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Biotechnology

LOCKHEED MISSILES & SPACE COMPANY, INC.
Sunnyvale, California

for

NATIONAL AERONAUTICS & SPACE ADMINISTRATION
Manned Spacecraft Center

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WATER ELECTROLYSIS SYSTEM

REFURBISHMENT AND TESTING

By B. M. Greenough

Prepared under Contract NAS 9-11848

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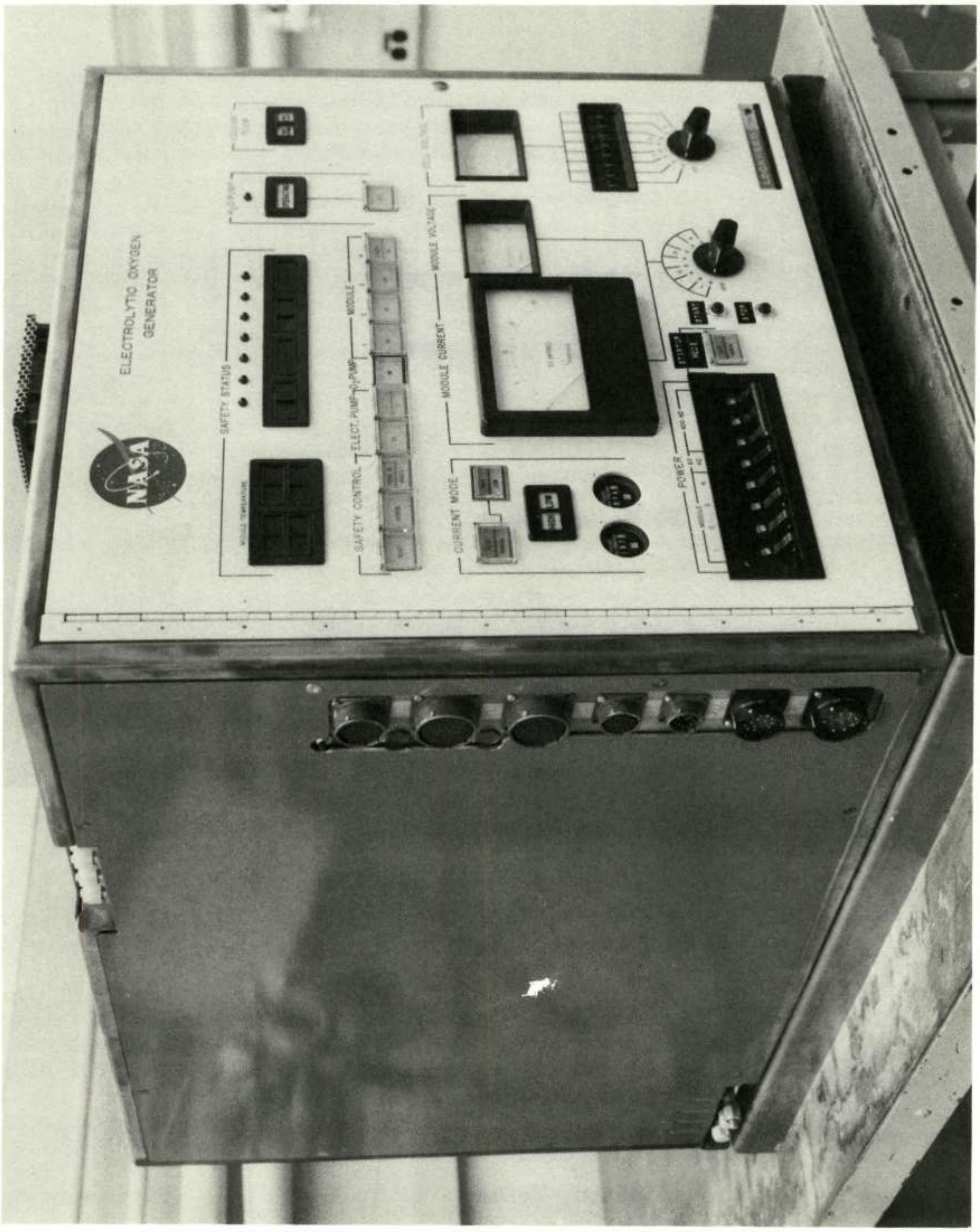

Frontispiece
Electrolytic Oxygen Generator

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SUMMARY

The NASA-LMSC Electrolytic Oxygen Generator which was provided by LMSC as the back-up water electrolysis system for the NASA-McDonnell Douglas (MDAC) 90-Day Manned Test was refurbished, improved and subjected to a 182-day bench test at the MDAC facility in Huntington Beach, California.

Prior to delivery of the system to the test site, a program effort was accomplished which consisted of re-assembly and installation of components (all components with the exception of the electronics had been disassembled for post-test evaluation after the 90-Day Test), incorporation of design improvements indicated by the results of the 90-Day Test, performance of a 50-hour checkout and 100-hour acceptance test, and documentation of the system configuration, operating instructions and test results.

The test plan for the 182-Day Test at MDAC required system operation at the nominal design point (3.63 kg/day (8 lb/day) oxygen output) except for a one week period of orbital simulation and a five-week period at the maximum design oxygen output rate of 4.55 kg/day (10 lb/day). All of these test conditions were successfully met by the system.

The system operated for 160 cumulative days of the 182-Day Test period (88 percent on time) and was shut down on weekends or awaiting replacement parts for 10 days. The remaining 12 days of normal working shift (96 hours) were required for fault diagnosis and repairs. The system was shut down a total of 24 times, 13 times because of primary failures or malfunctions, and 11 times for diagnostic purposes. Over half of the total number of shutdowns and two-thirds of the primary shutdowns were related to an intermittent malfunction of a single electronic component. No cell or module failures of any kind occurred, and no shutdowns were caused by interface problems or operator error.

The performance of the system during the test demonstrated the soundness of the basic electrolysis concept, the high development status of the automatic controls which allowed completely hands-off operation, and the capability for orbital operation. The following design improvements were indicated by the test experience:

- Develop a more efficient control device for the electrolysis module power.
- Utilize high reliability electronic components and more rigorous quality control in future hardware programs.
- Incorporate a modular maintenance concept in the design, utilizing completely internal manifolding of the liquid electrolyte to prevent ambient exposure during maintenance or repair.

Section 1

INTRODUCTION

Lockheed Missiles and Space Company (LMSC), under NASA-Langley Research Center Contract NAS 1-9728, provided a water electrolysis system in 1970 as a back-up for the primary system in the NASA-McDonnell Douglas 90-Day Manned Test (NAS 1-8997). This system, the NASA-LMSC Electrolytic Oxygen Generator, was designed, fabricated, acceptance tested, and delivered to the MDAC site in a four-month period. The system was located outside the manned chamber but was integrated to the extent that it used chamber water, provided hydrogen to the chamber accumulator and oxygen via chamber accumulator to the four-man crew. It operated successfully for 70 days of the 90-Day Test as the primary system supplying the manned chamber.

At the conclusion of the 90-Day Test, the system was returned to LMSC for post-test evaluation. It was then completely disassembled, excepting electronics, to examine for wear or corrosion of components.

After the results of the 90-Day Test were published,[1,2,3,4] the question existed of whether the 70 days of successful operation of the LMSC system outside the chamber could be directly compared with less than 100 hours of operation of the primary unit installed inside the chamber. The difference in accessibility to trained personnel for diagnosis and repair seemed to preclude a direct comparison of hardware maturity of the two systems.

