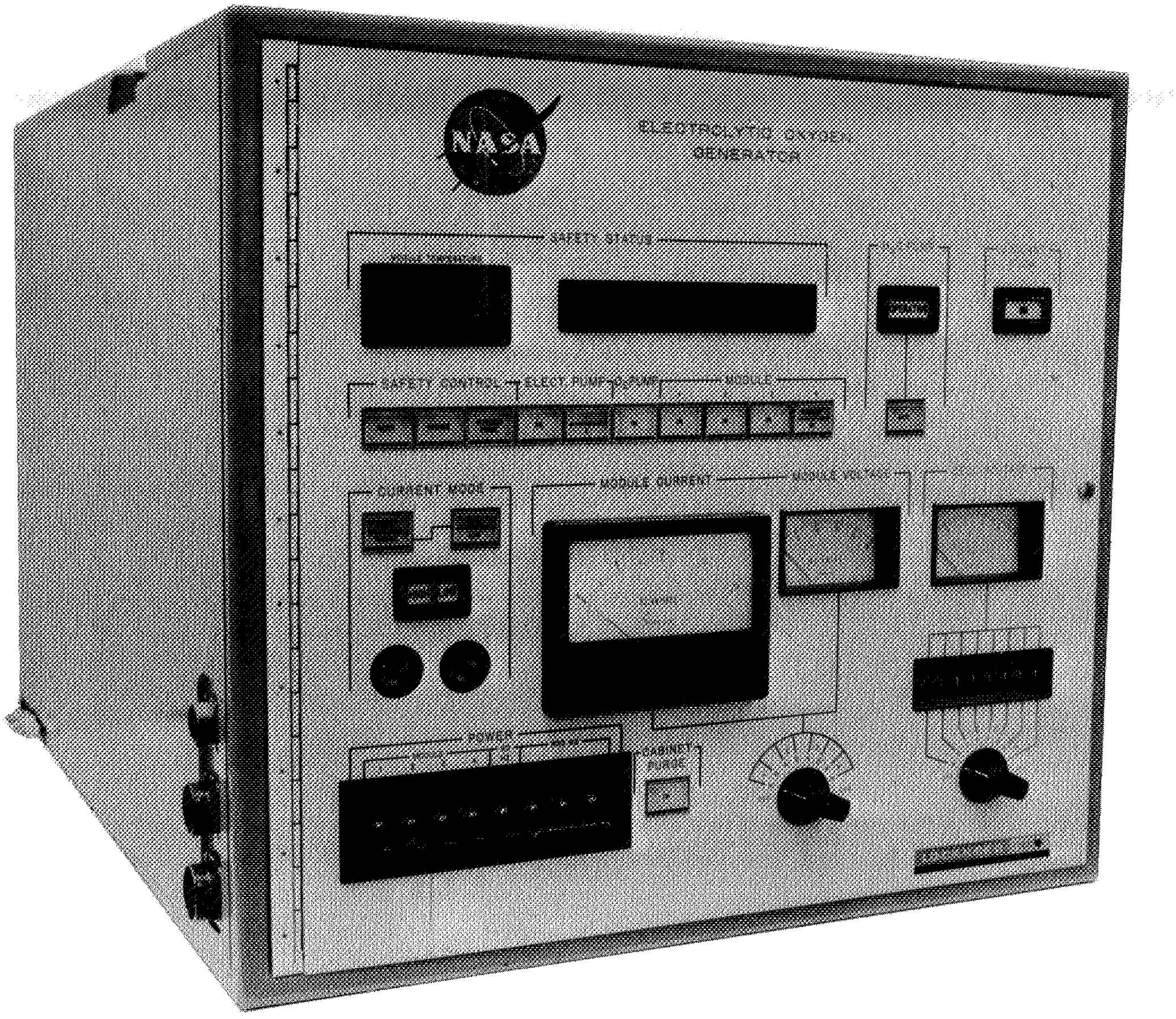

Electrolytic Oxygen Generator

LIST OF CONTRIBUTORS

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SUMMARY

In the program reported herein, a circulating-electrolyte water electrolysis system – Electrolytic Oxygen Generator – was designed, fabricated, acceptance tested, delivered, and operated on the outside of the chamber in support of the NASA/McDonnell Douglas 90-Day Manned Test.

Prior to delivery to the 90-Day Test site, the Electrolytic Oxygen Generator was subjected to an acceptance test, in which it operated successfully for 100 hours in a continuous, automatic, hands-off mode.

The system has provisions for manual startup and shutdown, automatic safety shutdown, and fault diagnosis and performance monitoring by means of front panel indicators. It features automatic control of water balance, temperature, differential pressure, and gas generation rate. The design oxygen generation capacity is 8 lb/day, at a discharge pressure of 21-27 psig. Hydrogen is discharged at 9 psig. The outside dimensions of the system enclosure are 24 inches across the front, 22 inches high, and 31 inches deep. The unit weighs 285 pounds fully charged with electrolyte and coolant.

The system operated successfully for 70 days and was required to furnish oxygen at rates up to 25 percent in excess of its design capability. Of 36 shutdowns identified, 27 were automatic and nine were manual; 14 were attributed to system component malfunctions, 20 to interface problems, and two yet unknown.

The 90-Day Test and a post-test examination indicated the following design improvements:

- Incorporating an automatic startup to minimize the man/machine interface
- Reducing the system sensitivity to downstream pressure pulses by providing an improved electrode-matrix configuration in the electrolysis cells
- Employing modular maintenance by providing individual, self-contained hydraulic assemblies with no electrolyte lines or fittings
- Improving the reliability of the electronic controls by providing shielding, isolation, temperature compensation, and thermistor temperature circuits.

In the design phase, a completely gravity-independent approach was evolved; but development problems and delivery schedule precluded incorporation of the closed reservoir device. The device was subsequently demonstrated successfully in another program.

Section 1

INTRODUCTION

In 1970, a 90-day operational manned test was performed under closed-door conditions in order to further the technology base for extended manned space missions (Contract NAS1-8997).[1] This test was conducted in the Space Station Simulator (SSS) of McDonnell Douglas Astronautics Company (MDAC), Huntington Beach, California. The Environmental Control/Life Support System (ECLSS) for this test included several new life support subsystems as well as previously demonstrated subsystems integrated in a total system. Among the objectives of the 90-Day Test was the determination of long-term operating characteristics of the individual subsystems.

The program described herein was concerned with a water electrolysis subsystem, which was provided as a backup for the primary McDonnell Douglas electrolysis system as a part of the ECLSS. This Electrolytic Oxygen Generator, a circulating-electrolyte type water electrolysis system, was procured by NASA/LRC for this purpose and designed to be suitable for operation and integration with the ECLSS either inside or outside the SSS. An extensive test experience with the circulating electrolyte technique in programs representing over 65,000 hours of cumulative test time on single cells, cell modules, and complete prototype systems has greatly facilitated the design effort. The first prototype circulating electrolyte water electrolysis system, which was integrated into a regenerative life support system in 1965, operated successfully during a 5-day manned and a 30-day unmanned test.[2] The capability of generating nitrogen admixed with the oxygen by the controlled addition of hydrazine to the basic circulating electrolyte system was experimentally demonstrated in single cells in an initial feasibility program.[3,4] Subsequently, a one-man model hydrazine-water electrolysis system was integrated with a cabin and metabolic/leakage simulator. With this system it has been demonstrated that completely automatic control of a space cabin total pressure and oxygen partial pressure can be achieved under varying metabolic and leakage loads.[5,6]

The program to design, fabricate, test, and deliver the Electrolytic Oxygen Generator was accomplished in a 4-month period, as shown in Fig. 1. The system was initially configured as a completely gravity-independent unit. Development problems with the closed reservoir and the short delivery schedule precluded the use of this device. However, the zero-gravity features of this design have been successfully demonstrated in another program (Contract NAS9-10405).

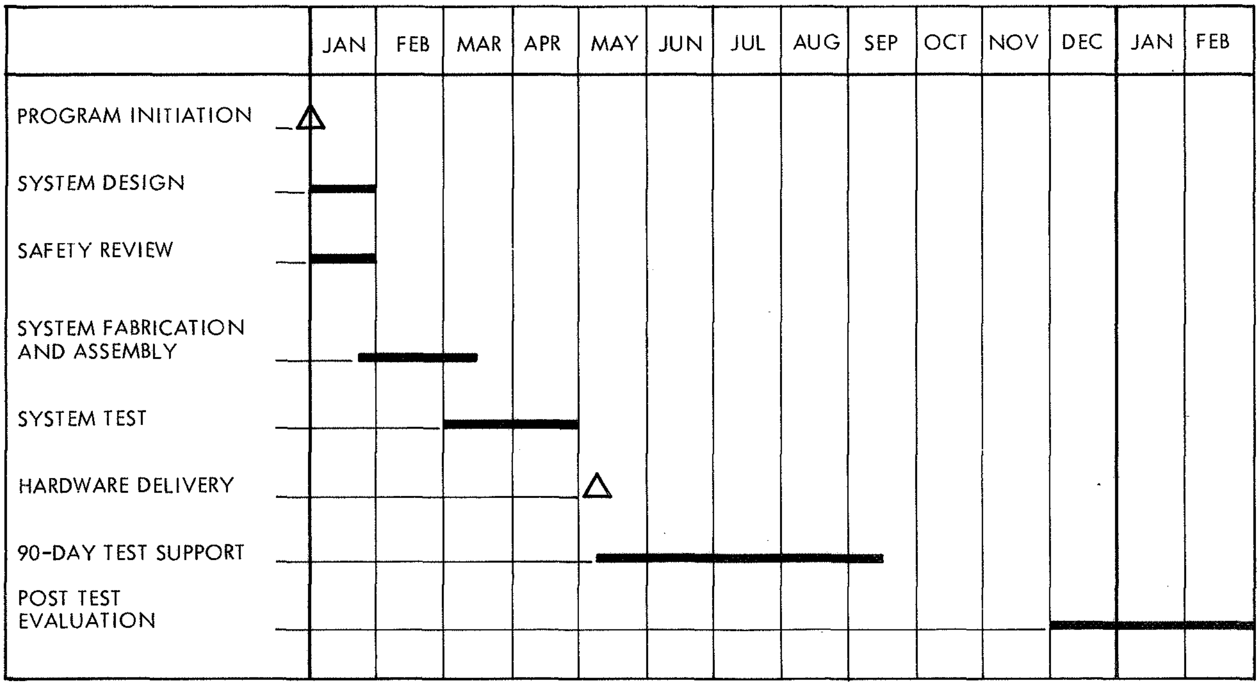


Fig. 1 Ninety-Day Test Program Schedule

The Electrolytic Oxygen Generator was subjected to a 100-hour acceptance test, delivered to MDAC, and installed for the 90-Day Test outside the SSS with interface connections to the chamber oxygen, hydrogen, and water accumulators. The system provided for manual startup and automatic operation thereafter except for automatic safety shutdown. Information was displayed on the front panel for fault diagnosis and safety monitoring and to indicate system performance. The design oxygen output capacity of the system was 8 lb/day at a discharge pressure of 21-27 psig. The hydrogen discharge pressure was 9 psig.

The system operated successfully during 70 of the 90 days. After the 90-Day Test was concluded, the Electrolytic Oxygen Generator was subjected to a post-test evaluation. The results of the 90-Day Test and the post-test evaluation have been used as a basis for recommendations for design and operational improvements in the system to enhance its potential flight worthiness.

Section 2
SYSTEM DESCRIPTION

2.1 ELECTROMECHANICAL COMPONENTS

A schematic of the Electrolytic Oxygen Generator is shown in Fig. 2. The concepts employed in the system design include the use of dual-matrix, liquid center electrolysis cells with a circulating 30% potassium hydroxide electrolyte. The outside dimensions of the system enclosure are 24 inches across the front, 22 inches high, and 31 inches deep. The unit weighs 285 pounds fully charged with coolant and electrolyte and redundant components.

2.1.1 Electrolysis Modules

The generating unit consists of three electrolysis modules and a spare in-line module. Each contains 16 cells, connected hydraulically in parallel and divided electrically into two eight-cell banks. Cells within an eight-cell electrical bank are connected in series. Peripheral manifolding within the module provides separate paths for electrolyte circulation, oxygen and hydrogen discharge, and nitrogen purge. By differential pressure control, the gas-liquid interface in the absorbent matrices contiguous to the electrodes is maintained to achieve phase separation.

2.1.2 Electrolyte Circulation

Electrolyte is pumped through a closed circulation loop by using one of two in-line magnetic-coupled centrifugal pumps. (The second pump is an inline spare.) The electrolyte leaving the pump passes through the tube side of a shell-and-tube heat exchanger. Coolant supplied to the shell side removes waste heat generated in the electrolysis modules. The electrolyte flow is split at a set of flowmeters into four paths leading to the electrolysis modules. Flow control valves in these lines are used to balance the flowmeters. Valves in the electrolyte discharge lines from the modules are provided so that a disabled module can be isolated from the circulation loop. During normal operation, these discharge valves are fully open.

Downstream of the discharge valves, the electrolyte is manifolded together and enters the electrolyte reservoir to be returned to the pump. Reference pressure is utilized from an external nitrogen pressure source controlled to the desired system pressure.

Water feed for the electrolysis process is supplied by direct injection into the reservoir. The proper water pressure and flow rate are effected by means of a gear pump, a manually adjustable flow control valve, and solenoid valve.

2.1.3 Gas Interfaces

Hydrogen is delivered from the electrolysis modules at approximately 9 psig. Oxygen discharged from the electrolysis modules at approximately 9 psig is pumped to 21-27 psig by means of a diaphragm pump. A pressure regulator across the pump maintains the pump suction pressure at 5 psig.

Nitrogen purge is provided to maintain gas-liquid differential pressure during startup and interim shutdown. When this function is actuated, whether manually or automatically during safety shutdown, inlet and outlet solenoid valves in the hydrogen and oxygen discharge lines open, allowing nitrogen to flow through the oxygen and hydrogen chambers of the electrolysis modules. A micrometer valve is used to adjust the nitrogen flow rate.

2.1.4 Internal Controls and Displays

The internal controls, which are manually adjustable, and displays are listed in Table 1 and portrayed in Fig. 3 through 6.

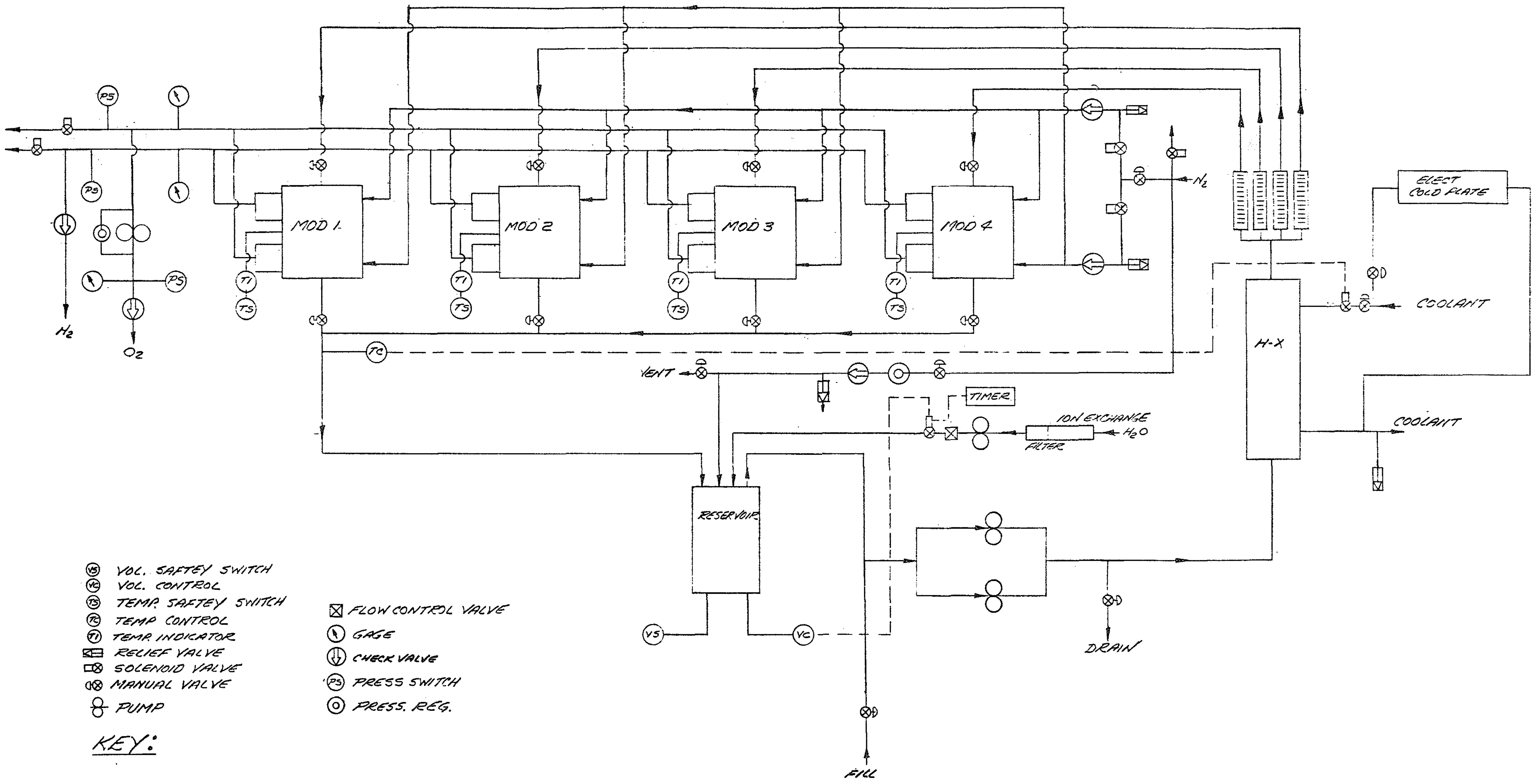


Fig. 2 System Schematic

Table 1

INTERNAL CONTROLS AND DISPLAYS

Controls	Displays	Location
ELECTROLYTE CIRCULATION SYSTEM		
Flow Control Valves		In front of modules 1 & 2
Discharge Valves		On top of modules
Fill Valve		Upstream of electrolyte pump
Drain Valve		Downstream of electrolyte pump
Vent Valve		Between module 4 and oxygen pump
	Electrolyte Flow Meter	In front of reservoir
HYDROGEN AND OXYGEN GAS DELIVERY SYSTEM		
Oxygen Pump Supply Pressure Reg.		Above oxygen pump
	Hydrogen Pressure in Modules	Above module 3
	Oxygen Pressure in Modules	Above module 4
	Oxygen Pump Supply Pressure	Above oxygen pump
	Oxygen Pump Discharge Press.	Above oxygen pump
NITROGEN PRESSURIZATION SYSTEM		
Module Purge Flow Control Valve		Above oxygen pump adjacent to cold plate
Reservoir Pressurization Reg.		Between reservoir and module 2
Reservoir Pressurization Supply Valve		Between reservoir and module 2
COOLANT SUPPLY SYSTEM		
Heat Exchanger Flow Control Valve		Behind oxygen pump downstream of solenoid
Cold Plate Flow Control Valve		Behind oxygen pump upstream of solenoid
WATER FEED SYSTEM		
Water Flow Control Valve		Downstream of Water Pump