Two contracts were then awarded: the present contract, to LMSC, to refurbish the Electrolytic Oxygen Generator and provide field support for long duration testing, and the other to MDAC, Contract NAS 9-12048, to complete the checkout testing of the static vapor-feed electrolysis system (which was installed inside the chamber for the 90-Day Manned Test), and to conduct a 182-Day bench test of the two competing systems at the MDAC facility.

This report describes the results of the program effort conducted by LMSC to build the Electrolytic Oxygen Generator, incorporate specific design improvements, make modifications necessary to meet the new test interface and operating conditions, conduct checkout testing, produce documentation of configuration changes, and provide field support at MDAC for the duration of the 182-Day Test. All of the program effort leading up to hardware delivery was completed in less than four months. The report documents performance results of the 182-Day Test (for the LMSC system only), an analysis of these results, and conclusions and recommendations for future spacecraft system designs.

Section 2

SYSTEM DESCRIPTION

2.1 INTRODUCTION

The NASA-LMSC Electrolytic Oxygen Generator as configured for the 182-Day Test at McDonnell Douglas is described in this section. The unit is designed to be operated in a completely automatic mode, including startup, shutdown, and safety shutdown with limited fault diagnosis. Ninety-three channels of system data are provided at the unit interface. Oxygen production rate is variable from 0 to 4.55 kg/day (10 lb/day). The outside dimensions of the system closure are 0.61 m (24 in.) across the front panel, 0.56 m (22 in.) high, and 0.79 m (31 in.) deep.

2.2 ELECTROMECHANICAL COMPONENTS

A schematic of the Electrolytic Oxygen Generator system is shown in Figure 1. The concepts employed in the system design include the use of dual-matrix, liquid center electrolysis cells with a circulating 30% potassium hydroxide electrolyte.

2.2.1 Electrolysis Modules

The generating unit consists of four electrolysis modules, each containing 16 cells connected hydraulically in parallel and divided electrically into two 8-cell banks. Cells within an 8-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. Differential pressure control is used to maintain gas-liquid phase separation across absorbent matrices contiguous to the electrodes.

2.2.2 Electrolyte Circulation

Electrolyte is pumped through a circulation loop using one of two in-line magnetic-coupled centrifugal pumps; the second pump is an in-line 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 flow-meters into four paths leading to the electrolysis modules. Flow control valves

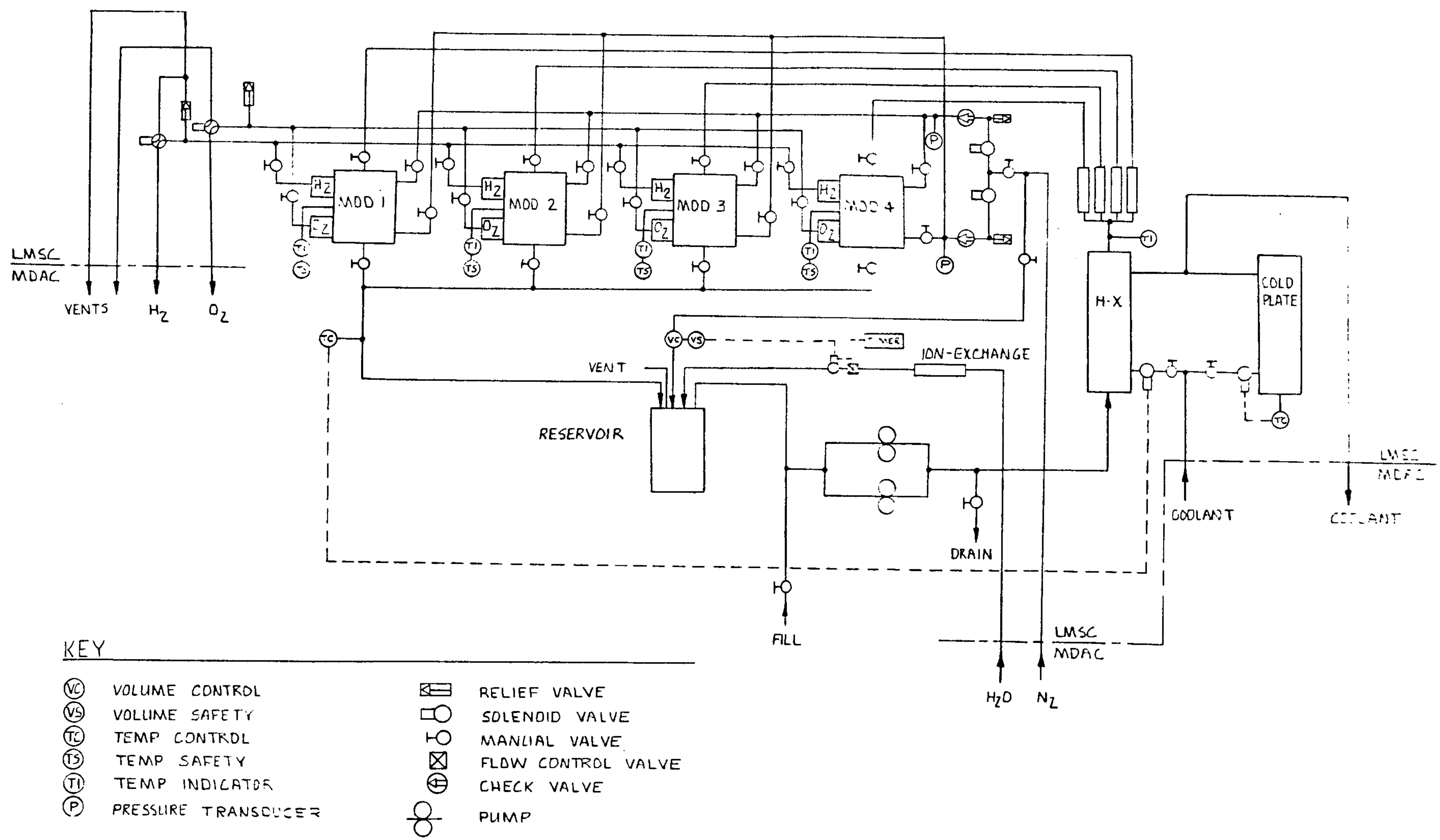

Figure 1 Electrolytic Oxygen Generator Schematic

in these lines are used to balance the flowmeters. Valves in the discharge electrolyte 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.

Water feed for the electrolysis process is supplied by direct injection of liquid water into the reservoir. A flow control valve provides the proper feed rate and a solenoid valve is actuated when feed is required.

2.2.3 Oxygen and Hydrogen Delivery

Hydrogen and oxygen are delivered from the electrolysis modules at approximately 10.35 kN/m^2 (1.5 psig).

2.2.4 Nitrogen Purge

Nitrogen purge is provided to maintain gas-liquid differential pressure during startup and interim shutdown. When this function is actuated, either 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.

2.3 AUTOMATIC CONTROLS

The Electrolytic Oxygen Generator is designed to function in an automatic mode during normal operation. Startup and shutdown can be accomplished either manually or automatically. The individual control functions are described in the following paragraphs.

2.3.1 Automatic Startup and Shutdown

The automatic startup feature performs the following functions in a sequential manner. It turns on the electrolyte pump, resets the system, enables all automatic safety shutdown functions, commands the high, low, and automatic current modes to the modules, and enables the automatic water feed system. The automatic startup is controlled by the use of an electronic digital counter.

The digital counter consists of a 10 pps pulse oscillator which is enabled upon actuation of the "start" push-button switch. The oscillator output signal is fed to the input of a divide by one hundred BCD counter of which the output pulse rate is 1/10 pps on one pulse every 10 seconds. This signal is used to strobe a "one" bit into a seven bit serial write/parallel read shift register. Thus, at $t_{(o)}$ "1" is written into bit position zero of the register. At $t_{(10)}$ the "1" bit is shifted into bit position one and another "1" bit is written into bit position zero. This process continues at ten second intervals until the register is full of "ones". In the automatic mode, the parallel outputs of the register provide command signals to operate the necessary components within the electrolysis system. Table 1 illustrates the auto start-up sequence of events.

2.3.2 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 by a flow control 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 24°C (75°F). During normal operation, the dewpoint of the product oxygen will be no greater than 24°C (75°F); the hydrogen dewpoint will be approximately 5°C (41°F).

Coolant flow to the electronics cold plate is controlled to maintain 25°C (77°F) and is regulated with an electrically actuated flow control valve.

2.3.3 Water Feed System

Water balance in the circulating electrolyte is maintained by controlling the electrolyte volume. A pressure transducer in the reservoir senses the liquid head and provides the signal to actuate the water feed control. 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 level reaches the bottom

TABLE 1

AUTO STARTUP SEQUENCE OF EVENTS

Time	Event
$t_{(0)}$ (+)	• Safety Override • Electrolyte pump on
$t_{(10)}$	• Reset system * • Enable all system safeties
$t_{(20)}$	• Low mode module current on • Turn off purge
$t_{(30)}$	• High mode module current on
$t_{(40)}$	
$t_{(50)}$	• Transfer current mode to automatic
$t_{(60)}$	• Enable automatic water feed system.

* The purpose of this function is to guarantee that the system is in a reset condition prior to the application of module current. If any of the safety limits are exceeded at this time, the system will not reset and the unit will automatically shut down.

of the control band, the water feed solenoid valve opens; and the 12-second water feed timer starts. Twelve seconds is the maximum feed time; the flow control valve is set to deliver sufficient water in approximately seven seconds. As water is fed to the reservoir, the liquid level rises and reaches the top of the control band. At this point, the solenoid valve closes, the 12-second timer resets, and a 10-minute timer starts. During this 10-minute period, the water feed signal is overriden so that another water feed cannot occur until the timer resets.

The feed water supplied to the system passes through an ion canister containing approximately 0.69 kg (1-1/2 pounds) of mixed anion-cation exchange resin. The outlet of the canister contains a particulate filter.

2.3.4 Differential Pressure

Two differential pressure controllers mounted on each module are set to control the hydrogen and oxygen pressures at 6.22 kN/m^2 (25 in. 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 diaphram. The valve seat is adjusted so that 6.22 kN/m^2 (25 in. H_2O) higher pressure on the gas side of the diaphram than on the liquid side is required to overcome the spring and open the valve.

2.3.5 Current Regulation and Oxygen Output Control

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

Control Signals			
A (on-off)	B (high-low)	C (standby)	Current Amperes
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%.

Module 4 is the only module which can be operated in the Standby Mode. In this mode, it can only be operated 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, an external signal determines the high or low current value.

The current controlled switching regulation consists of 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 2 is a control circuit block diagram.

The power supply provides 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 multivibration generates a positive square wave signal of about 13 KHz for about 10% 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 controlled 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 3 is a schematic diagram of the power circuitry.