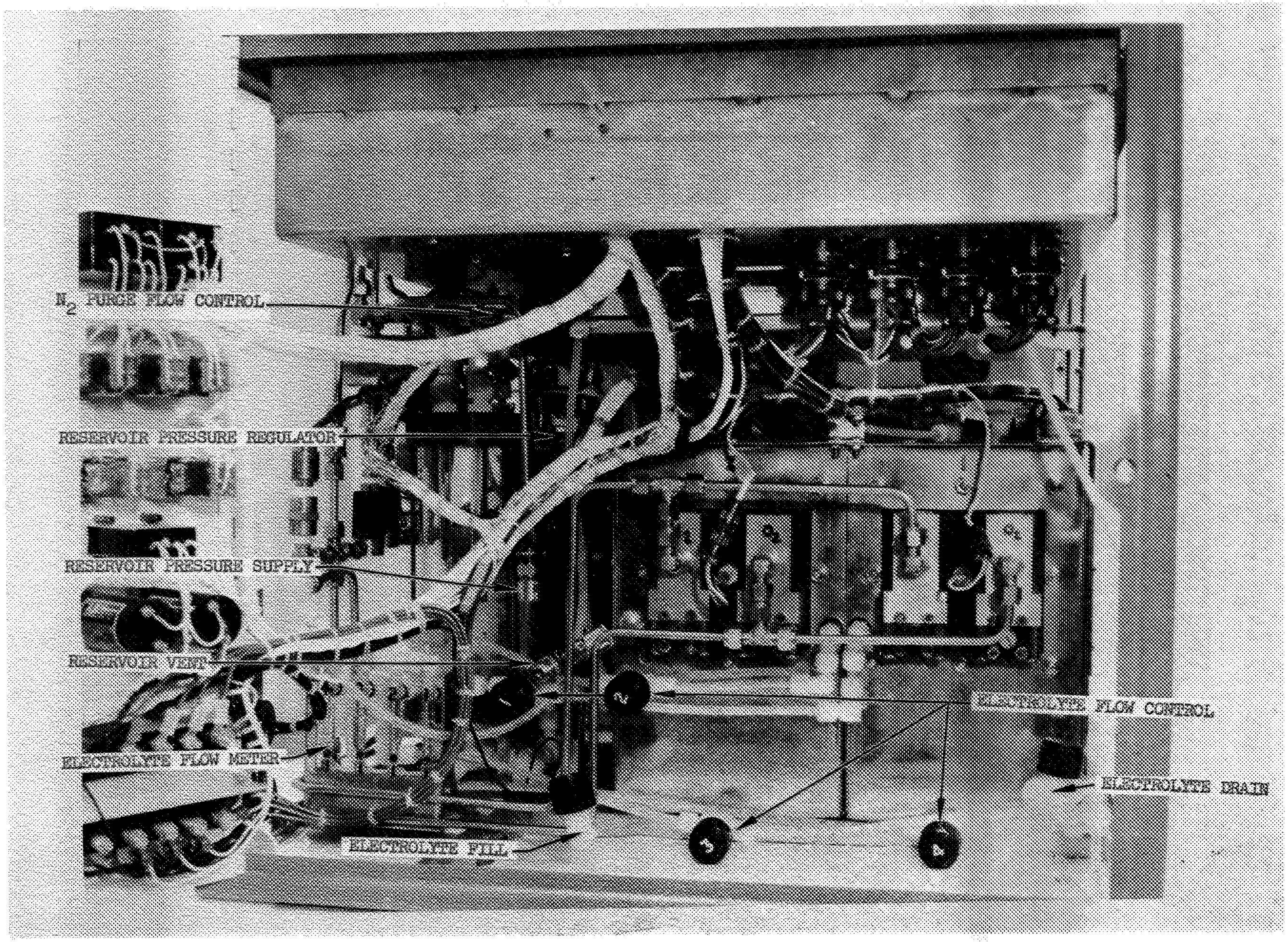
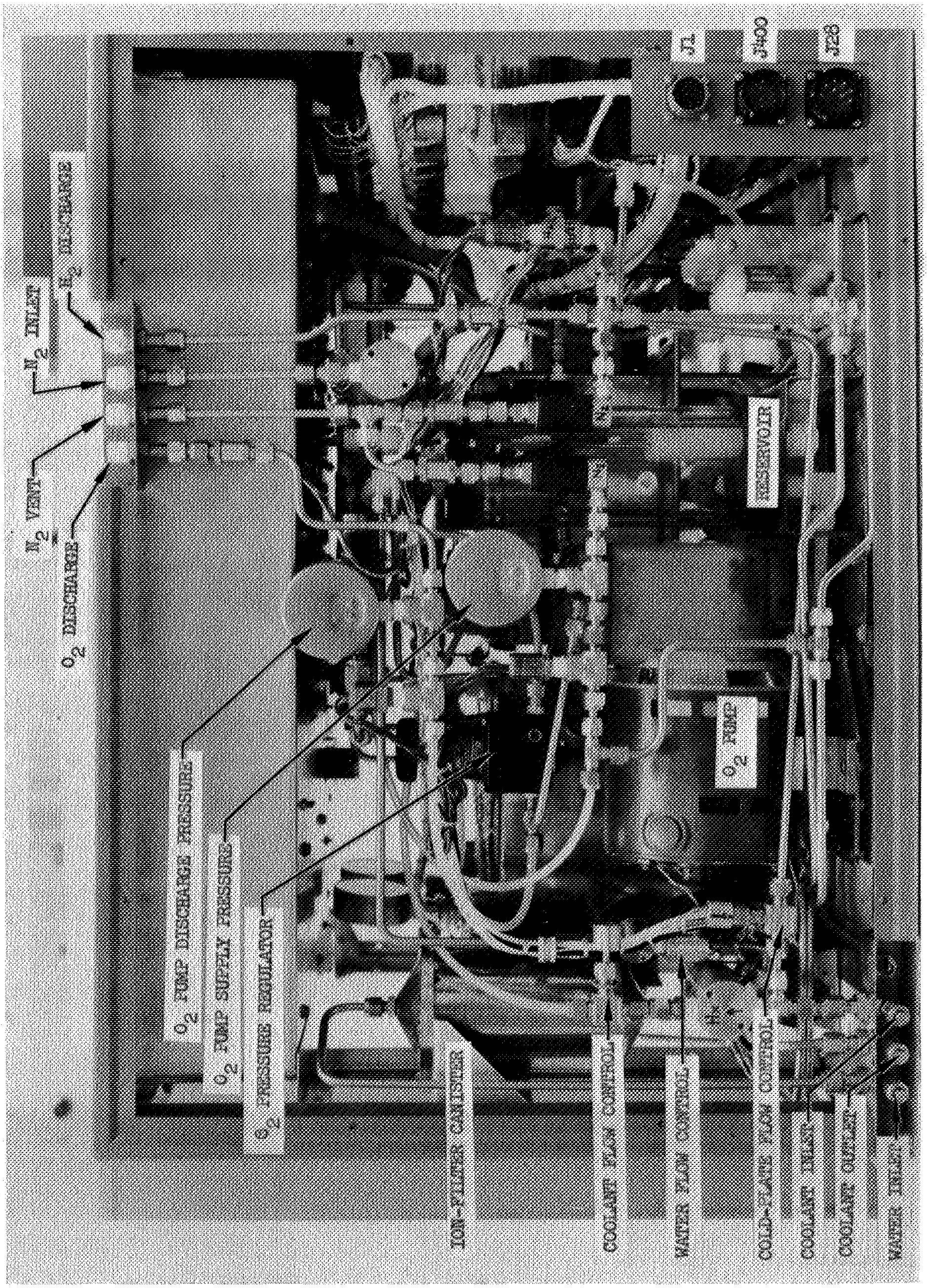


Fig. 3 Front Internal View


N_2 VENT
O_2 DISCHARGE
N_2 INLET
N_2 DISCHARGE
J1
J400
J28
RESERVOIR
O_2 PUMP
O_2 PUMP DISCHARGE PRESSURE
O_2 PUMP SUPPLY PRESSURE
O_2 PRESSURE REGULATOR
ION-FILTER CANISTER
COOLANT FLOW CONTROL
WATER FLOW CONTROL
COLD-PLATE FLOW CONTROL
COOLANT INLET
COOLANT OUTLET
WATER INLET

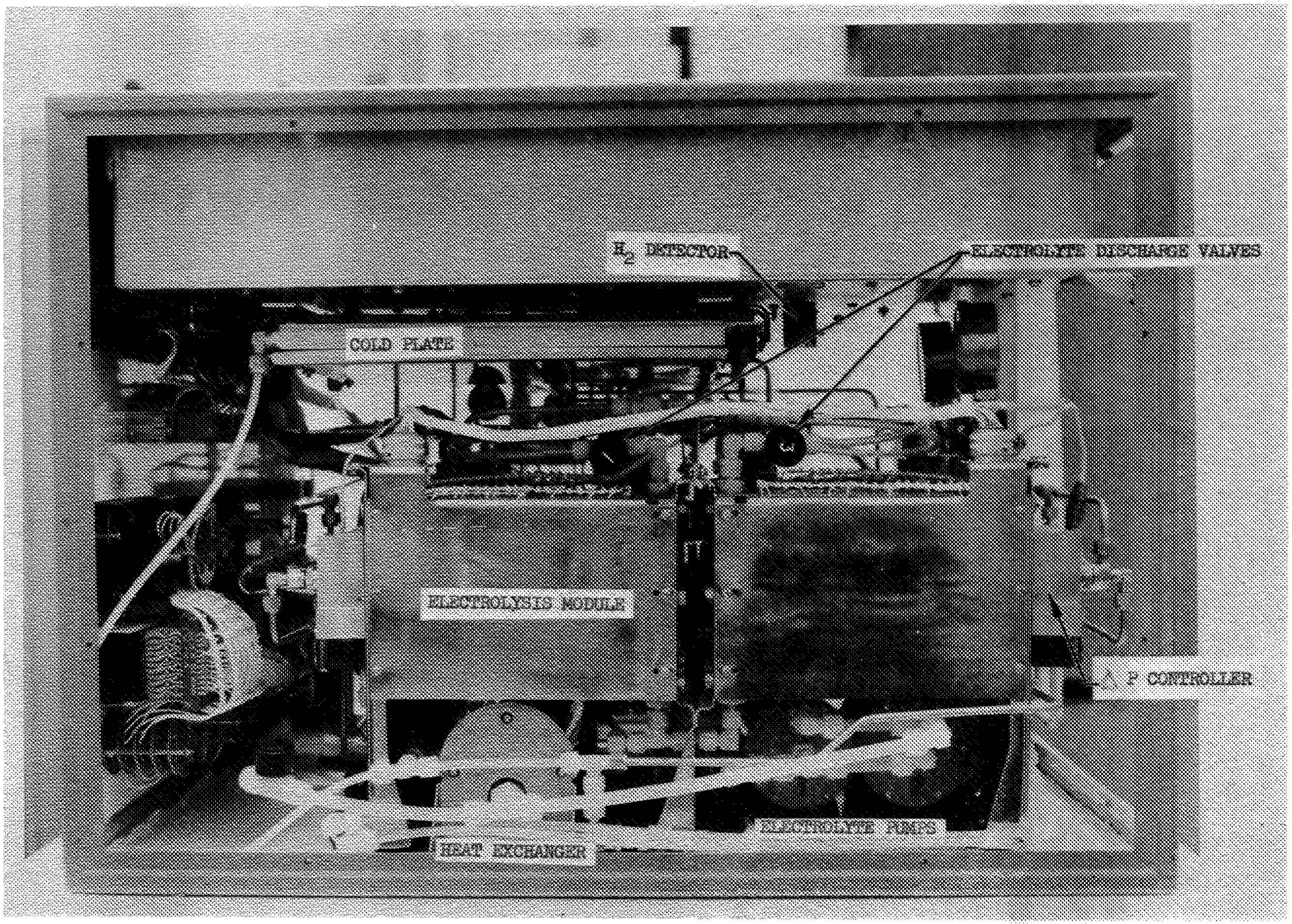


Fig. 5 Right-Side View

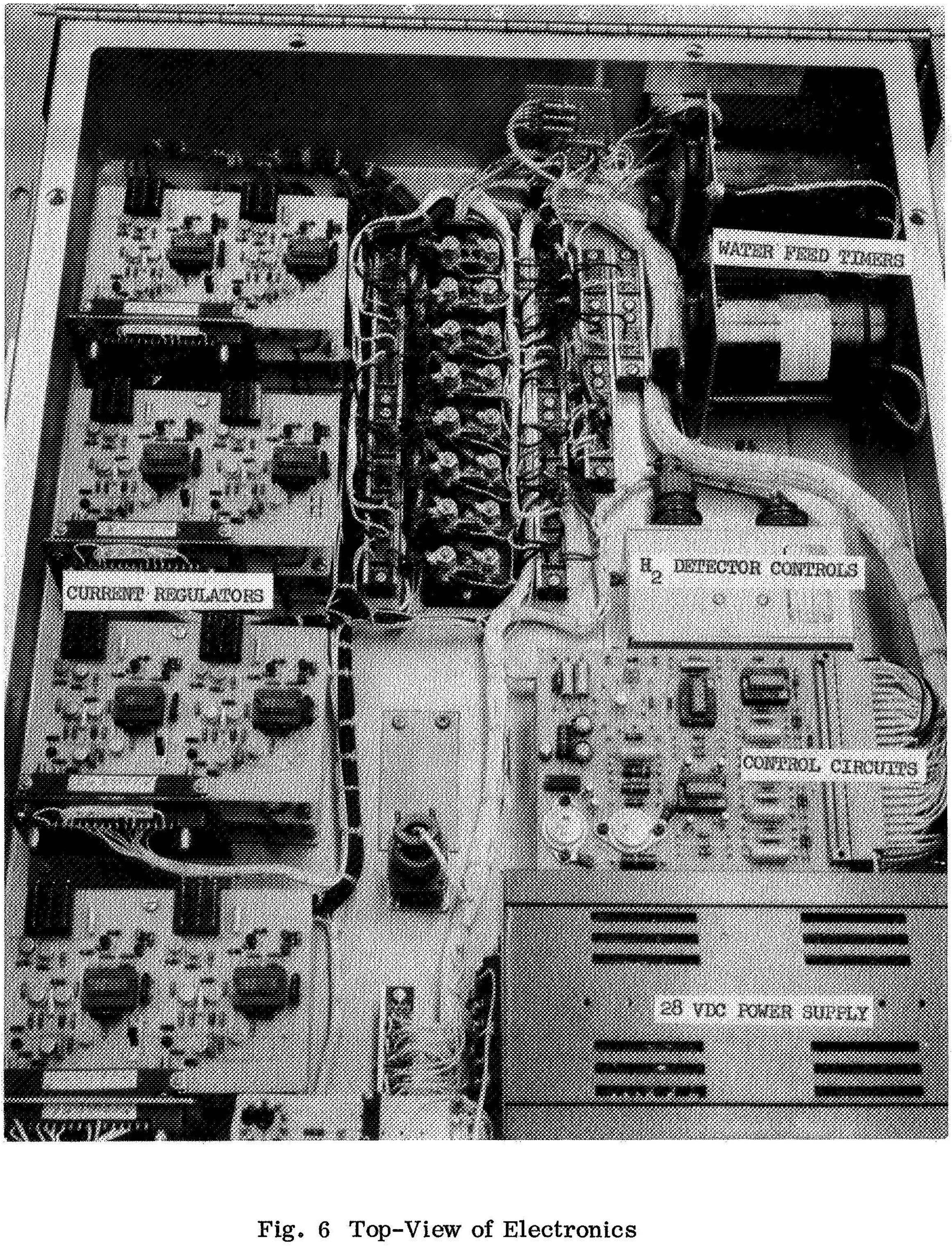


Fig. 6 Top-View of Electronics

2.2 AUTOMATIC CONTROLS

The Electrolytic Oxygen Generator is designed to function automatically during normal operation, except during manual startup and shutdown. The individual control functions are described in the following paragraphs, and detailed logic circuit diagrams are included in Appendix A.

2.2.1 Temperature Control

Control of the electrolyte temperature, necessary because of the waste heat generated in the electrolysis reaction, is accomplished by using a thermostat in the electrolyte discharge line from the modules to provide a control signal to a coolant solenoid valve. On demand, the solenoid valve opens to allow coolant to flow through the electrolyte heat exchanger. The flow rate is set with a manual valve. Control of the electrolyte temperature also provides control of the dewpoints of the generated oxygen and hydrogen. The thermostat provided in the Electrolyte Oxygen Generator has a switch-closure setting of 75°F. During normal operation, the dewpoint of the product oxygen will be no greater than 75°F and the hydrogen dewpoint will be approximately 40°F.

The continuous coolant flow to the electronics cold-plate is regulated with a manually set valve.

2.2.2 Water Feed System

Water balance in the circulating electrolyte is maintained by controlling the electrolyte volume. Two floats in the electrolyte reservoir actuate high- and low-level switches to provide a water-feed control band. A water-feed cycle occurs as follows: water is consumed in the electrolysis modules, causing the liquid level in the reservoir to drop. When the floats reach the lower limit of the control band, the water-feed pump is actuated, the water-feed solenoid valve opens, and the 15-second water-feed timer starts (according to a preset maximum feed time). The flow control valve is then set to deliver sufficient water in approximately 5 seconds. As water fills the reservoir, the liquid levels rises and the floats reach the upper limit of the control band. At this point, the water pump is shut off, the solenoid valve closes, the 15-second timer resets, and another timer which is preset for 5 minutes starts. During this period, the water-feed signal is overridden so that another water feed cannot occur until the timer resets.

The feed water supplied to the system passes through a resin canister, containing approximately 1-1/2 pounds of mixed anion-cation exchange resin. The outlet of the canister contains a particulate filter.

2.2.3 Differential Pressure

Two differential pressure controllers mounted on each module are set to control the hydrogen and oxygen pressures at 25-inch H_2O above the electrolyte pressure in order to maintain gas-liquid phase separation. Each ΔP controller is essentially a valve in operating principle with a spring-loaded valve stem attached to a rolling diaphragm. The valve seat is adjusted so that 25-inch H_2O higher pressure on the gas side of the diaphragm than on the liquid side is required to overcome the spring and open the valve.

2.2.4 Current Regulation and Oxygen Output Control

Each electrolysis module is provided with a current controlled switching regulator to control the DC input. Oxygen output is a direct function of the current value, which is selected by digital command (positive digital logic) according to the following:

Control Signals			Current Amperes
A (on/off)	B (high/low)	C (standby)	
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	4.5
1	0	1	4.5
1	1	0	12.0
1	1	1	Undefined

These currents are maintained over a module voltage range of 13.5 to 17.5 volts and a supply voltage range of 25 - 31 volts with an efficiency greater than 75 percent.

Module 4 is the only one that can be operated in the standby mode; and, in this mode, it can be operated only at the low current value. In the on mode, all modules can be manually operated at either high or low current. In the normal automatic mode of operation, a pressure switch in the oxygen discharge line determines the high or low current value. In this latter mode, all modules that are on will automatically switch to the low current value at 27 psig and to the high current value at 21 psig.

The current controlled switching regulation is accomplished by a control circuit, mounted on a plug-in circuit board and the external power circuitry.

Each control circuit board contains two identical control circuits. Figure 7 is a control circuit block diagram.