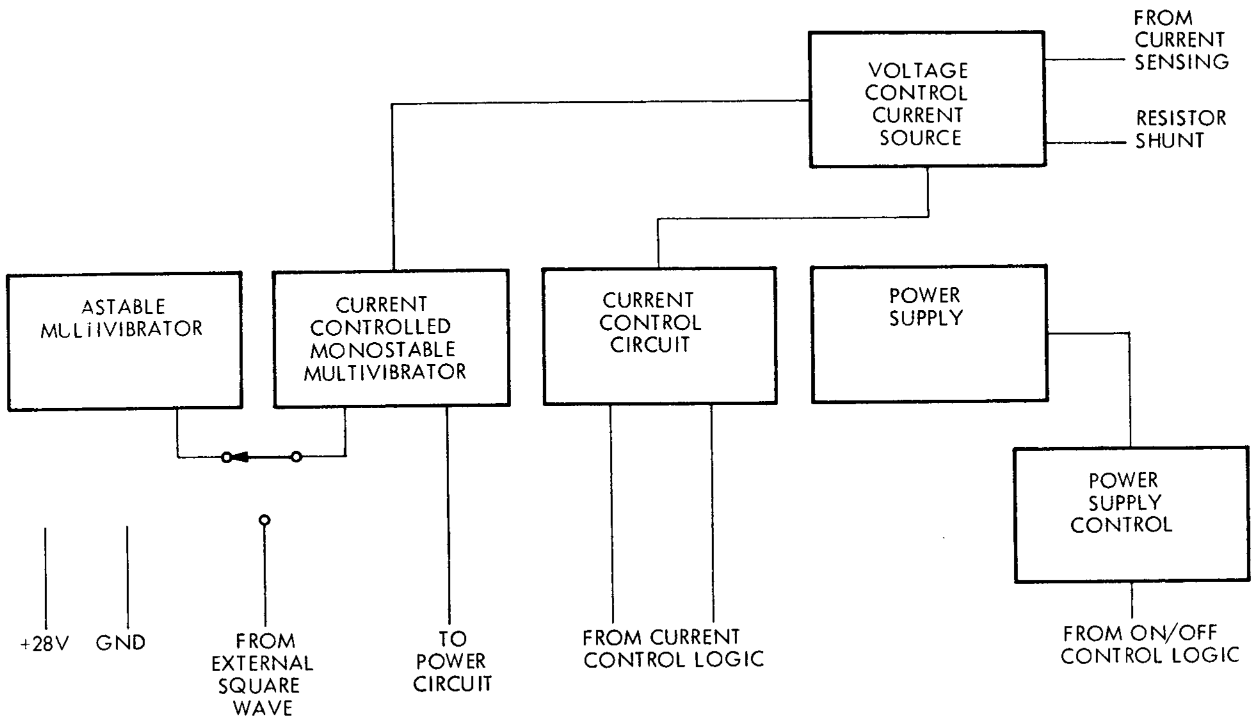

Fig. 2 Control Circuit Block Diagram

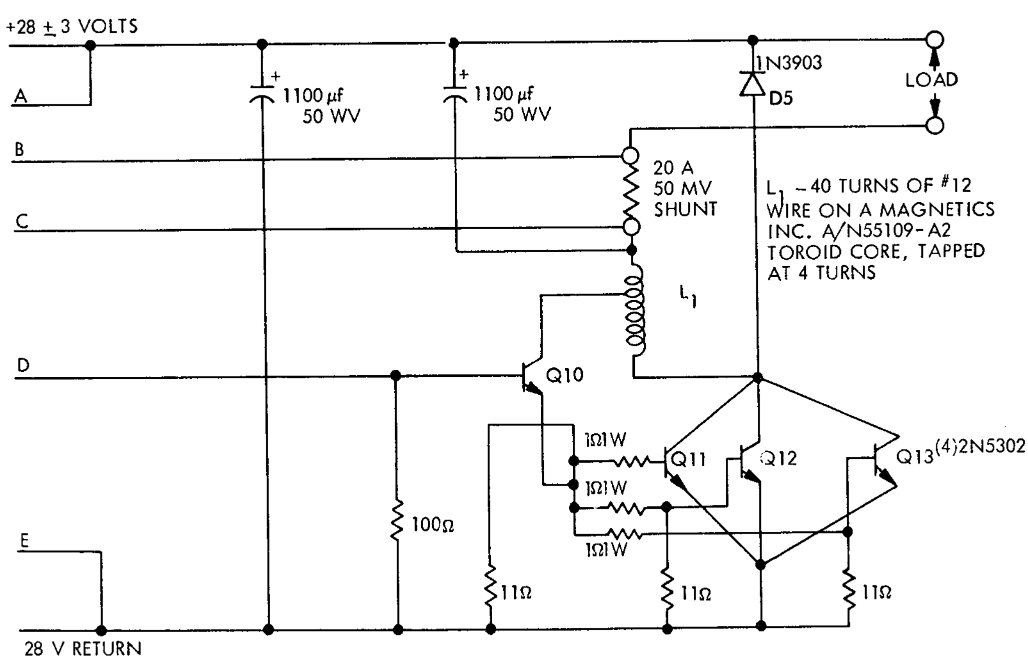

Fig. 3 Current-Regulating Power Unit

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 4 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.

2.4 SAFETY CIRCUITS

Safety circuits, as shown in Figure 5, are provided to automatically shut down the system under abnormal operating conditions. In an automatic safety shutdown, electrolysis module power is turned off, the electrolyte pump, water feed system and system reset are turned off, nitrogen purge to the module 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 $\overline{F}$ output of a nor-gate memory latch. This latch is identified as Z1 on card W2. The circuit is normally in a

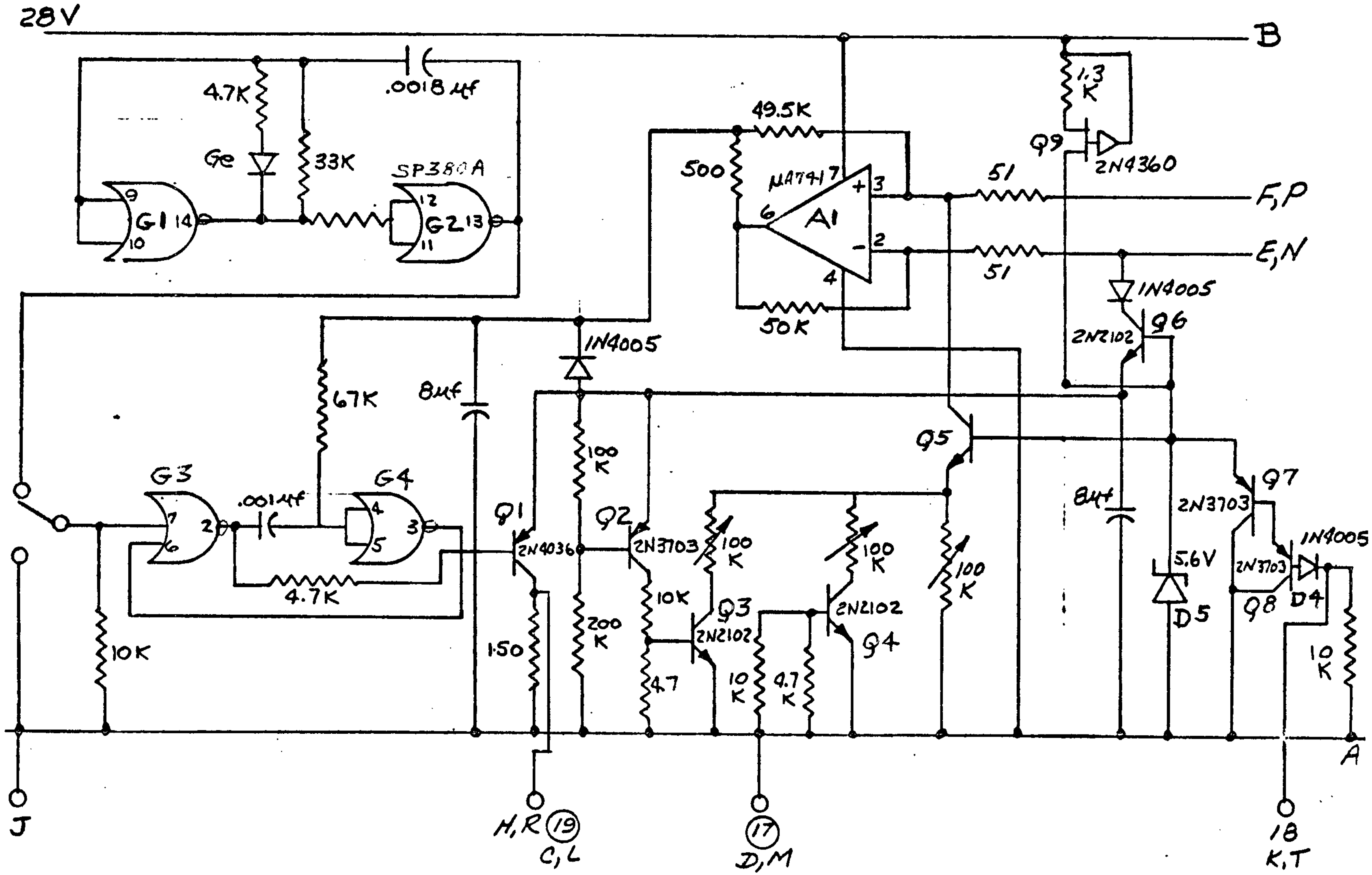

Figure 4 Switching Regulator Control Circuit

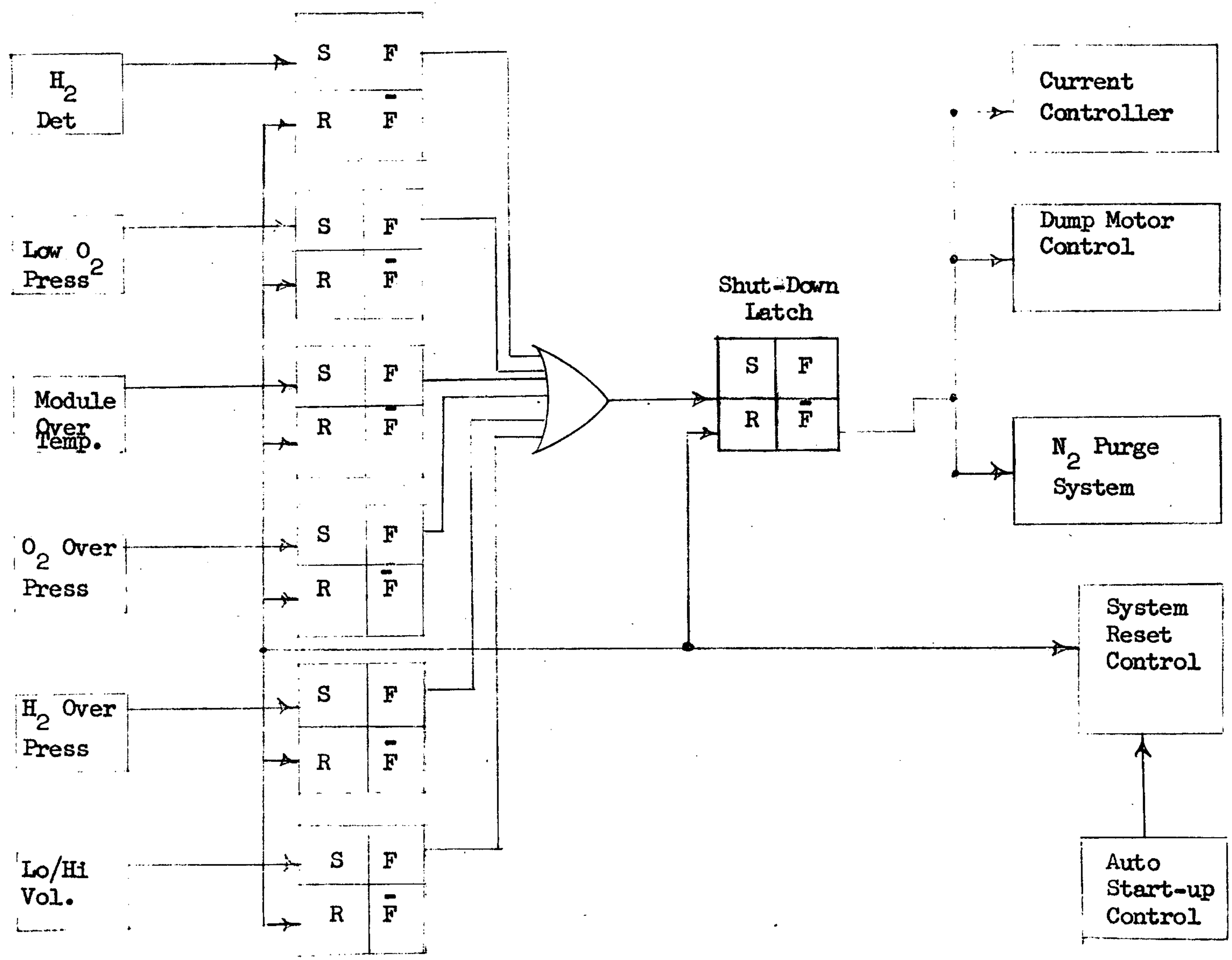

Figure 5 SAFETY SHUTDOWN LOGIC DIAGRAM

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 nor-gate circuitry which continuously monitors the following safety circuits: (1) module temperatures, (2) O_2, H_2 and system 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 indicate 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 will be "set". A reset condition can be obtained by depressing the system reset button S1.

2.4.1 Module Temperature

A thermister is located in each module, in contact with an end electrode. The logic circuits for these sensors have two settings: one at 30°C (86°F) and the second at 40°C (104°F). The 30°C (86°F) point provides a warning signal; the 40°C (104°F) point signals automatic system shutdown. Any one of the four temperature sensors can actuate the shutdown.

2.4.2 Gas Pressure

The oxygen and hydrogen lines in the modules each contain a pressure transducer set to actuate automatic shutdown if the pressure reaches approximately 20.7 kN/m^2 (3 psig). If the oxygen pressure is below 10.35 kN/m^2 (1.5 psig), the system will also automatically shut down.

2.4.3 Electrolyte Volume

The logic circuit for the reservoir pressure transducer has set points at liquid levels one inch above and below the water feed control band. Liquid level at either of these points will result in an automatic safety shutdown.

2.4.4 Hydrogen Detector

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

2.4.5 60 Hz Interrupt

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 restarted.

2.5 SYSTEM INTERFACES

2.5.1 Interface Instrumentation

The instrumentation available for external monitoring of the unit is provided at the five connectors (J102 through J106) on the left-hand side of the unit. The instrumentation consists of the following: three pressures, seven temperatures, sixty-four cell voltages, eight module voltages and currents, one total current, and two event (status) monitors. Refer to Table 2 for the type and range of stimulus monitored and to Figures 6 through 12 for connector identification.

The temperature and pressure signals are conditioned within the unit and emit a short-circuit protected voltage of 0-5 vdc for their respective stimulus ranges. The open circuit output impedance for these channels is $\leq 350\ \Omega$ unbalanced to signal return with a shunt capacitance of approximately 1.0 μf.

The module, cell, and shunt current voltages are balanced differential outputs. Each channel is short-circuit protected through its own passive isolation network. The open circuit output impedance of the cell and module voltage monitors is approximately 20 kΩ while that of the module current shunt (0-50 mV) voltages is approximately 2kΩ.

2.5.2 Interface Requirements

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

Feed Water	
Temperature	Ambient
Pressure	20.7 kN/m^2 (3 psig) min.
Quality	Commercial distilled
Coolant	
Fluid	Water
Temperature	$9 \pm 4^{\circ}$C ($48 \pm 7^{\circ}$F)
Flow rate	6.3 x 10^{-5} m^3/sec (1 gpm) max.
Nitrogen	
Pressure	207 kN/m^2 (30 psig)
Power	
	115 Vac, 60 Hz 208 Vac, 60 Hz, 3 Phase
Pressure Drop in Discharge Lines	10.35 kN/m^2 (1.5 psig) max.

Table 2

LMSC INSTRUMENTATION LIST

Qty.	Stimulus	Location	Xducer Range	Output Voltages	Characteristic
1	Press	O_2 Outlet	0-34.5 kN/m^2 (0-5 psig)	0-5 Vdc	Analog
1	Press	H_2 Outlet	0-34.5 kN/m^2 (0-5 psig)	0-5 Vdc	Analog
1	Press	Reservoir	0-34.5 kN/m^2 (0-0.5 psig)	0-5 Vdc	Analog
4	Temp	Modules	18-43°C (65°-110°F)	0-5 Vdc	Analog
2	Temp	Electrolyte	18-29°C (65°-85°F)	0-5 Vdc	Analog
1	Temp	Cold Plate	18-43°C (65°-110°F)	0-5 Vdc	Analog
1	Current	Total 28 Vdc Input	0 - 75 A	0 - 50 mV	Analog
8	Currents	Module 1A-4B	0 - 20 A	0 - 50 mV	Analog
64	Voltage	Cell Voltage Modules 1A - 4B	0 - 25 V	0 - 2.5 Vdc	Analog
8	Voltages	Module Voltages	0 - 20 V	0 - 20 Vdc	Analog