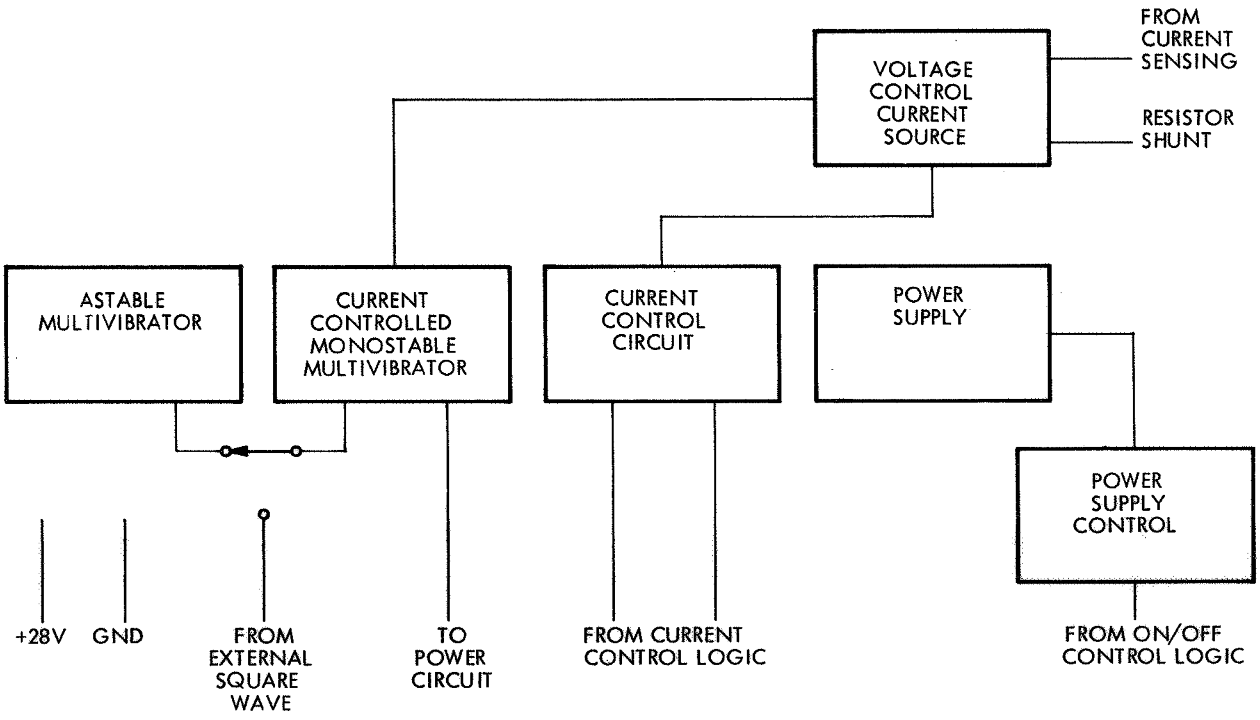


Fig. 7 Control Circuit Block Diagram

The power supply is regulated power for all blocks except the voltage controlled current source. An input signal from the on/off control logic disables the power supply, which stops drive signals to the power circuitry.

The astable multivibrator generates a positive square wave signal of about 13 Kc and about 10 percent duty cycle. Either this signal or a similar externally generated signal drives the current controlled monostable multivibrator. The monostable period of this multivibrator is controlled by the voltage controlled current source. The output is buffered and used to drive the power circuitry.

The voltage controlled current source has two input signals, the voltage across the current sensing resistor, and the current from the current control circuit. The output is a current proportional to the difference between these two signals. This output controls the power circuit duty cycle through the current controlled monostable multivibrator.

The current control circuit provides three levels of control current for the voltage controlled current source – a standby level and two higher current levels as controlled by current control logic digital signals. Figure 8 is a schematic diagram of the power circuitry.

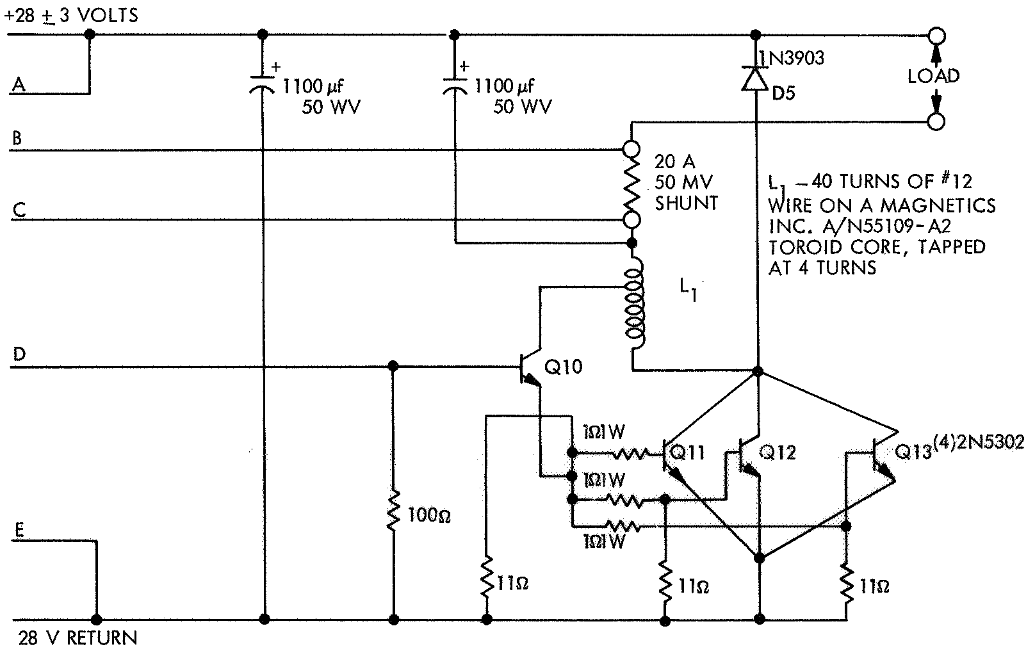


Fig. 8 Current-Regulating Power Unit

The signal from the current controlled monostable multivibrator switches transistors Q11, Q12, and Q13 on and off through driving transistor Q10. When the transistors are switched on, the current steadily increases through coil L and the load. When the transistors are switched off, the current flows through diode D5 and steadily decreases. Thus, the switching duty cycle controls the average current.

A summary of the circuit operation is as follows: The cell current is sensed by the current sensing resistor and compared with the current control circuit signal. The difference (error) changes the monostable multivibrator, thus changing the duty cycle of the power switching circuitry and correcting the load current to reduce the error. Figure 9 is a schematic diagram of the control circuit. Gates G1 and G2 form the astable multivibrator. Q1 buffers the output to the power circuitry. Amplifier A1 forms the voltage controlled current source. Q5 is the current source for the current control circuit, and Q2, Q3, and Q4 provide current control by switching in different emitter resistance for Q5. Q9 acts as a low value current source for zener diode D5. The zener voltage is used as the base reference for Q5 and also for Q6, which provides power to the digital circuits. Q7, Q8, and D4 are used to disable the power supply when the on/off control signal is off or low.

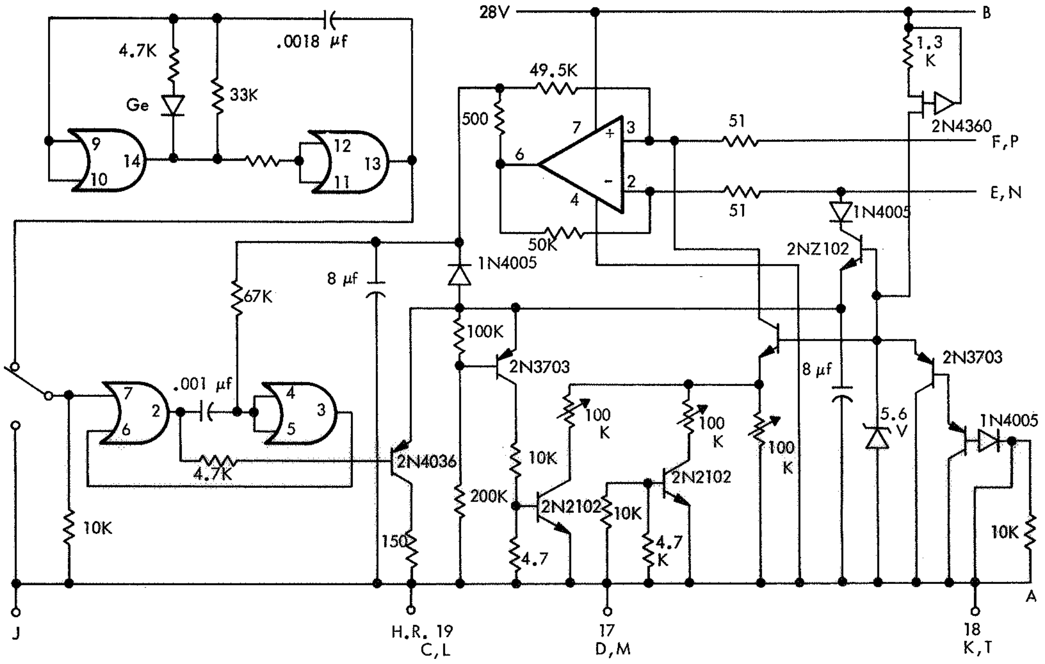


Fig. 9 Switching Regulator Control Circuit

2.2.5 Front Panel and Displays

The controls and displays presented on the front panel are shown in Fig. 10. The controls and displays are divided into switches, which are illuminated when the function is energized and not illuminated when the function is de-energized. Indicators are used to describe the status of some functions. Indicators have a black border and switches do not. The indicator and switch color codes are as follows. Green indicates a normal condition, yellow indicates an abnormal condition or caution status, and red indicates an unsafe condition. During normal automatic operation, only green lights or nonilluminated lights should be visible.

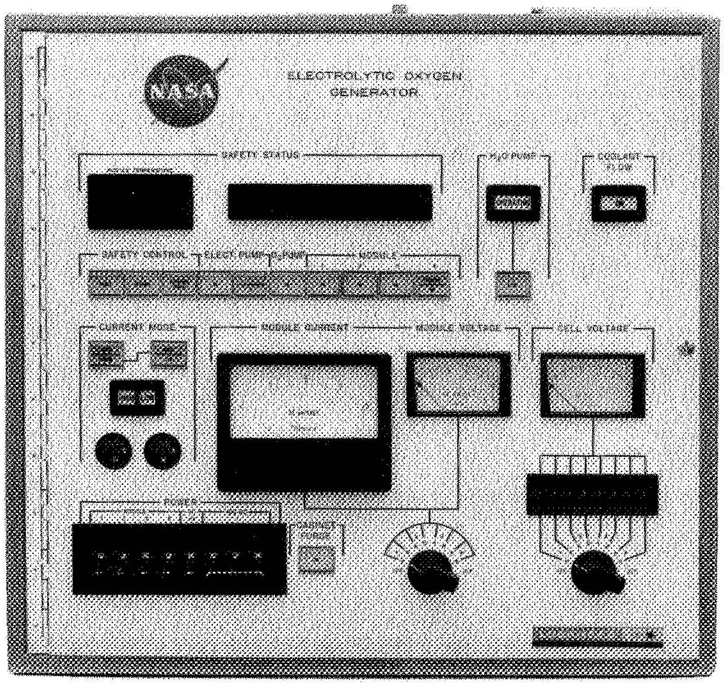


Fig. 10 Front Panel Controls and Displays

2.2.5.1 Safety Status. The module temperature indicator and logic can display two different temperature levels for each module. The first level indicated by a yellow lamp would be 85°F, and the system would not shut down. This indicator was intended only to warn of an impending over-temperature condition. The second temperature level is 100°F and is indicated by a red light. If any of these indicators are illuminated, the system automatically shuts down. The temperature sensors used in the 90-Day Test had only the upper temperature switch closure; consequently, the lower temperature warning could not be used.

The next safety status indication is excess hydrogen gas pressure. If the hydrogen gas pressure in the discharge manifold exceeds 13 psig, the indicator is illuminated in red and the system is automatically shut down. The next safety status indication is excess oxygen pressure. If the oxygen gas pressure in lines discharging from the cells but upstream of the oxygen supply pump exceeds 13 psig, the indicator is illuminated in red and the system is automatically shut down. The next safety status indication is electrolyte volume. If the electrolyte level rises to near the top or drops to near the bottom of the reservoir (± approximately 3 percent of total electrolyte volume), the indicator is illuminated in red and the system is automatically shut down. The next safety status indication is hydrogen detected in the cabinet. If the hydrogen detector senses a hydrogen concentration of 0.8 percent by volume, the indicator is illuminated in red and the system is automatically turned off.

2.2.5.2 Safety Controls. The safety controls are located below the module temperature displays. The first control is the system reset. When the system is de-energized, either automatically or by interruption of the 60-Hz power supplied to the unit, the reset switch lamps are de-energized. Before the system can be restarted, the reset switch must be depressed and illuminated in green. If the safety condition that caused the shutdown has not been corrected, the system will not reset and the switch light will not illuminate. During initial startup, the reset must also be depressed if the light is not illuminated.

One important factor in the operation of the reset switch is that when the switch is not illuminated, the remaining control switches indicate the switch position, not the status of the component. This is done to allow the operator to know what components will be energized when the reset switch is actuated. When the reset is off, the electrolyte pumps, the water feed system, and the electrolysis modules are de-energized.

The next safety control is the over-ride switch. When this switch is illuminated in yellow, the safety circuits are over-ridden and they will not automatically turn the system off. The final safety switch is the nitrogen purge. When the reset switch is not illuminated, the module nitrogen purge solenoid valves are open. When the reset switch is illuminated, the nitrogen purge solenoid valves are closed except when the nitrogen purge switch is illuminated in yellow.

2.2.5.3 System Controls and Displays. The group of controls located to the operator's right of the safety controls and status indicators are for the electrolyte pump, oxygen pump modules, water feed system, and coolant supply to the heat exchanger. The electrolyte pump switch operates the pump selected by the adjacent switch. The oxygen pump switch operates the oxygen pump. The module switches energize the four electrolysis modules. The first three modules have two switch positions: off and on. The fourth module switch has three positions: off, standby, and on. The function of the standby mode is discussed in connection with the current mode selector. The next control and indicator is for the water feed system (H_2O pump). The water feed system has two modes of operation: automatic and off. The indicator located above the water feed system pump indicates when the pump is operating and feeding water to the system.

The indicator of coolant flow to the electrolyte heat exchanger is located adjacent to the water feed system control. This is an entirely automatic function, with no front panel control.

Located below the safety control switches are the current mode controls and displays. There are two operating current modes for modules 1, 2, and 3 and three modes for module 4. The modes for modules 1, 2, and 3 are high and low current. These can be selected manually by positioning the auto/manual switch so that the manual light is illuminated in yellow. Then the current mode is selected with the high/low switch. When the auto/manual switch is in the auto mode, the high/low switch has no control over the current mode and its indication should be disregarded. The indicator located below these switches always displays the actual current mode. When automatic operation is selected, the auto portion of the auto/manual light will be illuminated in green and the current mode will be controlled by the oxygen supply pump discharge pressure switch. Two elapsed time meters are located below the current status indicators and record the elapsed time in each mode.

The fourth module has the same current modes as modules 1, 2, and 3. In addition, it has a standby mode for selecting a fixed low current that is not controlled by the current mode controls.

2.2.5.4 Voltage and Current Monitoring. The voltage and current displays located to the right of the current mode control present current for the individual modules, module voltage, and all of the cell voltages.

The four modules are each electrically divided into two 8-cell banks, designated A and B. The voltage and current for banks A and B can be selected with the rotary switch located below module current and voltage meters.

The individual cell voltages for each bank can be observed by placing the rotary switch below the cell voltage meter on the desired bank and selecting the desired cell within that module with the digital selector switch.

2.2.5.5 Circuit Breakers. On the lower left-hand side of the panel are located the power circuit breakers. The first four circuit breakers control the 28-volt DC power to the electrolysis cell modules. The next circuit breaker controls the 115-volt, 60-Hz power for the electrolyte pump, oxygen pump, and all controls and displays. All DC power required by the unit other than that required for electrolysis is generated from the 115-volt, 60-Hz power with power supplies located within the unit. The next three breakers are for the 208-volt, 400-Hz power used for the water feed pump.

2.2.5.6 Cabinet Purge. Depressing this switch which is located adjacent to the circuit breakers, energizes the cabinet nitrogen purge solenoid. When the solenoid is energized, the switch is illuminated in red.

2.3 SAFETY CIRCUITS

Safety circuits are provided to shut down the system automatically under abnormal operating conditions. In an automatic shutdown, electrolysis module power is turned off; the electrolyte pump, water feed system, and system reset are turned off; nitrogen purge to the modules comes on; and the cause of shutdown is indicated on the front panel. The "on" command signal for those components controlled by the automatic shutdown logic is gated with an "operate" signal. When the "operate" signal is in a logical "false" state, these inhibit gates command the system to the "off" condition. Thus, normal system operation depends on a logic true "operate" signal. The "operate" signal is derived from the $\bar{F}$ output of a nongate memory latch, identified as Z1 on card W2. The circuit is normally in a reset condition and gets set by initiation of a shutdown signal. Switch S2 provides a manual override of the shutdown signal for module startup purposes. The shutdown signal is derived from nongate circuitry, which continuously monitors the following safety circuits: (1) module temperatures, (2) O_2 and H_2 safety pressure, (3) H_2 detector, (4) electrolyte volume, and (5) interruption of 60 Hz power. Each safety circuit except for item (5) above has its own memory latch, which allows the system to remember what type of malfunction caused the shutdown. The input to these memory latches is driven by the safety sensors. When an out-of-tolerance condition exists, the respective latch is set. A reset condition can be obtained by depressing the system reset button S1. Circuit diagrams are included in Appendix A.

2.3.1 Module Temperature

A temperature sensor is located in each module, in contact with an end electrode. These thermostats have a switch-closure at 100°F. Any one of the four temperature sensors can actuate the shutdown.

2.3.2 Gas Pressure

The oxygen and hydrogen discharge lines from the modules each contain a pressure switch set to actuate automatic shutdown if the pressure reaches approximately 13 psig.

2.3.3 Electrolyte Volume

Switches located at the top and bottom of the electrolyte reservoir are actuated by the floats if the electrolyte level in the reservoir reaches either of these two points. Either of these points represents a 3 percent change in the total electrolyte volume.

2.3.4 Hydrogen Detector

A hydrogen detector located directly over the electrolysis modules will signal automatic shutdown if the hydrogen concentration reaches 0.8 percent.

2.3.5 Power Interruption

The loss of the 115-VAC, 60-Hz power input to the unit, even if momentary, will automatically put the system in the shutdown mode, from which it will have to be manually restarted.

2.4 SYSTEM INTERFACE REQUIREMENTS

The service requirements for the operation of the Electrolytic Oxygen Generator are the following:

Feed water	
Temperature	60 - 80°F
Pressure	<10 psig
Solids	<100 ppm
Conductivity	<80 μmho/cm
Coolant	
Fluid	water
Temperature	40 ±4°F
Flow rate	1 gpm
Nitrogen	
Pressure	70 psig
Power	28 ±3 VDC 115 VAC, 60 Hz 208 VAC, 400 Hz, 3 phase

The system was designed to deliver oxygen at an average rate of 8 lb/day at a pressure range of 21 - 27 psig. The hydrogen is delivered at approximately 9 psig.

The water connection and coolant conditions are located on the left-hand side at the lower back corner of the unit; elbow fittings, pointing toward the back, are provided with 1/4-inch male connectors. The oxygen, hydrogen, nitrogen purge and vent lines, located on the left-hand side at the top, are provided with 1/4-inch male Swagelok connections.

The electrical interface is located on the left-hand side near the front of the unit. The interface consists of the connections P28 - J28, P400 - J400, and the junction half of J1. Pin assignments for these connectors are included in Appendix A.

Section 3
SAFETY REVIEW

3.1 NONMETALLIC MATERIALS

Because of the concern in a manned test for flammability and toxic off-gassing of nonmetallic materials, a careful analysis was made of these materials and how they were to be used in the Electrolytic Oxygen Generator.

3.1.1 Nonmetallic Materials Summary

All of the nonmetallic materials used in the Electrolytic Oxygen Generator are itemized in Table 2, in which the location, type of material, and estimated weight are indicated. Stainless steel housings were used throughout the system to provide fire protection.

3.1.2 Nonmetallic Materials Tests

Flammability and off-gassing tests were conducted on plastics that constituted the major amount of nonmetallic materials in the system. The results of these tests are given in Table 3.

3.2 FAILURE MODES AND EFFECTS ANALYSIS

A detailed failure modes and effects analysis, given in Table 4, indicated that no single assumed failure mode of a mechanical or electrical component of the system would result in a fire hazard.

Table 2

NONMETALLIC MATERIAL SUMMARY

Component	Material	Weight	Remarks
Cell Modules			
Frames	High Temp Epoxy	16 lb	The four modules are packaged to form a cube with stainless cover plate on four sides.
"O" Ring	Ethylene Propylene	1.3 lb	
Electrode Tape	Vinyl	<1 gm	
End Plates	Polysulfone	8 lb	
ΔP Controller			
Lower Body	Polysulfone	0.25 lb	The upper body housing the valve body, valve stem and "O" rings is constructed of stainless steel. The lower body housing the bellofram is attached to the upper body and is filled with liquid.
Valve	Polyphenolene oxide	0.10 lb	
Bellofram	Ethylene Propylene	<1 gm	
"O" Ring	Ethylene Propylene	<1 gm	
Heat Exchanger			
Inner Shell	Acrylic	0.25 lb	The outer shell and end plates that completely enclose the heat exchanger are constructed of stainless steel.
Tubes	Nylon	0.25 lb	
Headers	High Temp Epoxy	0.125 lb	
End Plates	Polysulfone	0.375 lb	
Reservoir			
End Plates	Polysulfone	0.375 lb	The outer shell covering the unit is made of stainless steel.
Inner Shell	Acrylic	0.125 lb	
Flow Meter	Acrylic	0.50 lb	Flow meter filled with electrolyte and mounted on stainless steel bracket.

Table 2 (Cont.)

Component	Material	Weight	Remarks
Electronic Chassis			
Terminal Boards	Glass Filled Teflon	0.40 lb	All electronics are enclosed in an aluminum box with the exception of the power transistors which are mounted on a cold plate. This cold plate is mounted on the outer surface of the electronic chassis and has coolant circulation thru internal passages.
Resistors	Phenolic	0.30 lb	
Shunt Base	Bakelite	0.25 lb	
Terminal Strips	Silicone Rubber	0.25 lb	
Terminal Strips	Bakelite	0.12 lb	
Wire insulation	Teflon	0.75 lb	
Connectors	Phenolic	0.40 lb	
Control Panel			
Switches (Rotary)	Phenolic	0.05 lb	
Switches (Push)	Acrylic/Phenolic	0.3 lb	
Indicator Lights	Acrylic/Phenolic	0.5 lb	
Switches (Breaker)	Phenolic	0.5 lb	
Meter (Volt)	Acrylic/Phenolic	0.2 lb	
Meter (Amp)	Acrylic/Phenolic	0.1 lb	
KOH Plumbing			
Fittings	Nylon	0.5 lb	All nonmetallic fittings and lines are filled with KOH.
Tubing	Polyethylene	1.0 lb	
Valves	Nylon	1.0 lb	
Ion Exchange Resin	Amberlite MB-3	1.0 lb	Installed in stainless steel canister filled with water.
Mat	Asbestos impregnated with boric acid	1.0 lb	
Paint	Epoxy	0.1 lb	

Table 2 (Cont.)

Component	Material	Weight	Remarks
KOH Pumps			
Pump Heads	Polypropylene	1.0 lb	The pump head has a stainless steel outer jacket.
Wiring Insulation	Teflon	1.0 lb	

Table 3

NONMETALLIC MATERIAL TESTS SUMMARY

Flammability Test Results Summary*

Material	Burning Rate	Comments
Epoxy	0.25 Inches/Second	Completely Consumed
Polysulfone	Self-Extinguishing	Flame out in two seconds – no dripping

Off-Gassing Test Results Summary

Material	Products	Rate	Allowable**
Polysulfone	Total Hydrocarbon	4.2 µgm/gm	100 µgm/gm
	Carbon Monoxide	0.82 µgm/gm	25 µgm/gm
	All Others	1 µgm/gm	10 µgm/gm

*Modified ASTM D635 Procedure in which sample is held at 60° to the horizontal. Tests run in air.

**Reference – MSC-D-NA-002

Table 4

FAILURE MODE AND EFFECTS ANALYSIS

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Ion Exchange/Filter	Plugged Filter	Debris/dirt in supplied water	Reduced water feed; electrolyte volume will decrease with time.	Water feed light on control panel will stay lighted instead of cycling Reservoir low level light is activated	No
	Leaks	Mfg. defect	Same as above plus local flooding	Auto-shut-down of system by reservoir level switch or module overtemp switch	
Water Pump Motor	Motor fails	Timer fails in off mode Loss of power supply Uncouples Seized bearings	Reduced water feed; electrolyte volume will decrease with time	Same as above	No
Water Pump	Breaks/disintegrates	Mat'l or mfg. defect	Reduced water feed; electrolyte volume will decrease with time	Water feed light on control panel will stay lighted instead of cycling Reservoir low level light is activated Auto-shut-down of system by reservoir level switch or module overtemp switch	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
	Leaks	Mat'l or mfg. defect	Same as above plus local flooding	Same as above	No
Timer	Fails in "off" mode Fails in "on" mode	Open, shorted Loss of power supply, or jammed	Reduced water feed; electrolyte volume will decrease with time One safety feature of water feed system is negated	Reservoir level light is activated Auto-shut-down of system from reservoir level switch or module overtemp switch Reservoir safety still operative	No No
Solenoid Valve	Fails "open" or "closed"	Open, shorted Loss of power or spring breaks	No effect No water feed; electrolyte volume will decrease	Check valve prevents loss of Water feed light on control panel will stay lighted instead of cycling Reservoir low level light is activated Auto-shutdown of system by reservoir level switch	No No
Electrolyte Volume Control Switch	Fails "open" or "closed"	Same as above	Too much or too little water feed	Reservoir level light is activated Auto-shut-down of system from reservoir level switch or module overtemp sw	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Volume Safety Switch	Fails "open" or "closed"	Same as above	Possible loss of auto-shut-down feature or system is shut-down by the failure	Reservoir level light is activated if level goes out of limits Concurrent failure of reservoir level switch and electrolyte supply anomaly is very remote Module overtemp switch provides backup	No
Electrolyte Reservoir	Leaks	Mfg. defect/ faulty material	Local flooding	Reservoir level light is activated Auto-shut-down of system from reservoir level switch or module overtemp switch	No
KOH Flowmeter	Leaks	Mfg. defect/ faulty material	Local flooding	Auto-shut-down of system by module overtemp switch or reservoir level switch Module temp. indicator gives visual indication of module anomaly	No
Module	External KOH leak	Same as above	Same as above	Same as above	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
	Matrix failure	Same as above	Reduced output of oxygen or hydrogen. Gas enters electrolyte	Auto-shut-down of system by reservoir high level switch as added volume of gas overfills reservoir Module temp. indicator gives visual indication of module anomaly	No
	External Oxygen leak	Mfg. defect/ faulty material	Reduced output of oxygen	Low oxygen pressure indication	No
	External Hydrogen leak	Same as above	Reduced output of hydrogen	Low hydrogen pressure indication Hydrogen alarm system is activated and auto-shut-down of system occurs	No
Module Temp Indicator	Malfunctions	Mfg. defect/ faulty material	Spurious indication of module temp.	No adverse effect on system operation A decrease in module voltage will be indicated both inside and outside chamber	No
Module Temp. Switch	Fails "open" or fails "closed"	Same as above	Possible loss of module overtemp shut-down feature, or auto-shut-down is initiated by switch failure	Concurrent failure of overtemp switch and module temperature anomaly is very remote. Module temp indicator will indicate	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
				a temp anomaly. Module overtemp could only be caused by loss of electrolyte or excessive amperage to electrodes	
Electrolyte Temperature Controller	Fails in "on" mode	Mfg. defect/ faulty mat'l	Increase in power requitement (higher voltage)	Electrolyte temperature is reduced by continuous circulation thru heat exchanger Higher module voltages will be indicated both inside and outside the chamber	No
	Fails in "off" mode	Same as above	Decrease in power requirement (lower voltage)	Lower module voltages will be indicated both inside and outside the chamber Module overtemp switch will cause auto-shut-down	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Coolant Control Solenoid Valve	Fails in "open" mode	Mfg. defect/ faulty mat'l	Increase in power requirement (higher voltage)	Electrolyte temperature is reduced by continuous circulation thru heat exchanger Higher module voltages will be indicated both inside and outside the chamber	No
	Fails in "closed" mode	Same as above	Decrease in power requirement (lower voltage)	Lower module voltages will be indicated both inside and outside the chamber Module overtemp switch will cause auto-shut-down	No
KOH Pump	Breaks	Same as above	No electrolyte flow, module temperature increases	Auto-shut-down of system by module over-temp switch	No
	Leaks	Mfg. defect/ faulty mat'l	Local flooding	Auto-shut-down of module overtemp switch or reservoir level switch	No
KOH Pump Motor	Motor fails	Loss of power supply, uncouples, seized bearings shorted, open ckt.	No electrolyte flow, module temperature increases	Auto-shut-down of system by module over-temp switch	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Heat Exchanger	Internal leak	Mfg. defect/ faulty mat'l	Coolanol 35 is forced into KOH contaminating system	Auto-shut-down of system by reservoir level switch	No
	External KOH leak	Same as above	Local flooding	Same as above	No
	External Coolant leak	Mfg. defect/ faulty mat'l	Local flooding	Auto-shut-down of system by module over-temp switch	
Coolant (MDC Responsibility)	Loss of coolant supply	MDC responsibility	Module temperature increases	Same as above	No
Water (MDC Responsibility)	Loss of water supply	MDC responsibility	Reduced water feed; electrolyte volume will	Reservoir low level switch activates auto-shut-down	No
115 VAC Power (MDC Responsibility)	Loss of power	MDC responsibility	System goes to dormant mode with nitrogen purge	Auto-shutdown	No
28 VDC Power (MDC Responsibility)	Loss of power	MDC responsibility	Output of oxygen and hydrogen terminates	Auto-shut-down is activated by high level switch in reservoir as water added overfills reservoir	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Hydrogen ΔP Regulator	Fails to maintain pressure differential.	Mfg. defect/ faulty mat'l	KOH floods hydrogen cells of module and may contaminate hydrogen supply line	Auto-shut-down by low level switch in reservoir. Nitrogen purges contaminated hydrogen supply line	No
	Plugged Port	Same as above	Hydrogen is forced into KOH	Auto-shut-down by high level switch in reservoir	No
	Leaking	Mfg. defect/ faulty mat'l, loose connection	Reduced supply of hydrogen	Low hydrogen pressure indication. Hydrogen alarm system is activated and auto-shut-down occurs	
Oxygen ΔP Regulator	Fails to maintain pressure differential	Mfg. defect/ faulty mat'l	KOH floods oxygen cells of module and may contaminate oxygen supply line	Auto-shut-down by low level switch in reservoir. Nitrogen purges contaminated oxygen supply line	No
	Plugged Port	Same as above	Oxygen is forced into KOH	Auto-shut-down by high level switch in reservoir	No
	Leaking	Mfg. defect/ faulty mat'l, loose connection	Reduced supply of oxygen	Low oxygen pressure indication	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Nitrogen Supply Solenoids	Fails in "Open" mode	Mfg. defect/ faulty mat'l	Nitrogen contamination of oxygen and hydrogen lines	Periodic monitoring of current mode timers will reveal that a system anomaly exists	No
	Fails in "Closed" mode	Same as above	Loss of nitrogen purge capability	No adverse effect on system operation	No
Nitrogen Exhaust Solenoid Valves	Fails in "Open" mode	Mfg. defect/ faulty mat'l	Oxygen or hydrogen output is wasted	Periodic monitor of H_2 and O_2 pressure gages will reveal low pressure anomaly	No
	Fails in "Closed" mode	Same as above	Nitrogen purge may exhaust into the system during shutdown	Nitrogen will exhaust into hydrogen tank or oxygen tank This only occurs during shut down, and would not inhibit normal operation of the system	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Oxygen Pump	Breaks	Mfg. defect/ faulty mat'l	Impaired supply of oxygen to the supply tank	Oxygen overpressure switch activates auto-shut-down of system	No
	Leaks	Same as above	Loss of oxygen from supply tank	Oxygen downstream of ΔP regulator vents to ambient pressure KOH floods oxygen cells. Reservoir low level switch activates auto-shut-down. Periodic monitoring of current mode timers will reveal that a system anomaly exists	No
Oxygen Pump Motor	Motor fails	Loss of power, uncouples, shorted seized bearings, open ckt	Impaired supply of oxygen to supply tank	Oxygen overpressure switch activates auto-shut-down of system	No
Oxygen Pressure Regulator	Fails to maintain pressure differential	Mfg. defect/faulty material	No effect	None required	No
	Plugged Port	Same as above	Same as above	Same as above	No
	Leaking	Mft. defect/ faulty mat'l	Loss of oxygen from supply tank	Periodic monitoring of current mode timers will reveal that a system anomaly exists	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Oxygen Supply Pressure Switch	Fails in Oxygen Supply pressure "high" mode	Same as above	System operates in high amperage to electrode's mode – continuously high output of oxygen	Periodic monitoring of system operation will reveal that a system anomaly exists	No
	Fails in Oxygen Supply pressure "low" mode	Mfg. defect/ faulty mat'l	System operates in low amperage to electrodes mode – continuously low output of oxygen	Same as above	No
Overpressure Switch	Fails to actuate	Shorted, open ckt, loss of power	No effect on system during normal operation	Overpressure in oxygen line not relieved into oxygen supply tank will cause oxygen to be injected into KOH. High level switch in reservoir will activate auto-shut-down. Similar condition exists for hydrogen line overpressure	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Lines and Fitting	Leakage	Loose connections, mfg. defect or faulty mat'l	Negligible to total loss of outputs	KOH leakage will result in auto-shut-down if severe, or will be detectable as local flooding or a white crusty deposit if slight Hydrogen leakage will result in auto-shut-down Periodic monitoring of current mode timers will reveal that an anomaly exists in the oxygen lines	No
Current Regulator Module	Output high. Out of tolerance		Electrolysis voltages too high, possible production of ozone	Redundant module available by switching. Voltages are monitored	No
	Output low. Out of tolerance		Low production of O_2 from associated electrolysis module	Same as above	No
	Output open circuit		No production of O_2 from associated bank(s) of electrolysis cells	Low probability of this failure mode since output employs multiple redundant circuits	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Voltage Monitoring Circuit	No voltage indication for cell or bank of cells		None	Other indications of cell performance can be obtained	No
Control Logic Module	Coolant solenoid valve fails off		Electrolyte overheats	Overheat light is activated	No
	Module switching fails off		Affected module no longer generates oxygen	Other electrolysis modules furnish oxygen	No
Shutdown Logic	H_2 detector fails off		Fails to sense hydrogen if leak develops	Probability of double failure (cell deck plus H_2 detector) is very small	No
	Water feed system fails on or off		Either excess water or insufficient water is supplied	Electrolyte reservoir fills to limit which turns on volume safety switch and indicator	No
	Temp sensor fails on or off		Automatic control of temp of electrolysis module is lost. Possible module overheat	Redundant temperature sensors provide warning signal	No

Table 4 (Cont.)

Item	Assumed Failure Mode	Probable Cause of Failure	Effect on System	Compensating Factors and Recommendations	Safety Hazard
Shutdown Logic (Continued)	O_2 or H_2 pressure safety switch fails off		Shutdown will not occur in the event of a failure of the pressurization system	Backed up by pressure gauges for observation by operating personnel. Probability of double failure is small	No
Hi-Lo Mode Control	Hi-Lo automatic switching fails high or fails low		O_2 output remains on eigher high or low	Backed up by indicators and manual control	

3.3 RELIABILITY ANALYSIS

A qualitative analysis was made of the reliability of the Electrolytic Oxygen Generator using the best available data for components of the unit. Some specific test data were available on the electrolysis cells, but for most of the components failure rates were available only for flight hardware and not for the commercial components used in the unit. For this reason a realistic total system reliability number could not be determined. This limited reliability analysis was used, however, to determine redundancy and spares provisioning.

The following components were considered in the analysis and were spared or made redundant as indicated.

Electrolysis module	-	in-line redundant
Electrolyte pump	-	in-line redundant
Solenoid valves	-	replaceable spares
Water pump	-	replaceable spare
Current controllers	-	replaceable spare
Magnetic reed switches	-	replaceable spares
Temperature sensors	-	replaceable spares
Miscellaneous fittings and O-rings	-	replaceable spares
Pressure switch	-	replaceable spares

These components were considered to be easily maintainable/replaceable by the SSS crew members. Other components which would have been more difficult to replace, except by trained personnel, were not included.

3.4 POTENTIAL SPARK SOURCES

Sources of electrical sparks in the Electrolytic Oxygen Generator were evaluated, with the results shown in Table 5.

Table 5

POTENTIAL SPARK SOURCES

Component	Comment
Switches	All switches are enclosed with no open contacts.
Relays	All relays are hermetically sealed.
Oxygen Pump Motor	60 Hz, 115 Vac, 1φ induction motor, runs continuously 3.2 amps max. Motor has capacitor start with centrifugal switch. However, since pump motor runs continuously, spark generation is a "one time" occurrence at initial startup.
Electrolyte Pump Motor	60 Hz, 115 Vac, 1φ induction motor runs continuously. Motor is of the shaded pole variety and therefore no starting contacts are present.
Water Feed Pump Motor	400 Hz, 208 Vac, 3φ induction motor is inherently self-starting and induction coupled. Therefore, no contacts or spark sources are present.
Circuit Breakers	Circuit protection is provided for all circuits, and protection is set close to current requirements.

Section 4

CHECKOUT AND ACCEPTANCE TEST

4.1 CHECKOUT TEST RESULTS

The Electrolytic Oxygen Generator, in its initial configuration, was of a zero-gravity design. It consisted of a closed-reservoir volume control unit, an in-line bubble separator, and high performance (11,000 rpm) electrolyte pumps.

During the system checkout testing, the closed reservoir, which contained a spring to provide system pressure, was found to give an unacceptably high pressure rise over the water feed control band. Overpressure in the electrolyte system resulted in failure of the bubble separator.

The problem with the closed reservoir was that the spring was not of the correct diameter and was buckling at the water feed control position. It was not possible within the program delivery schedule to obtain a replacement spring or to rebuild the bubble separator. To maintain the program schedule, the zero-gravity reservoir and bubble separator were replaced with a laboratory model reservoir in which a liquid-level water feed control system and a pneumatic system pressurization were used. A new spring of the correct size was subsequently installed in the closed reservoir under another program, and both components have been successfully operated in a laboratory model system.

One of the high-performance pumps decoupled periodically during the checkout tests. The reduction in system pressure drop, which resulted from the substitution of the laboratory model reservoir, permitted the substitution of more reliable, lower performance pumps (3000 rpm). These changes are reflected in the system description given in Section 2.

The initial configuration of the nitrogen purge inlet to the modules consisted of a manual flow control valve, a solenoid valve, and a branch to two check valves upstream of the modules. One leg of the branch led to the 0_2 side of the purge system and the other to the H_2 side. Gas samples were taken between the check valves and the solenoid valve, and back-diffusion of oxygen and hydrogen was detected. The nitrogen purge inlet plumbing was modified to include a solenoid shutoff valve and a high pressure check valve in each leg of the N_2 purge line branch to the modules. This change is reflected in the schematic in Figure 2. Subsequent gas analyses showed no mixing of hydrogen and oxygen in this line.