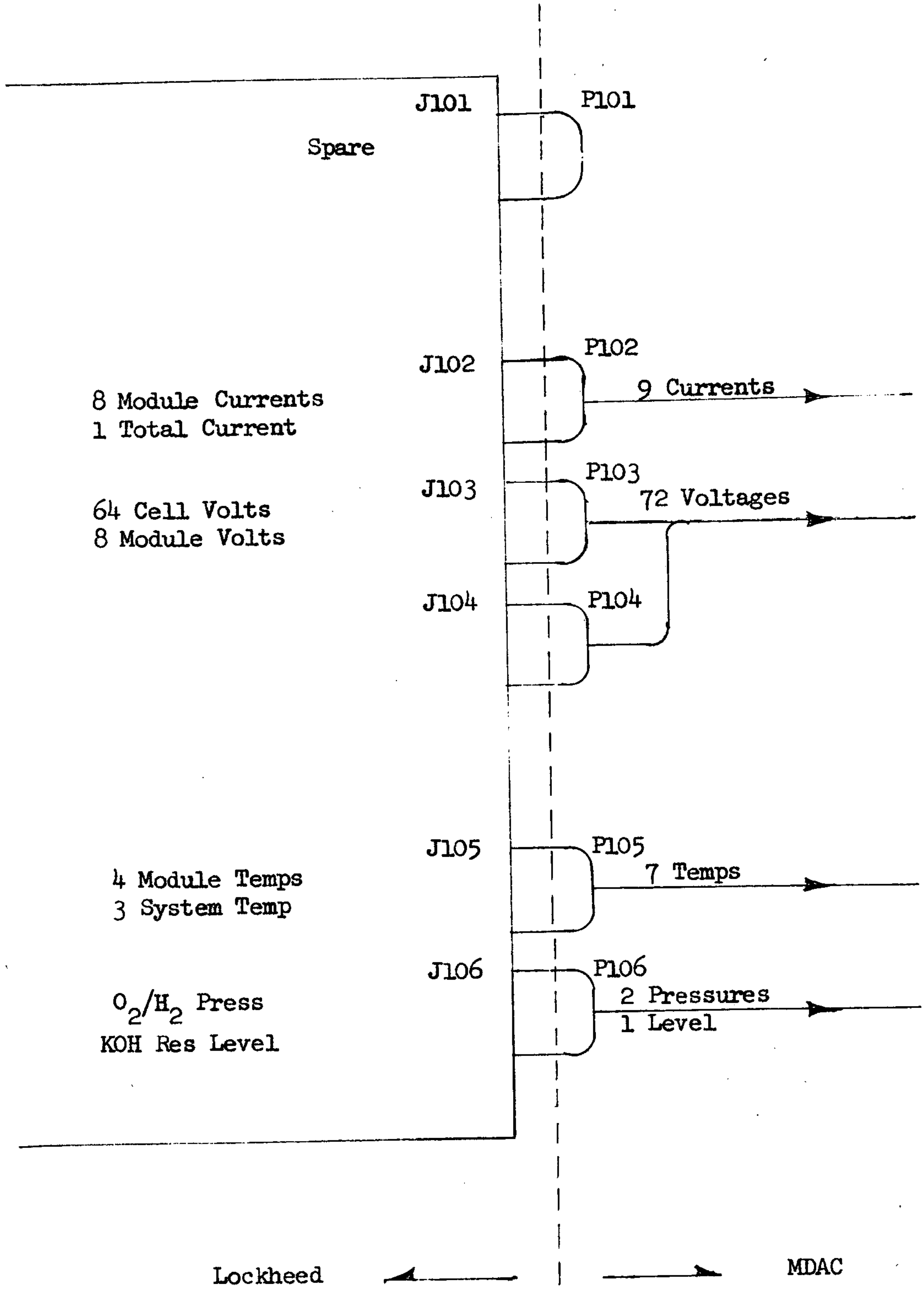

Figure 6 Cable Block Diagram

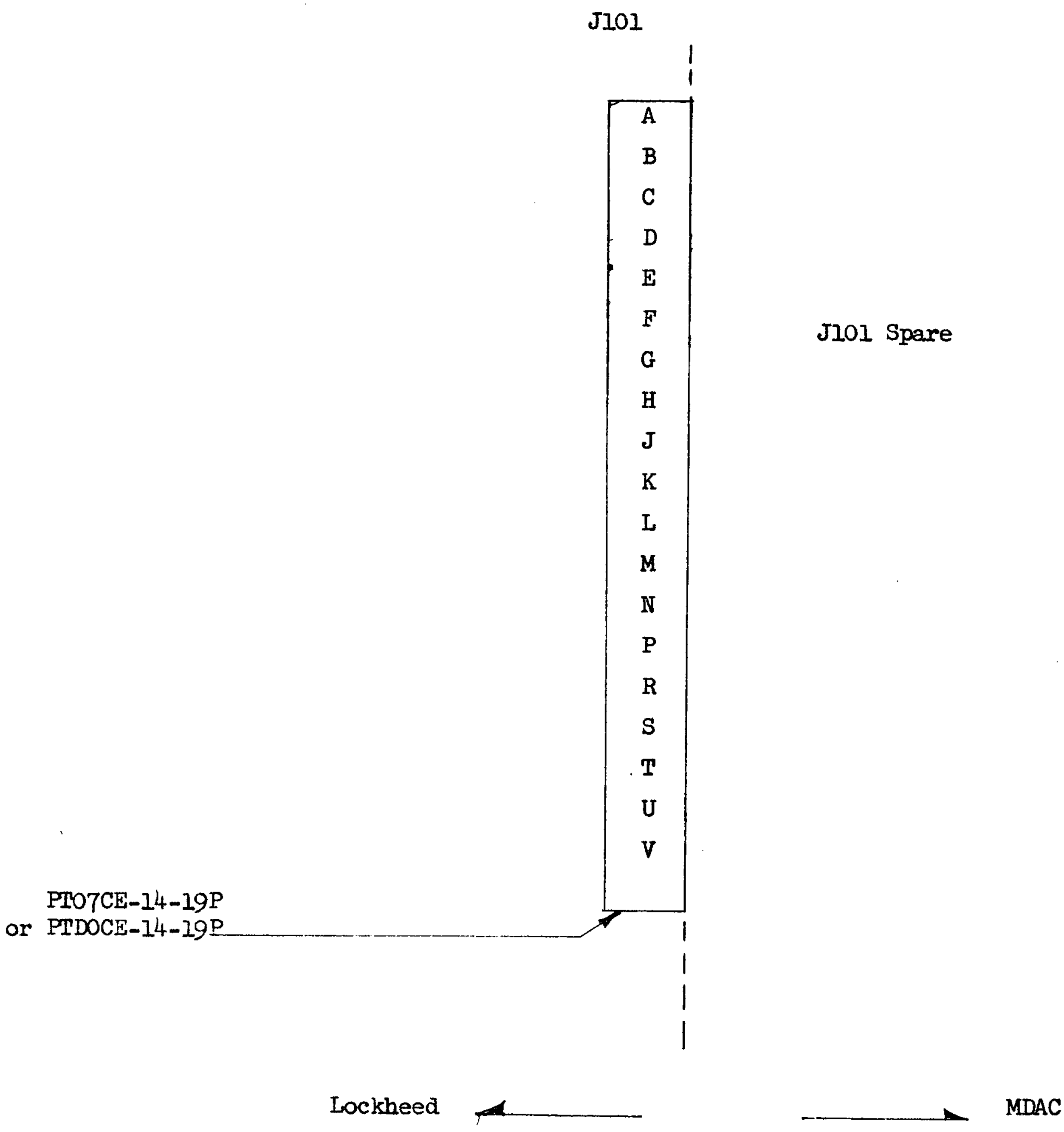

Figure 7 Spare Interface Receptacle