4.2 ACCEPTANCE TEST RESULTS

The Electrolytic Oxygen Generator was subjected successfully to a 100-hour continuous test prior to delivery to the 90-Day Test site. The performance and service requirements for this test are given in Table 6, in which 90-Day Test requirements are also shown for reference. The acceptance test configuration is shown in Fig. 11. Operation of the system was completely automatic. An average oxygen output of 8.0 lb/day was achieved with automatic cycling of the output between 3.5 and 10 lb/day to maintain the pressure in an accumulator between 21 and 27 psig. Hydrogen was discharged at approximately 9 psig.

Gas analyses were made every 4 hours during the test of samples from the oxygen and hydrogen effluent streams. At the end of the test, the system was sealed in a plastic bag and allowed to stand for 64 hours. Gas samples were then taken from the inside of the bag and analyzed. A summary of the gas analysis results is given in Table 7. Within the sensitivity of the instruments used in the analyses (gas chromatograph, IR, and mass spectrometer), these results indicate gas purities to be:

Oxygen:	99.85%
Hydrogen:	99.55%
System outgassing:	None

Table 6

ONE-HUNDRED-HOUR TEST CONDITIONS

Performance Requirements	90-Day Test	100-Hour Test
Oxygen output		
Capacity	8 lb/day	8 lb/day
Purity (exclusive of water vapor)	99.7%	99.7%
Admixed hydrogen	≤0.1%	≤0.1%
Discharge Pressure	20-27 psig	20-27 psig
Hydrogen output		
Purity (exclusive of water vapor)	99.3%	99.3%
Admixed oxygen	≤0.2%	≤0.2%
Discharge pressure	≥7 psig	≥7 psig
Services Requirements		
Feed Water		
Temperature	75°F	75°F
Pressure	<10 psig	3 psig
Solids	<100 ppm	distilled water
Conductivity	<80 mho/cm	
Coolant		
Fluid	Water	Ethylene glycol
Temperature	40° ± 4°F	40° ± 4°F
Flow Rate	1 gpm	1 gpm
Nitrogen Purge		
Pressure	70 psig	70 psig
Vent	Annulus	Ambient
Power	28 ± 3 Vdc 115 Vac, 60 Hz	28 ± 3 Vdc 115 Vac, 60 Hz

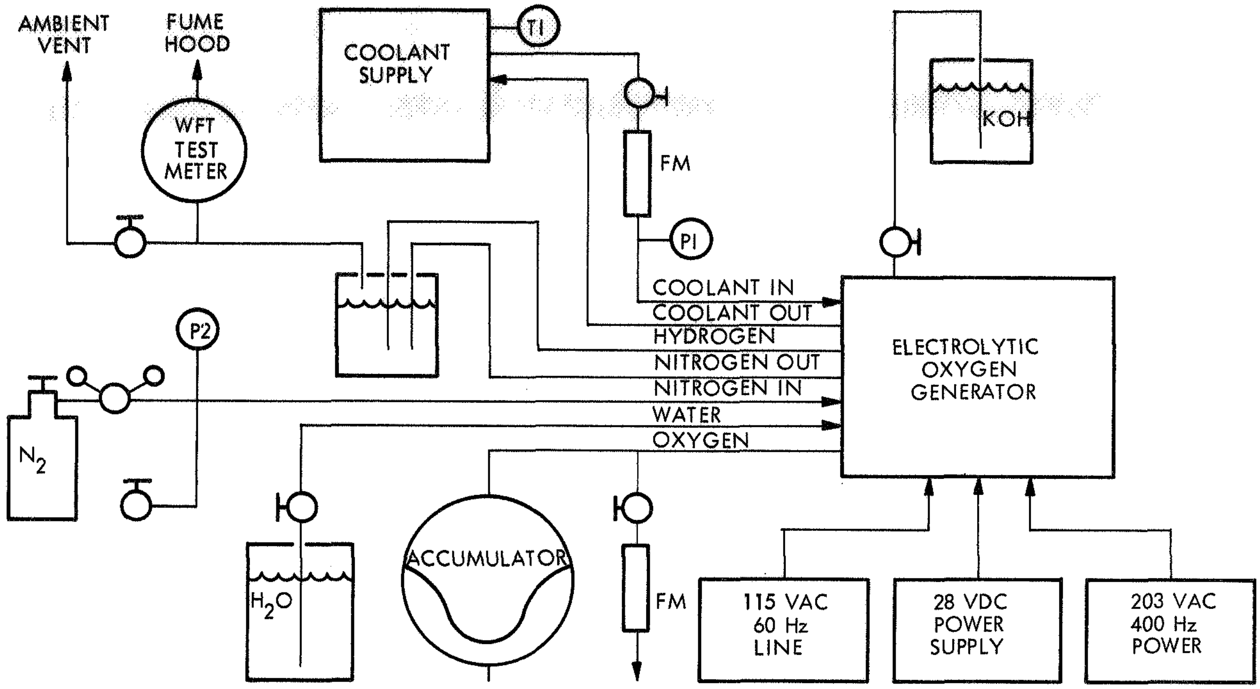


Fig. 11 Acceptance Test Configuration

Table 7

GAS ANALYSIS SUMMARY

Gas Sample	Contaminants	
Oxygen effluent from system during acceptance test	Total Hydrocarbons	≤20 ppm (l.s.)*
	Carbon Monoxide	6.6 ± 0.2 ppm
	Hydrogen	≤0.05% (l.s.)
	Nitrogen	0.093 ± 0.16%
	Methane	≤2 ppm (l.s.)
	Sulfur Dioxide	10 ppm
Hydrogen effluent from system during acceptance test	Total Hydrocarbons	≤20 ppm (l.s.)
	Carbon Monoxide	≤2 ppm (l.s.)
	Oxygen	0.068 ± .007%
	Nitrogen	0.38 ± .04%
	Methane	≤2 ppm (l.s.)
System Outgassing**	Total Hydrocarbons	≤20 ppm (l.s.)
	Carbon Monoxide	≤2 ppm (l.s.)
	Methane	≤2 ppm (l.s.)

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* Limit of sensitivity

**After 64 hours of offgassing

Section 5

NINETY-DAY TEST

5.1 INSTALLATION

The Electrolytic Oxygen Generator was delivered to the McDonnell Douglas facility in Huntington Beach, California, and initially installed inside the Space Station Simulator (SSS).

Connections were not made to the H_2 accumulator, O_2 accumulator, and annulus vent lines during the preliminary checkout of the electrolysis system. The sequence of events, problems encountered, and corrective actions taken are summarized as follows:

- High current (>20 amps) to Module 1 was observed on startup. The problem was traced to cross-talk in the wiring carrying control signals to the Module 1 current regulator. The wiring was rerouted to eliminate this problem.
- The primary McDonnell Douglas 28-VDC power supply was found to be unstable under full current load. The backup power supply operated satisfactorily.
- Hermetically sealed mercury thermostats used in the water electrolysis system to control the electrolyte temperature and to provide over-temperature protection of the system were rejected for use in the chamber. Bi-metallic thermostats were procured as replacements.
- After the new thermostats were installed, connection to the O_2 and H_2 lines in the chamber was undertaken. It was found that O_2 lines contained liquid potassium hydroxide. A check valve in the O_2 discharge line in the electrolysis system prevented this liquid from backflowing into the electrolysis system. The chamber O_2 line and the check valve in the electrolysis system were disconnected, flushed with water, and dried with nitrogen.
- Extremely noisy contact closure of the new bi-metallic temperature control thermostat produced a severe hydraulic hammer in the electrolysis system heat exchanger. After the system was operated through a number of temperature cycles, the heat exchanger was found to be leaking, attributed to the stress caused by the hydraulic hammer. A new heat exchanger was fabricated and installed to replace the failed unit. Additional control logic circuits were added to provide a time-delay in the coolant solenoid signal from the control thermostat.

- The liquid-liquid heat exchanger provided in the SSS was found to be undersized and to provide inadequate cooling of the electrolysis system.

The system was reinstalled outside of the chamber prior to the start of the 90-Day Test. Interface connections were made so that the system could be operated in a standby mode or as the primary unit supplying the SSS.

5.2 SYSTEM STATUS SUMMARY

The status of the Electrolytic Oxygen Generator during the 90-Day Test is shown in Fig. 12. As the primary unit, the system was supplying the manned chamber with metabolic oxygen, and hydrogen for the Sabatier reactor. It was using chamber feed water. In the standby mode, the system was fully operational but not being used to supply the chamber. Total operating time of the system was 70 days of the 90-Day Test period.

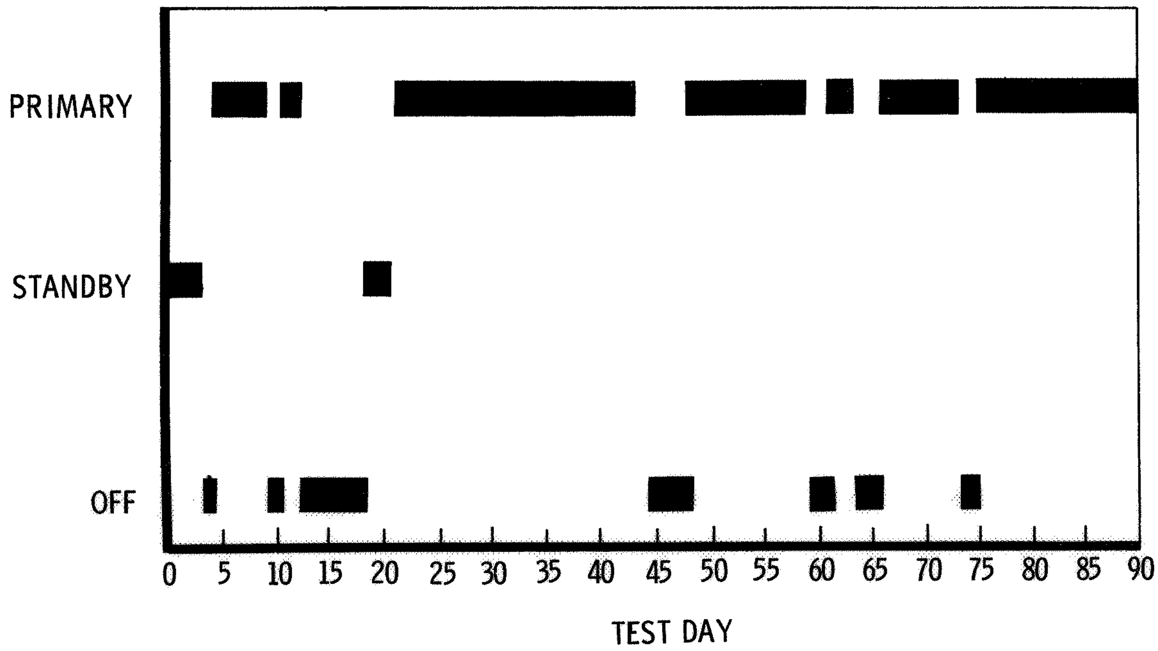

Fig. 12 Ninety-Day Test System Status

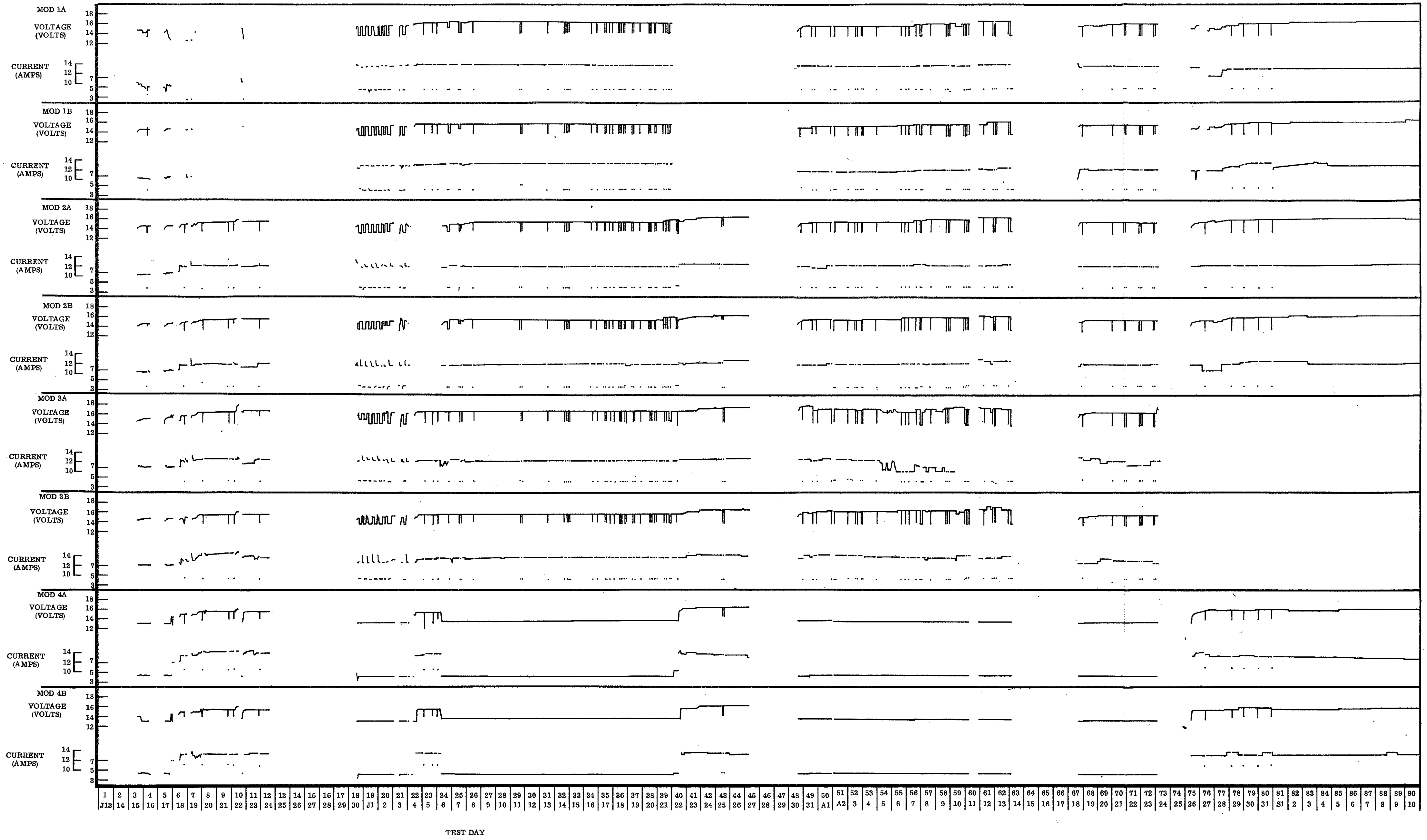

Fig. 13 Ninety-Day Test System Electrical Performance

5.3 PERFORMANCE DATA

Electrical performance of the electrolysis modules during the 90-Day Test is shown in Fig. 13. The voltage and current data presented were taken from the MDAC log sheets.

The average oxygen production rate for the period of each day that the system was operating was computed by summing the ampere-hours for each cell in the high and low current modes. Elapsed time in the high and low modes and the module currents were taken from the MDAC log sheets. Faradaic conversion of ampere-hours to pounds per day of oxygen was made. The results of these computations are shown in Fig. 14. The dark line in this figure represents the design output of the unit. Oxygen output was not an internal function; it was determined by the demand of the chamber oxygen accumulator. It can be seen that on four occasions the design point maximum output of 10 pounds per day was actually exceeded.

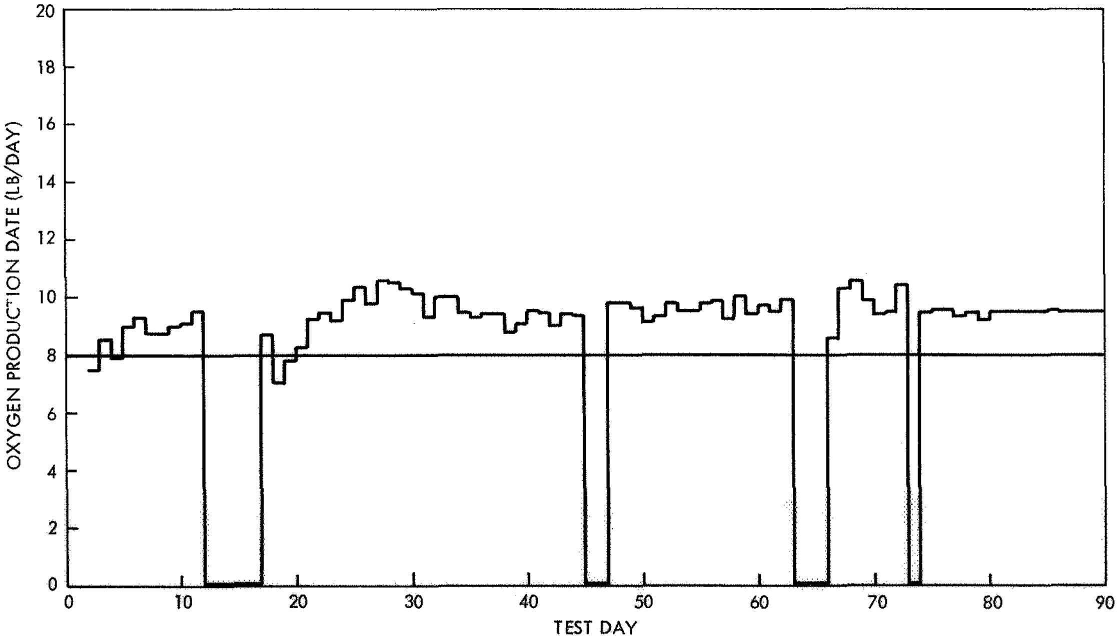

Fig. 14 Ninety-Day Test System Oxygen Production

5.4 FAILURE ANALYSIS

A summary of the significant failures of the Electrolytic Oxygen Generator during the 90-Day Test, the diagnoses, and corrective actions required is presented in Table 8. This table does not include failures of test support equipment, unless they resulted in a subsequent electrolysis system failure. The period of time that the unit was off is also indicated in the table; this was not the time required for maintenance, since on some occasions, time was required to obtain purchased replacement parts.

None of the failures that occurred during the 90-Day Test was major in nature; the failures were primarily associated with accessory components and, in most cases, are attributable to the accelerated program under which the system was fabricated and delivered. The following examples are cited:

- The use of shielded wiring in the current control circuits would have precluded the loss of current control noted in Table 8. Teflon-coated shielded wire could not be obtained in time to meet the delivery schedule.
- The overtemperature switches initially provided with the unit were of a type that had been used extensively in the laboratory and whose reliability had been demonstrated. These sensors were hermetically sealed mercury switches. They were rejected for use in the MDAC facility and non-mercury replacements had to be obtained. The only type of switch that could be used without altering the control logic circuitry was the bimetallic type. These proved to be unreliable and on four occasions failed closed.

More significant than the component failures noted in Table 8 is the complete absence of any failures attributed to the basic water-electrolysis concept used in this system. There were no failures related to the water feed control, temperature control, phase separation control, or the gas output control.

A complete chronological record of the maintenance activity on the Electrolytic Oxygen Generator during the 90-Day Test is presented in Appendix B. A discussion of the design and operational interfaces of the system with the test support equipment is given in Section 6.3.

Table 8

NINETY-DAY TEST FAILURE ANALYSIS

Test Day	Problem*	Cause	Corrective Action
4	N_2 purge fitting failed	Overtorquing	Replaced and retorqued
10	Loss of current control module 1	Electrical interference between oscillators	Added shielding
12–18	N_2 purge solenoid leaked	Buna-N seats deformed	Installed viton seats
45–48	Leakage of KOH from temperature sensor	Defective O-ring in sensor	Replaced O-ring
	Short circuit in module 1	KOH crystals bridging electrodes caused by KOH	Replaced damaged parts in module 1
60	Internal 28 VDC power supply failed	Excessive operating temperature	Replaced power supply and relocated to cooler environment
63–66	Gas bubbles in electrolyte leaving module 2	Not determined at this time	Replaced matrix material in module 2
73–74	Gas bubbles in electrolyte leaving modules 1, 3, and 4	Overpressure due to setting of chamber H_2 relief valve	Reset chamber H_2 relief valve to proper value and replaced matrix material
	$0_2 \Delta P$ controller stems cracked or fractured	Pressure cycling of 0_2 pump	Replaced stems with higher strength material
77	Loss of current control module 1	Not determined at this time	Used backup modules

*Only shutdowns involving electrolysis system failures

Section 6

POST-TEST EVALUATION

6.1 PERFORMANCE CHECKOUT

After the conclusion of the 90-Day Test, the Electrolytic Oxygen Generator was received from McDonnell-Douglas for post-test evaluation. The condition of the system, as received, is noted by the following:

- A 1/4 Swagelok union fitting on the outlet of the electrolyte flowmeter to module 4 was found sheared on the tapped-hole side. This failure occurred after the 90-Day Test was completed.
- The N_2 purge solenoid on the H_2 outlet side was failed closed.
- The back-pressure regulator across the diapump was failed open.
- The relief valve on the reservoir pressurization system was stuck closed.
- The diapump was inoperative.
- A leak in the temperature control sensor housing was detected.

These items were repaired or replaced as required. Samples of debris and corrosion products in these components were bagged and labeled for subsequent chemical analysis.

The system was started up and operated in the automatic mode for approximately 4 hours. All controls and all four electrolysis modules were exercised and showed satisfactory performance.

6.2 COMPONENT EXAMINATION

After determining that the system was operational and that the mechanical and electromechanical components were performing properly (with the exceptions noted in Section 6.1), disassembly and examination of parts was performed.

6.2.1 Mechanical Components

The following observations about the condition of the various system components were made after disassembly and inspection:

- Electrolysis modules – All cell spacers and electrodes were intact and in good condition. There was no evidence of O-ring deformation. None of the matrices showed any damage.
- Differential pressure controllers – All eight controllers were pressure checked; no leaks were detected. Upon disassembly, several of the controller parts were made of polyphenylene oxide were found to have fractures and cracks. This indicates that this plastic is not entirely satisfactory for use in these devices. Stainless steel is recommended as a suitable substitute. Some of the controller base-plates made of polysulfone also showed evidence of stress-cracking; on inspection, however, it appeared that these stresses were the result of excessive localized machining temperature during fabrication and not an inherent weakness of the material.
- Ion-exchange canister and filter – A light brown deposit was found on the stainless-steel filter screen and a sample was taken for subsequent chemical analysis. The ion-exchange resin, which contains a color indicator of bed exhaustion, appeared to have been approximately 25 percent expended as a result of the operation during the acceptance test and the 90-Day Test; the bed had a capacity for 5 times the feedwater contaminant level given in the system specification.
- Reservoir – The reservoir was found to be in good condition. Some degradation of the silicone potting compound used to encapsulate the float magnets was detected, but the magnets had not been affected.
- Electrolyte pumps – Both electrolyte pumps were in good condition, with no evidence of wear or corrosion.
- Heat Exchanger – The heat exchanger was not disassembled; leak checking indicated the seals were still intact and in good condition.

6.2.2 Electromechanical Components

Examination of the electronics in the system led to the following observations:

- The internal 28 VDC power supply which was used to power the control logic circuits and which had failed during the 90-Day Test was bench-tested under load and found to be operative. However, when installed in the confined area of the system electronics chassis, it failed again from overheating.
- The malfunction of module 1 current regulator was determined to be due to stray magnetic fields induced into the signal input lines by physically paralleled output current lines. The fact that module 1 signal lines were longer than the signal lines for the other three module current regulators made it

more susceptible to interference. The magnetic fields set up by the reactors caused a small amount of crosstalk. Absence of shielded wires and lack of shields around the reactors contributed to the problem.

- The periodic actuation of module 4 "Standby" circuit without command was caused by an unstable flip-flop, Z6 on the control logic card. The flip-flop was being triggered occasionally by the coolant actuation. Replacing I.C. Z6 cured the problem.

6.2.3 Chemical Analyses

Samples were taken at various points as the system was disassembled and the components were taken apart. The complete chemical analyses of these samples are given in Table 9, which also includes the locations from which the samples were taken and an evaluation of the chemical analysis results.

6.3 DESIGN AND OPERATIONAL INTERFACE EVALUATION

In the 90-Day Test log presented in Appendix B, 36 shutdowns of the Electrolytic Oxygen Generator are identified. Of these, 27 were automatic shutdowns and nine were manual. These shutdowns are grouped by cause as follows:

Interface problems	20
System component malfunctions	14
Unknown causes	2

The interface problems, which are of concern in this Section, are grouped in the following categories:

Power supply	7
Man-machine	5
Coolant supply	6
Overpressure	2

Cutoff of the MDAC facility power supply used to provide 28 VDC power to the electrolysis modules occurred on at least seven occasions. While these shutdowns caused no damage to the system, they did increase the operator involvement with the unit. Each shutdown required a manual startup, with the associated potential for procedural error.

Table 9

CHEMICAL ANALYSIS SUMMARY

Sample	IR Analysis	Emission Analysis
A	Oxides	Major: chromium, iron Minor: nickel, aluminum Trace: magnesium, silicon
B	Sulphates Carbonates Oxides Organic oil (trace)	Major: copper Minor: aluminum, potassium Trace: chromium, silicon, iron, zinc, nickel
C	Carbonates	Major: copper Minor: cadmium, potassium Trace: lead, silicon, iron, aluminum, nickel, zinc
D	Oxides Silicone grease	Major: aluminum Minor: potassium, copper Trace: chromium, iron, nickel
E	Hydroxides Carbonates	Major: potassium, copper, silicon Minor: aluminum Trace: magnesium, nickel

---

A. Black deposit in H_2 purge outlet solenoid valve: The chemical analysis indicates corrosion of the stainless-steel valve body. The source of the chemical attack is not evident; no potassium was detected in the analysis.

B. Sample from the diapump check valve and diaphragm: The presence of potassium in sample indicates chemical attack by potassium hydroxide. There is evidence that problems with startup and shutdown may have at some time caused electrolyte to be pushed into pump.

C. White deposit on back pressure regulator across O_2 pump. Same as B.

D. Ion exchange filter: This filter, a fine-mesh stainless-steel screen, was located on the inlet to the ion-exchange canister. The sample was of a brown material found on the inlet side of the filter. Source of these contaminants was probably the feed water.

E. Liquid sample from electrolyte loop: A sample of the residual liquid in the electrolyte lines was taken when the unit was first received from MDAC. Impurities found in the analysis probably originated in the asbestos matrices.

Of the five shutdowns attributed to man-machine interface problems, three were due to incorrect startup procedure, one to incorrect manual shutdown procedure, and one to an error made in the repair of a module. Because of the accelerated program schedule, insufficient time was available to completely familiarize the test conductors with the operating procedure. The instruction manual provided with the unit gave a detailed step-by-step procedure for startup and manual shutdown. On day 7 of the 90-Day Test, a simplified procedure was prepared and posted on the equipment and in the test conductor's logbook.

Shutdowns resulting from problems with the interface coolant supply were in two instances caused by failure of the MDAC facility chiller. In the other four cases, the coolant supply temperature was too high. The Electrolytic Oxygen Generator design interface requirement for coolant was 1 gpm at $40^{\circ} \pm 4^{\circ}F$. The temperature requirement was not met; coolant supply temperature during the test was a minimum of $58^{\circ}F$, and on a number of occasions was even higher. This problem of insufficient cooling capacity was compounded by the excessive (over-specification) demand for oxygen. Four additional overtemperature shutdowns were attributed to drift in the overtemperature switch settings, and these shutdowns are included in the group of 14 shutdowns caused by "system component malfunctions."

Excessive pressure (over-specification) in the gas discharge lines downstream of the system was the cause of matrix failures in the electrolysis modules. Overpressure protection was provided in the unit by relief valves and by pressure switches to signal automatic shutdown. However, the settings of these devices were too close to the matrix breakthrough pressure. Repeated cycling of the downstream pressure to just below this value was, therefore, not detected until gas breakthrough into the electrolyte loop was observed.

6.4 RECOMMENDATIONS

On the basis of the 90-Day Test performance of the Electrolytic Oxygen Generator, the post-test examination of the unit, and the evaluation of the design and operational interfaces, the following recommendations are made to improve the design and to enhance the potential flight worthiness of a generator based on the circulating electrolyte concept.

- Development Testing. In the initial phases of the program, system configuration and definition should include the delineation of all components and component interfaces for which demonstrated performance under design conditions has not been achieved. The program should then include bench testing of these components under design conditions to verify performance. Of the 14 shutdowns during the 90-Day Test that were due entirely to system component malfunctions, in all but two the components that failed exhibited their first malfunction during the first 22 days of the test. This indicates that as much as 30 days of testing would be reasonable for components for which little or no test experience is available.
- Automatic Startup. The 90-Day Test experience indicates a definite need for improvement in the man-machine interface. In future applications, a completely automatic startup sequence is recommended to provide the operator with a single switch to actuate the automatic startup and a single switch to achieve a manual shutdown. The automatic safety shutdown was demonstrated to be effective and should, of course, be retained.
- Interface Sensitivity. The sensitivity of the matrix configuration in the Electrolytic Oxygen Generator to downstream oxygen and hydrogen pressure pulses was evident in the 90-Day Test. Tolerance to a much wider range of pressure variations can be achieved by improving the matrix support structure. It is also recommended that a wider margin of safety in the overpressure switch and relief valve settings be used.
- Modular Maintenance Concept. The experience of the 90-Day Test emphasizes the need for a maintenance concept that does not require breaking into electrolyte lines. Furthermore, the need for modular isolation is evident. In the Electrolytic Oxygen Generator, a redundant module was provided and provision was made for turning the power to each module on and off individually. It was necessary, however, to shut down the entire system to isolate or remove a module. It is recommended that the maintenance concept to be pursued provide individual, self-contained hydraulic assemblies, with no electrolyte lines or fittings.
- Automatic Controls. The electronic circuitry required for the control and safety functions in the electrolysis system can be made more reliable through the use of shielded wiring for all signal-carrying leads, temperature-compensated circuits for current control, and thermistor circuits and sensors for temperature control and protection functions.

Section 7

CONCLUSIONS

This program was successful in demonstrating the viability of the circulating electrolyte electrolysis system concept, in providing significant data on hardware and system integration, and in delineating design improvements that will enhance the flightworthiness of this technical approach.

Seventy days of automatic operation of the Electrolytic Oxygen Generator demonstrated the capability for long-duration operation. Automatic control of water balance, temperature, phase separation, and gas generation rate was accomplished.

Zero-gravity devices were designed under this program to make the Electrolytic Oxygen Generator operation gravity independent. There was not sufficient development time to incorporate these devices into the unit for the 90-Day Test, but they have been successfully tested under another program.

Design improvements which are indicated include automating the system startup, reducing the interface sensitivity, utilizing a modular maintenance concept with individual self-contained hydraulic assemblies, and improving the electronic controls. Design and development efforts in a company-sponsored program have yielded a substantial reduction in the system interface sensitivity. A modular maintenance concept has also been evolved in a preliminary design effort in Contract NAS9-10405.(6)

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2. Olcott, T., and Conner, W., "Thirty-Day Performance and Reliability Test of a Regenerative Life Support System," presented at the 19th International Astronautics Conference, New York (Oct 1969)
3. Greenough, B.M., "The Development and Preliminary Design of an Oxygen-Nitrogen Generation System," NASA CR 66940 (Jun 1970)
4. Greenough, B.M., and Olcott, T.M., "A Spacecraft Electrolytic Oxygen-Nitrogen Generation System," ASME 70-AV/Spt-15 (Jun 1970)
5. Greenough, B.M., "The Development of a Noncryogenic Nitrogen/Oxygen Supply Technique," NASA CR 114912 (May 1971)
6. Greenough, B.M., "Preliminary Design of a Space Station Electrolytic Oxygen-Nitrogen Generator," LMSC-A977498 (Mar 1971)

LIBRARY CARD ABSTRACT

An Electrolytic Oxygen Generator based on the circulating electrolyte water electrolysis concept was developed and built as a backup electrolysis unit for the NASA-McDonnell Douglas 90-Day Manned Test. This generator, operating in an automatic mode, supplied hydrogen and oxygen to the manned chamber environmental life support system for 70 days of the 90-Day Test. Design improvements identified as a result of this program enhance the viability of the design concept and improve the flightworthiness of the generator.

Appendix A

ELECTROLYTIC OXYGEN GENERATOR CIRCUIT DIAGRAMS

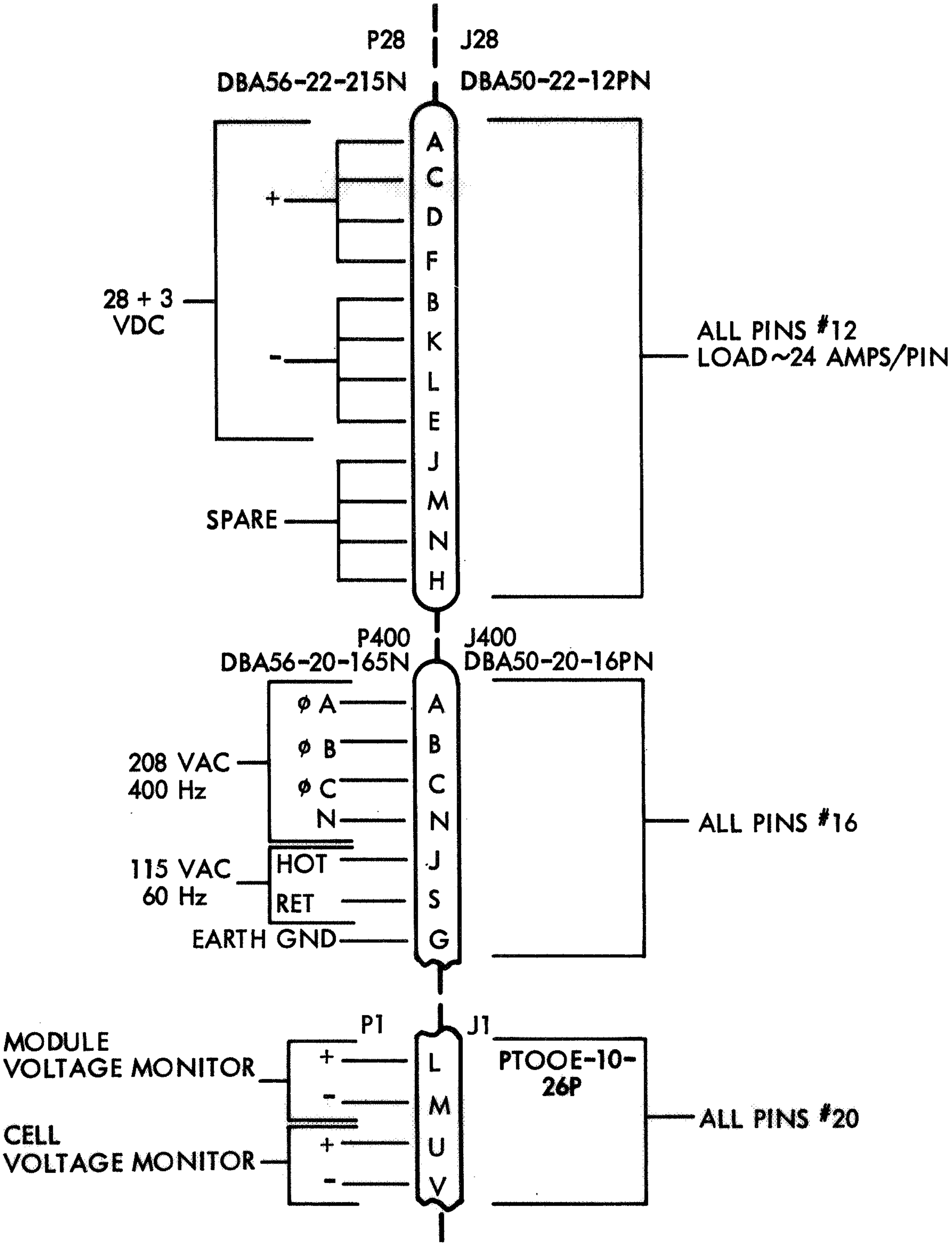
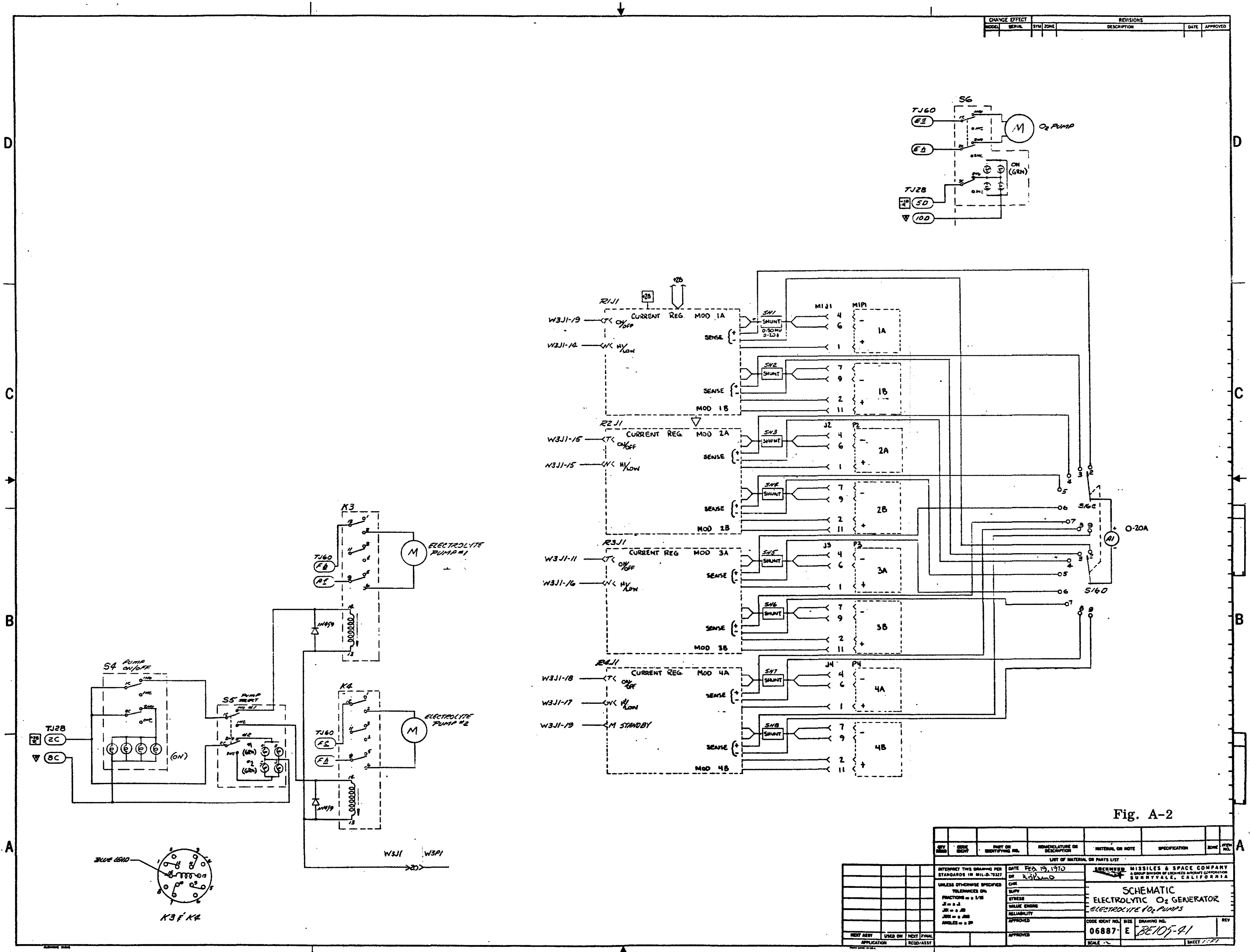