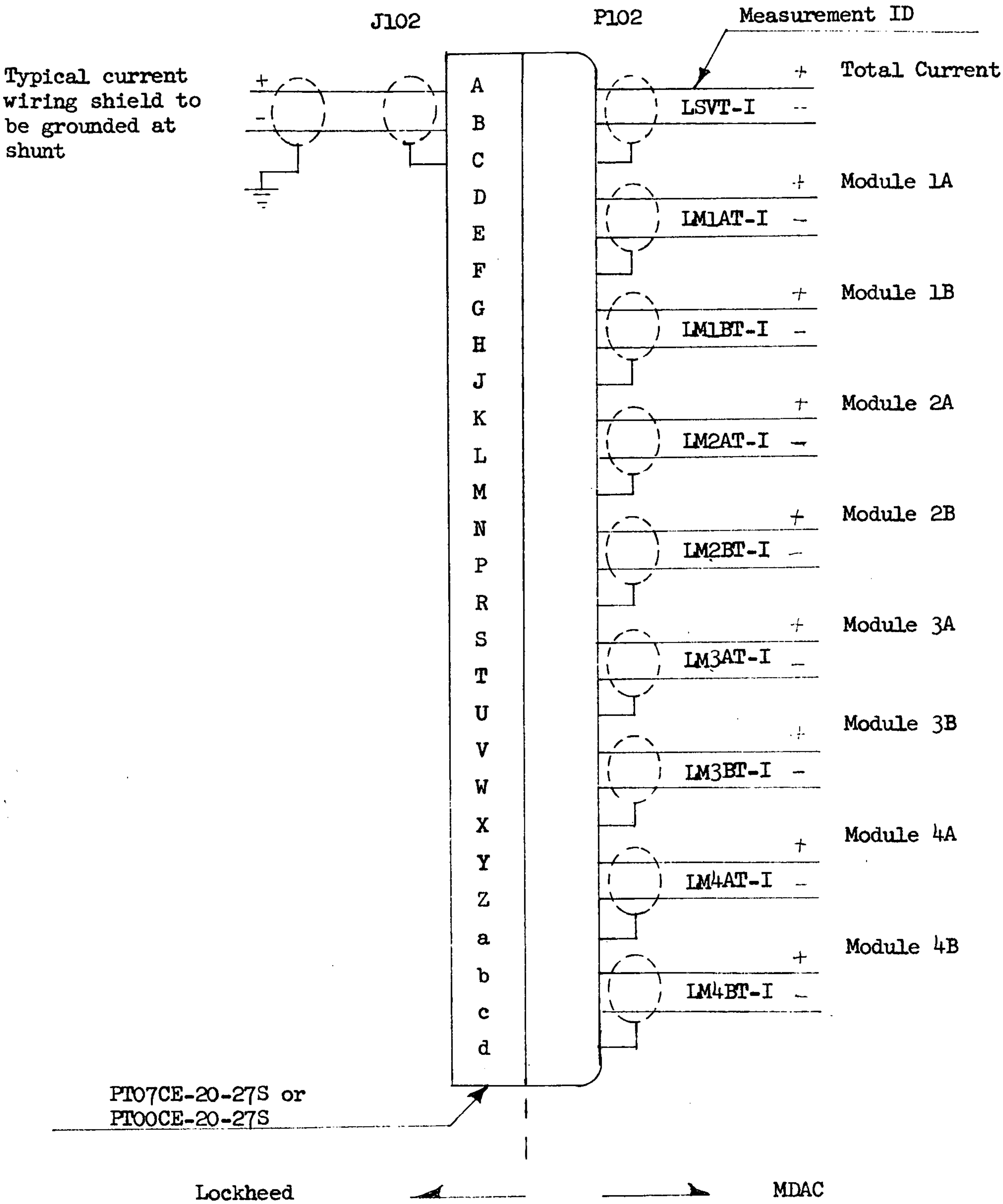

Figure 8 J102 - P102 Connector

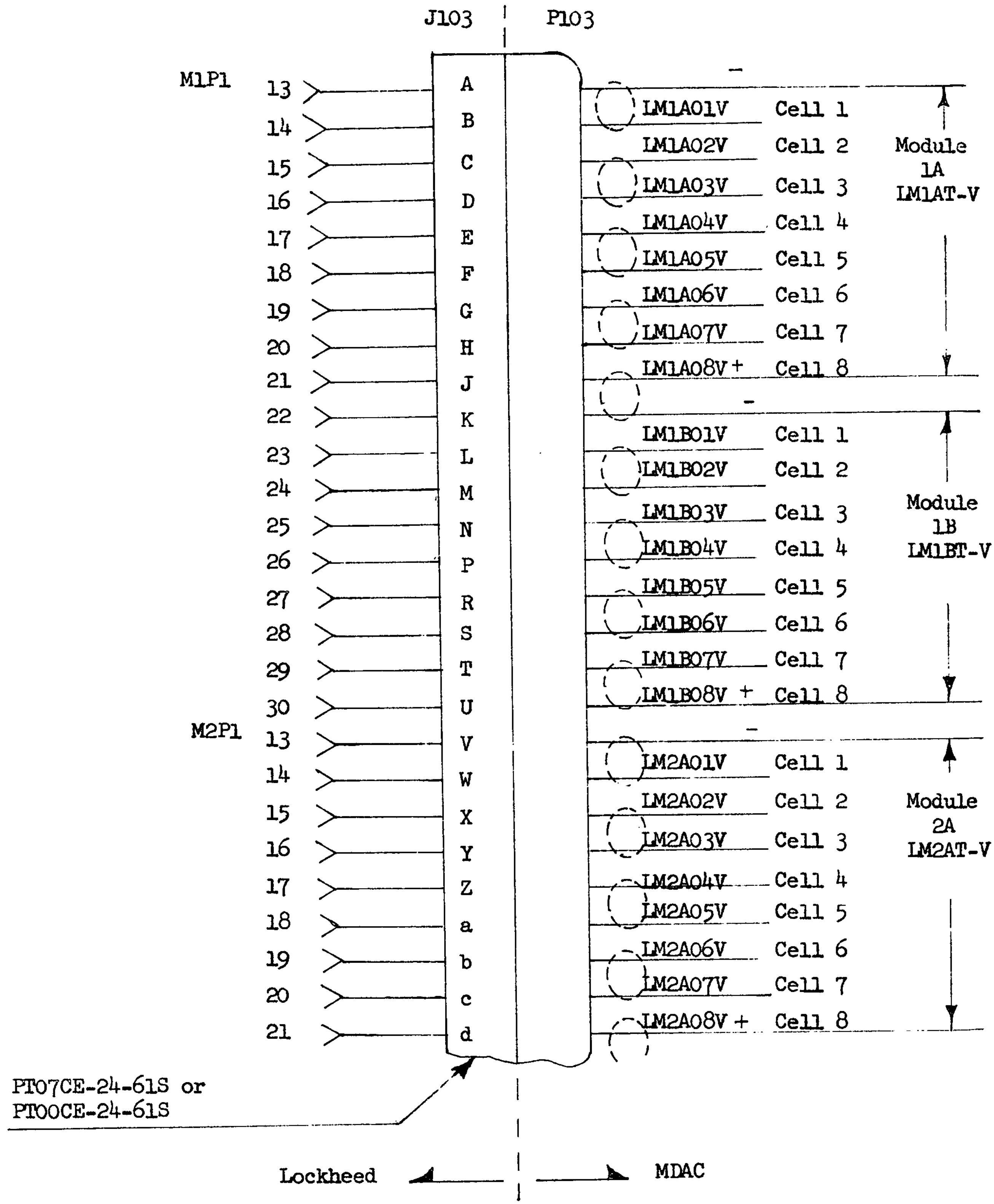

Figure 9A J103 - P103 Connector