Fig. A-1 Electrolytic Oxygen Generator Plug Pin Assignments


S6
TJ60
E_g
E_h
O_2 PUMP
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TJ28
+28
5D
10D
R1J1
+28
CURRENT REG MOD 1A
W3J1-19
ON/OFF
W3J1-14
HI/LOW
SENSE
SH1
SHUNT
0-50 MV
0-20 A
M1J1
M1P1
1A
SH2
1B
MOD 1B
R2J1
CURRENT REG MOD 2A
W3J1-15
W3J1-15
SH3
J2
P2
2A
SH4
2B
MOD 2B
R3J1
CURRENT REG MOD 3A
W3J1-11
W3J1-16
SH5
J3
P3
3A
SH6
3B
MOD 3B
R4J1
CURRENT REG MOD 4A
W3J1-18
W3J1-17
W3J1-19
M STANDBY
SH7
J4
P4
4A
SH8
4B
MOD 4B
S16C
S16D
O-20A
A1
K3
TJ60
F_B
A_E
ELECTROLYTE PUMP #1
1N459
S4 PUMP ON/OFF
S5 PUMP SELECT
TJ28
+28
2C
8C
(ON)
#1 (GRN)
#2 (GRN)
K4
TJ60
F_C
F_h
ELECTROLYTE PUMP #2
1N459
W3J1
W3P1
20
BLUE LEAD
K3 & K4
CHANGE EFFECT
MODEL
SERIAL
SYM
ZONE
REVISIONS
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APPROVED
APPROVED
LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA
SCHEMATIC
ELECTROLYTIC O_2 GENERATOR
ELECTROLYTE & O_2 PUMPS
CODE IDENT NO. 06887
SIZE E
DRAWING NO. BE105-41
REV
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SHEET
NEXT ASSY
USED ON
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B
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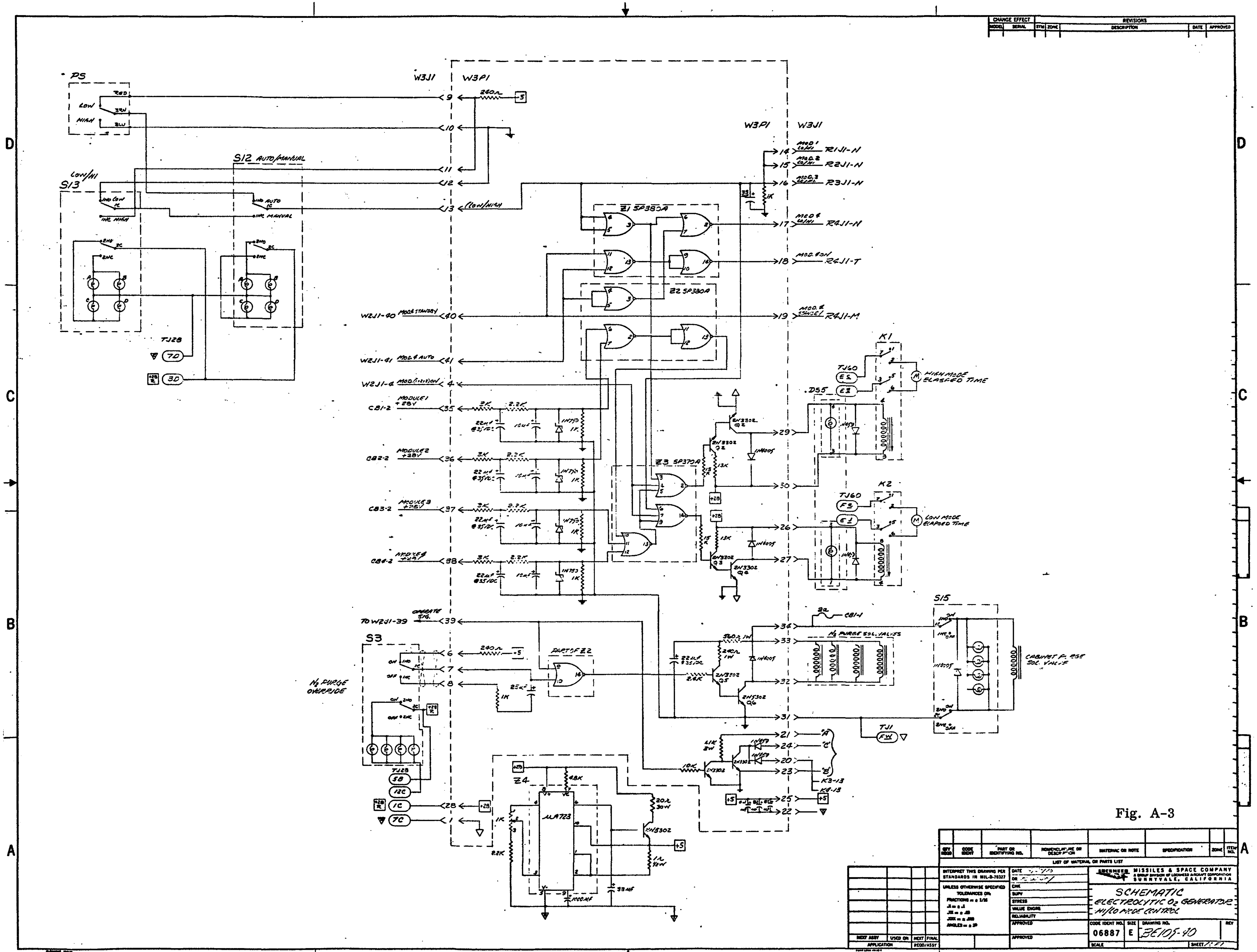
Fig. A-2


PS
RED
LOW
BRN
HIGH
BLU
W3J1
W3P1
240Ω
-5
S12 AUTO/MANUAL
LOW/HI
S13
1NO LOW
1C
1NC HIGH
1NO AUTO
1C
1NC MANUAL
2NO
2C
2NC
TJ28
7D
3D
+28
(LOW/HIGH)
W3P1
W3J1
MOD 1 LO/HI R1J1-N
MOD 2 LO/HI R2J1-N
MOD 3 LO/HI R3J1-N
1K
MOD 4 LO/HI R4J1-N
MOD 4 ON R4J1-T
MOD 4 STANDBY R4J1-M
Z1 SP380A
Z2 SP380A
Z3 SP370A
W2J1-40 MOD 4 STANDBY
W2J1-41 MOD 4 AUTO
W2J1-4 MOD (1-2-3) ON
CB1-2 MODULE 1 +28V
CB2-2 MODULE 2 +28V
CB3-2 MODULE 3 +28V
CB4-2 MODULE 4 +28V
3K
2.2K
22μF @35VDC
10μF
1N753
1K
2N3302 Q1
2N3302 Q2
2N3302 Q3
2N3302 Q4
1N4005
13K
15K
+28
K1
TJ60
E5
E3
HIGH MODE ELAPSED TIME
DS5
K2
F5
E1
LOW MODE ELAPSED TIME
TO W2J1-39 OPERATE SIG.
S3
N2 PURGE OVERRIDE
ON
OFF
1NO
1C
1NC
2NO
2C
2NC
PART OF Z2
25μF
1K
CB1-1
2Ω
N2 PURGE SOL. VALVES
560Ω 1W
240Ω 1W
22μF @35VDC
2.2K
2N3302 Q5
2N3302 Q6
S15
CABINET PURGE SOL. VALVE
TJ1
FW
1K 2W
1N753
10K
2N3302
"A"
"C"
"B"
K3-13
K4-13
+5
Z4
μA723
48K
1K
8.2K
20Ω 30W
2N3302
1Ω 1/2W
33μF
1000μF
TJ28
5B
12C
1C
7C
+28
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APPROVED
LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA
SCHEMATIC
ELECTROLYTIC O2 GENERATOR
HI/LO MODE CONTROL
CODE IDENT NO. 06887
SIZE E
DRAWING NO. 3E105-40
REV
SCALE
SHEET 1 OF 1
CHANGE EFFECT
MODEL
SERIAL
REVISIONS
SYM
ZONE
DESCRIPTION
DATE
APPROVED
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B
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Fig. A-3

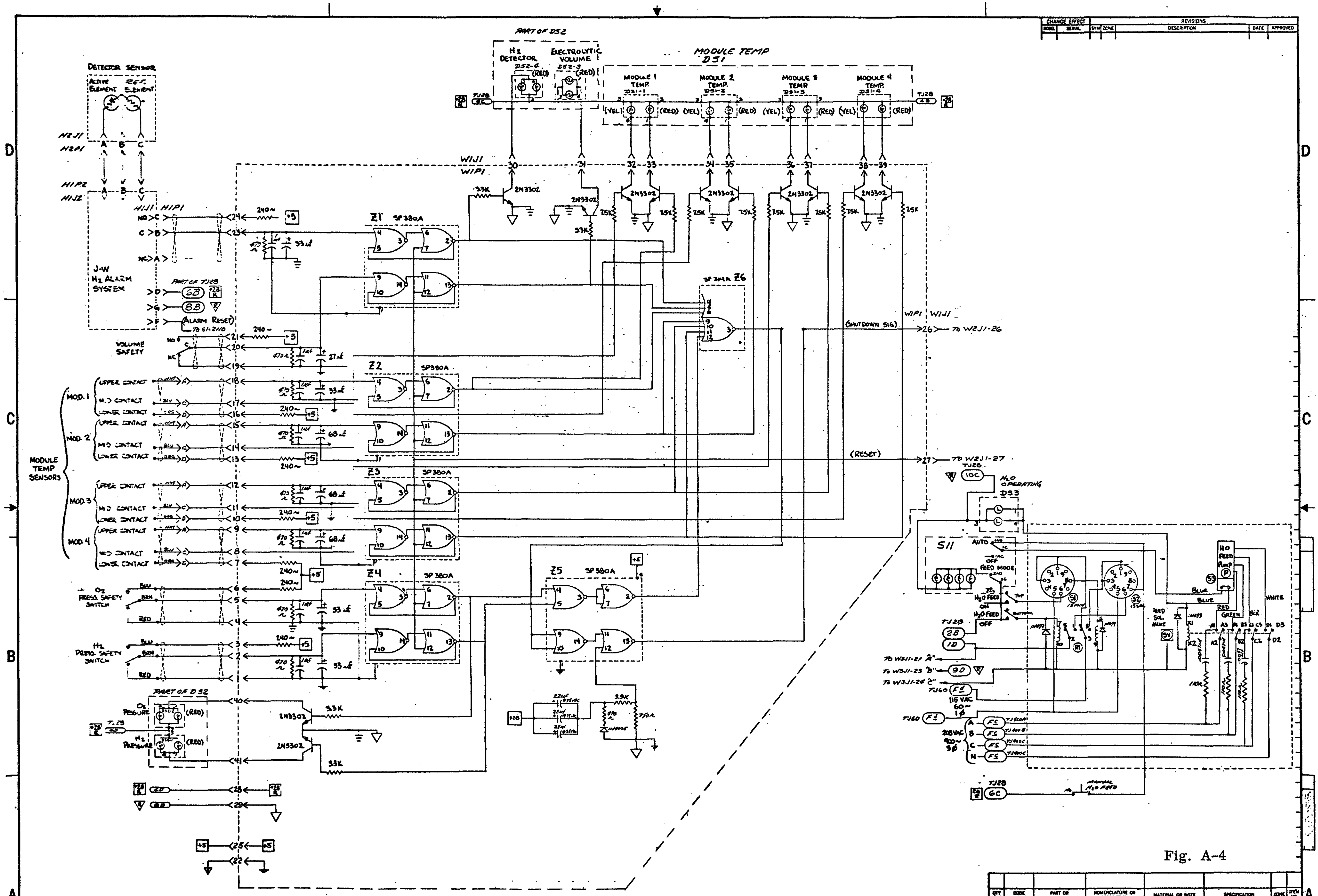

Fig. A-4

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APPROVED

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

SCHEMATIC
ELECTROLYTIC O_2 GENERATOR
(SHUTDOWN LOGIC)

CODE IDENT NO. 06887
SIZE E
DRAWING NO. BE105-39
REV
SCALE ~
SHEET

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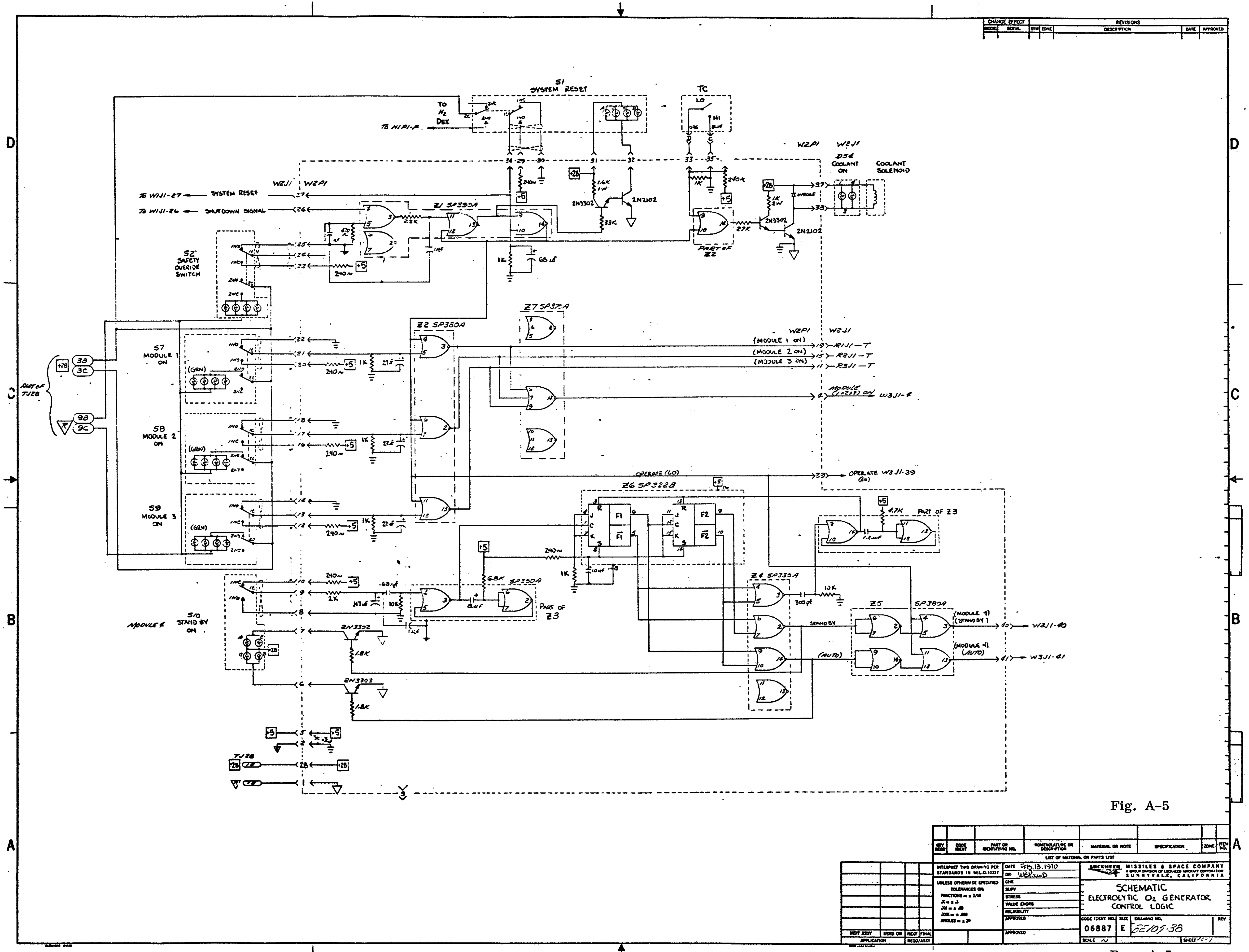
S1
SYSTEM RESET
To
H_2
DET
TO H1P1-F
TC
LO
HI
ORG
BLU
34
29
30
31
32
33
35
W2P1
W2J1
DS4
COOLANT
ON
COOLANT
SOLENOID
+28
+5
240Ω
1.6K
1W
2N3302
2N2102
33K
1K
240K
27K
1K
2W
1N4005
37
38
PART OF
Z2
TO W1J1-27
SYSTEM RESET
TO W1J1-26
SHUTDOWN SIGNAL
27
26
25
24
23
Z1 SP330A
2.2K
470Ω
1µf
68µf
S2
SAFETY
OVERIDE
SWITCH
Z7 SP370A
Z2 SP380A
S7
MODULE 1
ON
(GRN)
22
21
20
S8
MODULE 2
ON
18
17
16
S9
MODULE 3
ON
14
13
12
27µf
PART OF
TJ28
3B
3C
9B
9C
(MODULE 1 ON)
(MODULE 2 ON)
(MODULE 3 ON)
19
15
11
R1J1 – T
R2J1 – T
R3J1 – T
MODULE
(1+2+3) ON
W3J1-4
OPERATE (LO)
39
OPERATE W3J1-39
(LO)
Z6 SP322B
F1
F2
J
C
K
R
S
10µf
240Ω
68K
SP330A
PART OF
Z3
8µf
.68µf
47µf
10K
2K
PART OF Z3
4.7K
1.2µf
Z4 SP350A
300pf
10K
STAND BY
(AUTO)
Z5
SP380A
(MODULE 4)
(STAND BY)
(MODULE 4)
(AUTO)
40
41
W3J1-40
W3J1-41
MODULE 4
S10
STAND BY
ON
10
9
8
7
6
5
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DR WBReed
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VALUE ENGRG
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APPROVED
LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA
SCHEMATIC
ELECTROLYTIC O2 GENERATOR
CONTROL LOGIC
CODE IDENT NO. 06887
SIZE E
DRAWING NO. EE105-38
REV
SCALE ~
SHEET
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NEXT
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APPLICATION
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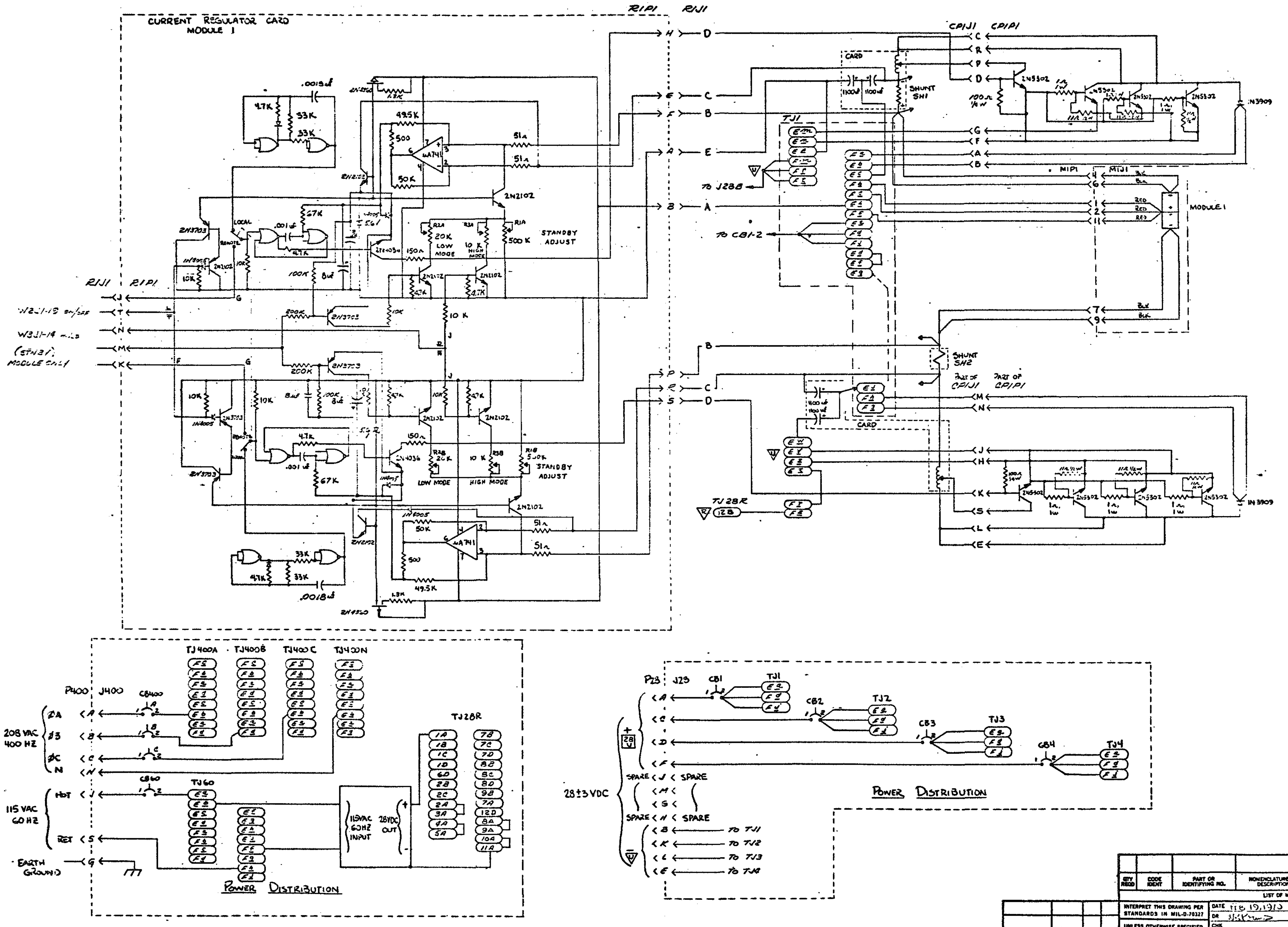
D
C
B
A

Fig. A-5



CHANGE EFFECT		REVISIONS				
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Fig. A-6

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DATE FEB 19, 1970
DR
CHK
SUPV
STRESS
VALUE ENGRG
RELIABILITY
APPROVED
APPROVED

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

SCHEMATIC
ELECTROLYTIC O_2 GENERATOR
(CURRENT REGULATOR MODULE I)

CODE IDENT NO.	SIZE	DRAWING NO.	REV
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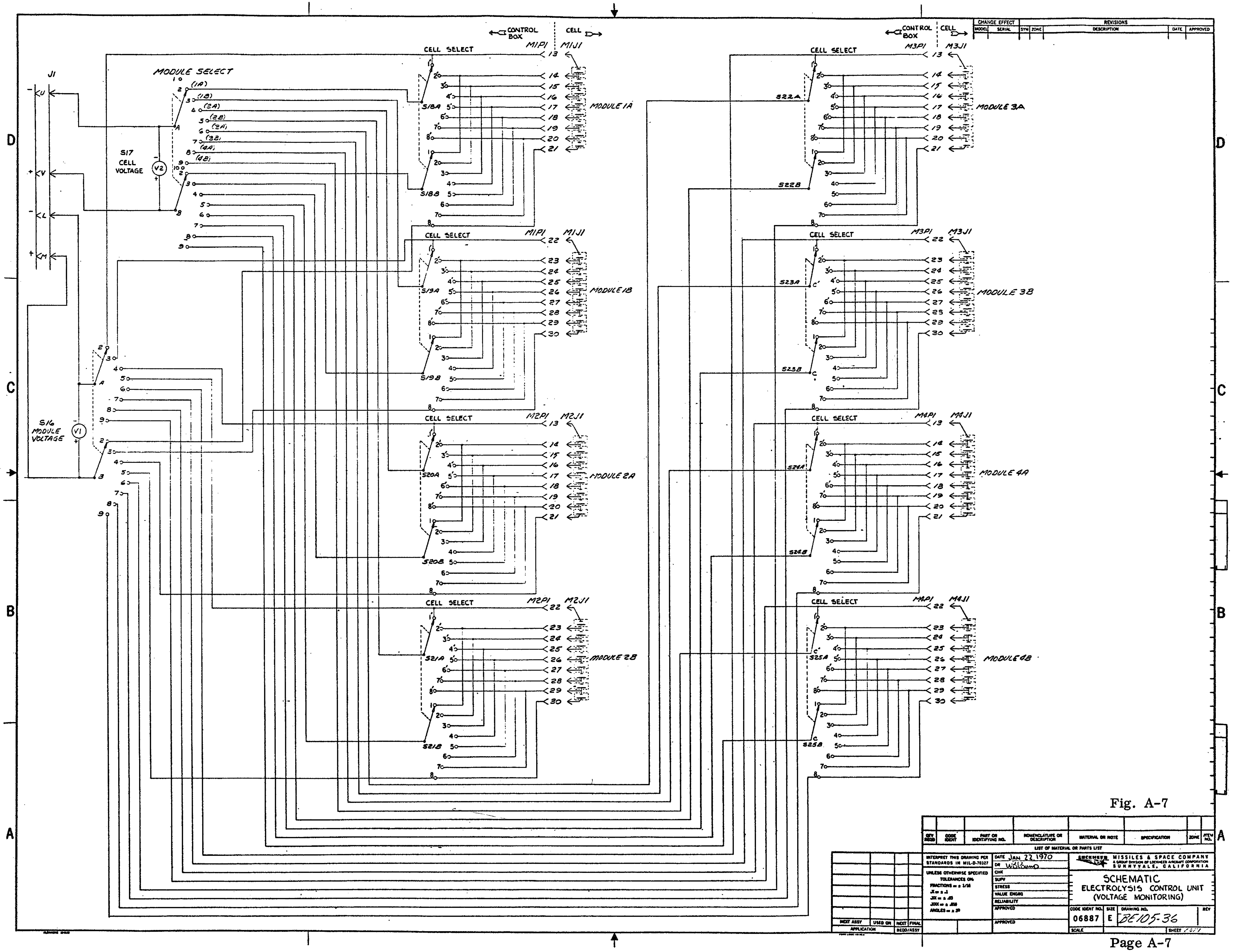

Fig. A-7

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DR W.B.Krumo
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APPLICATION | REQD/ASSY

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

SCHEMATIC
ELECTROLYSIS CONTROL UNIT
(VOLTAGE MONITORING)

CODE IDENT NO. 06887
SIZE E
DRAWING NO. BE105-36
REV
SCALE
SHEET 1 OF 1

Appendix B

90-DAY TEST RECORD OF SYSTEM SHUTDOWNS

Test Day	MDAC Log	Diagnosis/Comment	Shutdown	
			Auto.	Man.
1		MDAC power supply cutting out every 15 minutes, causing system shutdown. Interface test support equipment problem.	X	
		MDAC chiller temperature control inoperative. Interface test support equipment failure.		X
2		MDAC chiller being worked on. LMSC unit in standby mode.		
3	Unit on chamber	On standby part of day. On line – primary.		
4	Module No. 1 H_2 leak. Unit shut down.	H_2 leakage detected below Module 1. Component failure.	X	
5	Unit on chamber startup.	System leak checked and then switched to primary.		
	Power supply cut off-restart unit.	Interface test support equipment failure.	X	
	Cut off Module 1 not producing. Spec 0_2-Mod 4 on.	Current to Module 1 decreased to 20 amps. Mod. 1 switched off and Mod. 4 switched on. Current regulator malfunction.		
6	Power supply cut off. Restart unit.	Interface test support equipment failure.	X	
	Leak in H_2 side discovered; fixed.	A fitting had not been tightened after a previous inspection. Operator error (LMSC).		
	Unit back to cabin.	Interface test support equipment problem.		
	Actuated Mod #1 (#4 still on) in attempt to keep up with 0_2 demand.	A line in the chamber to the annulus was left open and the two-gas controller increased its set point. This caused an excessive demand for 0_2.		
		Shut down manually by MDAC. Procedure not followed: Module 4 left on with electrolyte pump off, causing over-temperature shutdown. Operator error (MDAC).	X	

Test Day	MDAC Log	Diagnosis/Comment	Shutdown	
			Auto.	Man.
		MDAC power supply cut off again. Interface test support equipment failures.	X	
7	Unit shutdown automatically. (Mod #2 circuit breaker). Restarted each time Mod. #2 circuit breaker would shut it off.	Electronics problem	X	
	Unit started without Mod. #2. Then got Mod. #2 going.	Operator error (MDAC).		
	Unit shutdown-overtemp on Mod. #2 (switched to Stuart Elec.)	Incorrect startup without 400 Hz breaker on caused N_2 purge of H_2O feed line-water line primed and then okay. Interface test support equipment failure.	X	
	Restarted unit-shut off Electrolyzer H_2 (O_2 still to chamber).	Interface test support equipment failure. Coolant supply inadequate; cooling supply temperature at 58°F instead of required 45°F.	X	
	Secured Mod. #1 to overcurrent.	Current regulator problem.		
	Lost power supply. Power restored and unit put back on line.	Interface test support equipment failure.	X	
	Unit shut down. Power supply problems – unit back on to chamber.	Interface test support equipment failure.	X	
8		On line – primary.		
9		On line – primary.		
10	Lost Mod. #1. Switched #4 on.	Current regulator problem. Added shielding.		
11		Current on Module 1A decreased to 2.0 amps. Module 1 turned off and Module 4 switched on. Current regulator problem.		

Test Day	MDAC Log	Diagnosis/Comment	Shutdown Auto.	 Man.
12	H_2 contaminated. switched H_2 to vent (using H_2 from Stuart. Can't keep up on O_2 (switching to backup often). Shutdown.	N_2 was observed in both H_2 and 0_2. System was shut down to leak check N_2 purge solenoids; one was leaking. New valve seats were ordered. Component failure. Buna-N valve seats not good for continuous service. New seats are Viton.		X
13 thru 17		System off, awaiting delivery of new valve seats.		
18 & 19		System on. In standby mode.		
20	Unit on line. New power supply.	System on and being used intermittently as primary unit.		
21	Mod. 2 hi-temp light on. Restart.	Coolant supply temp 60 to 62°F instead of required 45°F. Interface test support equipment problem.	X	
22	Automatic shutdown. Mod. #2 overtemp. Restarted.	Overtemperature switch setting on Module 2 drifted. Component failure.	X	
	Shutdown-overtemp Mod. #2. Restarted with Mods. 1, 3, & 4.	Overtemperature switch setting on Module 2 drifted. Component failure.	X	
23		On line – primary.		
24	Removed temp. switch on Mod. #2. Started #2, put #4 on standby.	Recommended action.		
25	Automatic shutdown. Cause not known. Restarted.	Restarted without water feed properly energized.	X	
26 thru 29		On line – primary.		

Test Day	MDAC Log	Diagnosis/Comment	Shutdown Auto.	Shutdown Man.
30	Shut down automatically due to overtemp on Mod. 4B. Water pump did not seem to be getting power. Switched to Stuart unit. Unit restarted.	Overtemp switch setting drifted. Component failure.	X	
31		On line – primary.		
32	Noted that O_2 compressor output pressure has begun oscillating excessively. Compressor making intermittent rattle.	Gage snubber had come loose. No effect on system performance.		
33		On line – primary.		
34	Noted that "high mode" timer failed to go into 400's. Went from 399 to 300.	No effect on system performance.		
35 thru 38		On line – primary.		
39	"High mode" timer again failed to go into 400's. Went from 399 to 300.	No effect on system performance.		
	Balanced electrolyte flow to modules.			
40	Facility power supply cut off. Unit back on in 10 min. Unit back on.	Interface test support equipment failure.	X	
	Automatic shutdown due to low electrolyte volume. Switched to Stuart unit.	Startup without water feed control properly energized. Operator	X	

Test Day	MDAC Log	Diagnosis/Comment	Shutdown Auto.	Shutdown Man.
40 (cont.)	During startup of unit, smoke noted coming from Mod. #1. Due to electrical short. Restarted Mods. 2, 3, and 4. Mod. #4 logic board not plugged in tight – had trouble going from "Standby" to "On." Unit on line to cabin.	KOH leak over module caused external electrical short. Component failure.		X
41	Automatic shutdown due to indicated over-temp. condition on Mod. #4. Disconnected overtemp switch as it was thought to be bad. Restarted unit and put back on line.	Component failure.		X
42		On line – primary.		
43				
44	"High mode" timer still failing to turn over to 400. Noted reduction in H_2 flow from unit in High Mode. Flow meter reading now 53% versus 59% previously.			
45 thru 47	Noted reduction in H_2 flow from 48% to 43% over several hours.			

Test Day	MDAC Log	Diagnosis/Comment	Shutdown	
			Auto.	Man.
45 thru 47 (cont.)	Discovered H_2 in module #2. Unit shut down to repair leak. Switched to Stuart unit. Repairs made to Mods. 1, 2, and 3. Replaced temp. switches 2 and 4 and added new electrolyte.	H_2 leak not from modules – mechanical failure of N_2 purge fitting – all fittings were replaced. Modules 1 and 3 were repaired. Module 1 had shorted on Day 40 and Module 3 was gassing on Day 45. Component failure.		X
48	Unit restarted and put back on line.	On line – primary.		
49	Noted erratic current readings on Mod. 3.	On line – primary.		
50 thru 53		On line – primary.		
54	Noted that Mod. 3A current has been fluctuating between 10 and 12 amps.	On line – primary.		
55		On line – primary.		
56				
57	Facility power supply cut off. Unit restarted after approximately 1 hour.	Interface test support equipment failure.		X
58	Noted drop in Mod. 3B current to 9 amps. Mod. 3A current still fluctuating between 10 and 12 amps.	On line – primary.		
	Temp reading up to 70°F due to cooling cart temp increase to 51°F. Switched over to Stuart unit & vented Lockheed unit.	Interface test support equipment failure.		

Test Day	MDAC Log	Diagnosis/Comment	Shutdown Auto.	Shutdown Man.
58 (cont.)	Lockheed unit put back on line.	On line – primary.		
59	Unit shut down due to cooling cart filter changed. Unit restarted.	Interface test support equipment failure.	X	
	Shut down – cause not known. Unit restarted.	Probably due to intermittent failure of internal 28 VDC power supply – see Day 60. Component malfunction.	X	
	Automatic shutdown due to low electrolyte volume. Switched to Stuart unit.	Incorrect startup procedure. Operator error.	X	
	Attempted to restart; however, N_2 supply solenoid valve stuck closed and had to be repaired. Unit back on line.	Component malfunction.		
60	Automatic shutdown. Cause unknown. 28 VDC logic power supply not working. Switched to Stuart unit. New control and logic power supply installed. Unit restarted.	Component failure.	X	
	Automatic shutdown. Reason unknown. Unit restarted.		X	

Test Day	MDAC Log	Diagnosis/Comment	Shutdown Auto.	Shutdown Man.
60 (cont.)	Automatic shutdown. New power supply drawing more 60 Hz power than the original unit. In order to maintain the auto shutdown and safety circuits involved with the 28 VDC power supply, a 115 VAC relay (coil) was connected to the 115 VAC line from the Lockheed unit and power for new power supply routed thru the relay contacts. Unit was then restarted. Noted that both high and low mode lights were on at the same time for a short period.		X	
61	Automatic shutdown due to high oxygen pressure. Unit restarted.	Cause unknown.	X	
62		On line – primary.	X	
63 thru 66	Automatic shutdown due to electrolyte volume. Volume high. System leaks found, relief valve popped. Gas bubbles noted in Mod. 2 liquid circulation line. Rebuilt mod. 2, cleaned and reinstalled plumbing.		X	

Test Day	MDAC Log	Diagnosis/Comment	Shutdown	
			Auto.	Man.
67	Unit back on line. Noted some gas bubbles in Mod. #3 electrolyte loop.			
68	Noted gas bubbles in electrolyte discharge lines from all modules H_2 back pressure 11.3 psig, O_2 back pressure 9.0 psig. High H_2 back pressure due to high venting rate of H_2 (Sabatier H_2 flow reduced at this time due to high temp) and fixed orifice in H_2 wet test meter. H_2 vent valve cracked temporarily while H_2 accumulator pressure relief valve setting was reduced. Noted that with reduced H_2 relief valve setting (9 psig), there are only infrequent bubbles in electrolyte.	Interface test support equipment malfunction.		
69				
70	Noted that temp controller not working correctly all the time.	Interface test support equipment malfunction.		
71		On line – primary.		
72				

Test Day	MDAC Log	Diagnosis/Comment	Shutdown Auto.	Shutdown Man.
73	Manual shutdown of unit after observing bubbles in electrolyte circulation loops of Mods. 1, 3, & 4. Switched to Stuart unit. Unit dumped approx. 1 liter KOH solution due to N_2 getting into liquid side of matrix and purging all electrolyte ? reservoir. Disassembled gas plumbing and cleaned out all KOH. Checked performance of all solenoid and relief valves. Drained all KOH out of unit.			X
74	Disassembled and rebuilt Mods. 1, 3 and 4.			
75	Unit shut down for further repairs to Mod. 3. Bubbles still existed in liquid side caused by misalignment during assembly and by attempt to straighten with compressive force on tension bolts. Unit back on line on Mod. 1, 2, & 4.	Isolated Mod. 3. Not repaired. Error in repair on Day 74.		X
76	Unit shut down. Mod. #1 circuit breaker opened due to excessive current (720 amp). Voltage reduced to 20 VDC. Cause seemed to be in electrical circuits and not in electrolysis module.	Current regulator malfunction.		X

Test Day	MDAC Log	Diagnosis/Comment	Shutdown Auto.	Shutdown Man.
76 (cont.)	Cross connected Mod. 1 to Mod. 3 electronics. Adjusted current pots to 12.5 amps.			
	Unit back on line. O_2 delivery less than required by chamber demands and currents on all three Mods. (particularly Mod. #1) are unstable and fluctuating excessively.	Excessive O_2 demand.		
	Unit shut down. Mod. #1 circuit breaker opened. Appeared to be excessive cell voltage on Mod 1A, Cell 8. Increased from 1.89 volts at 2300 to 2.25 volts at 2400. No overflow of electrolyte noted.	Current regulator malfunction		X
77	Unit back on line. Operation satisfactory. Adjusted all control pots to 12.5 amps. Average had been 12.0 amps. Noted ammeter fluctuating on all modules.	On line – primary.		
78 thru 80				
81 thru 90	Had to downshift to Stuart unit several times to keep with O_2 demand.	Excessive O_2 demand.		