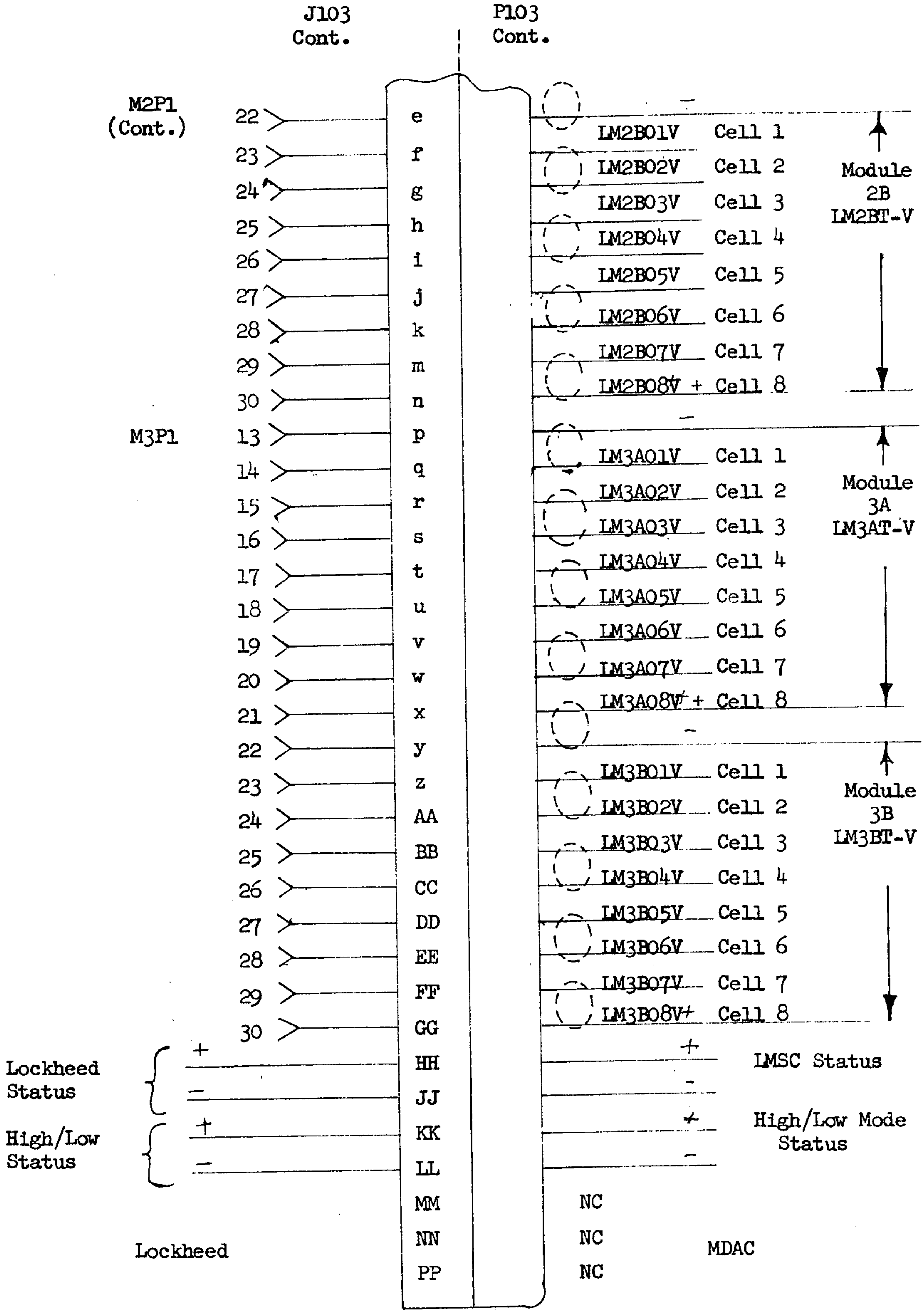

Figure 9B J103 - P103 Connector (Continued)

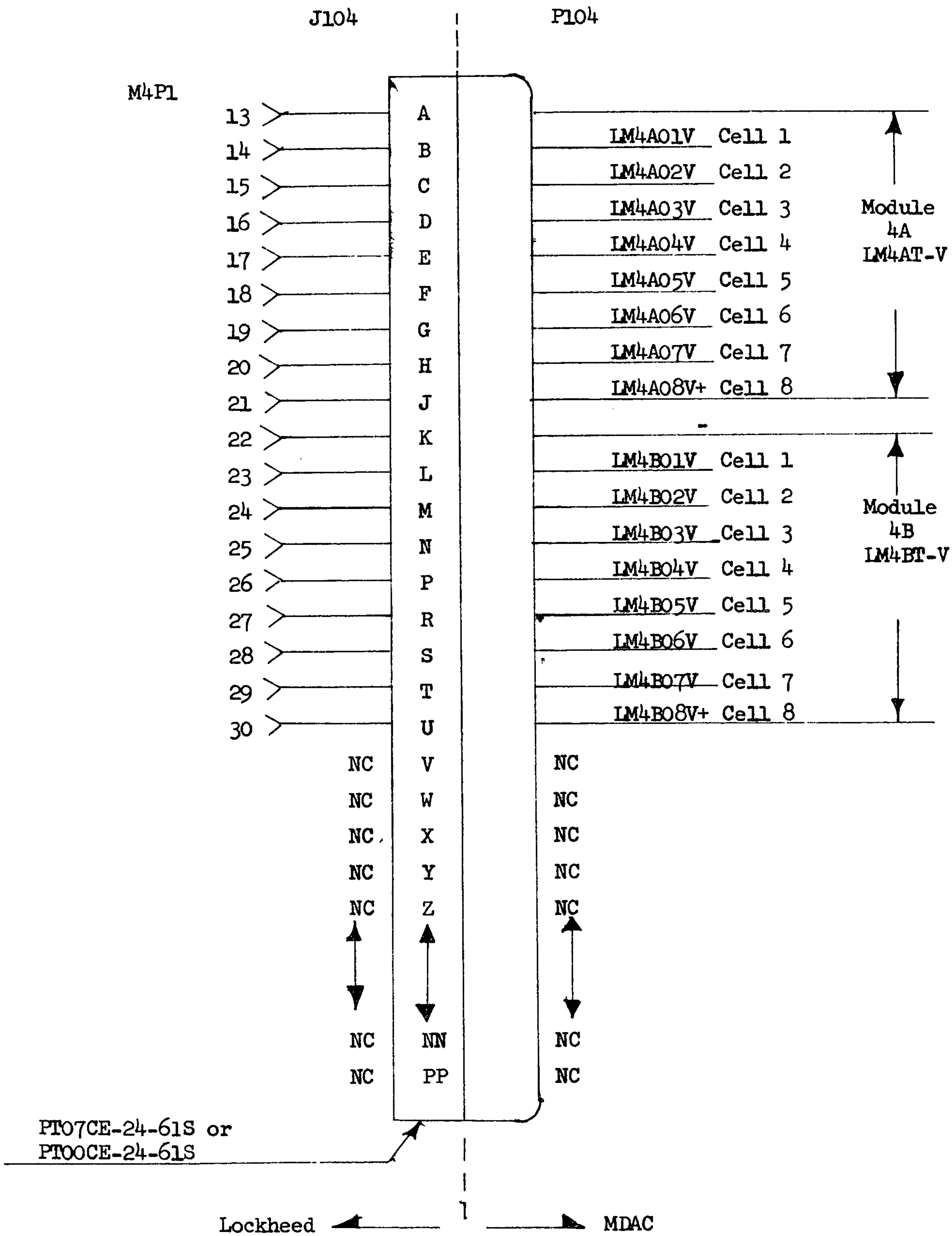

Figure 10 J104 - P104 Connector

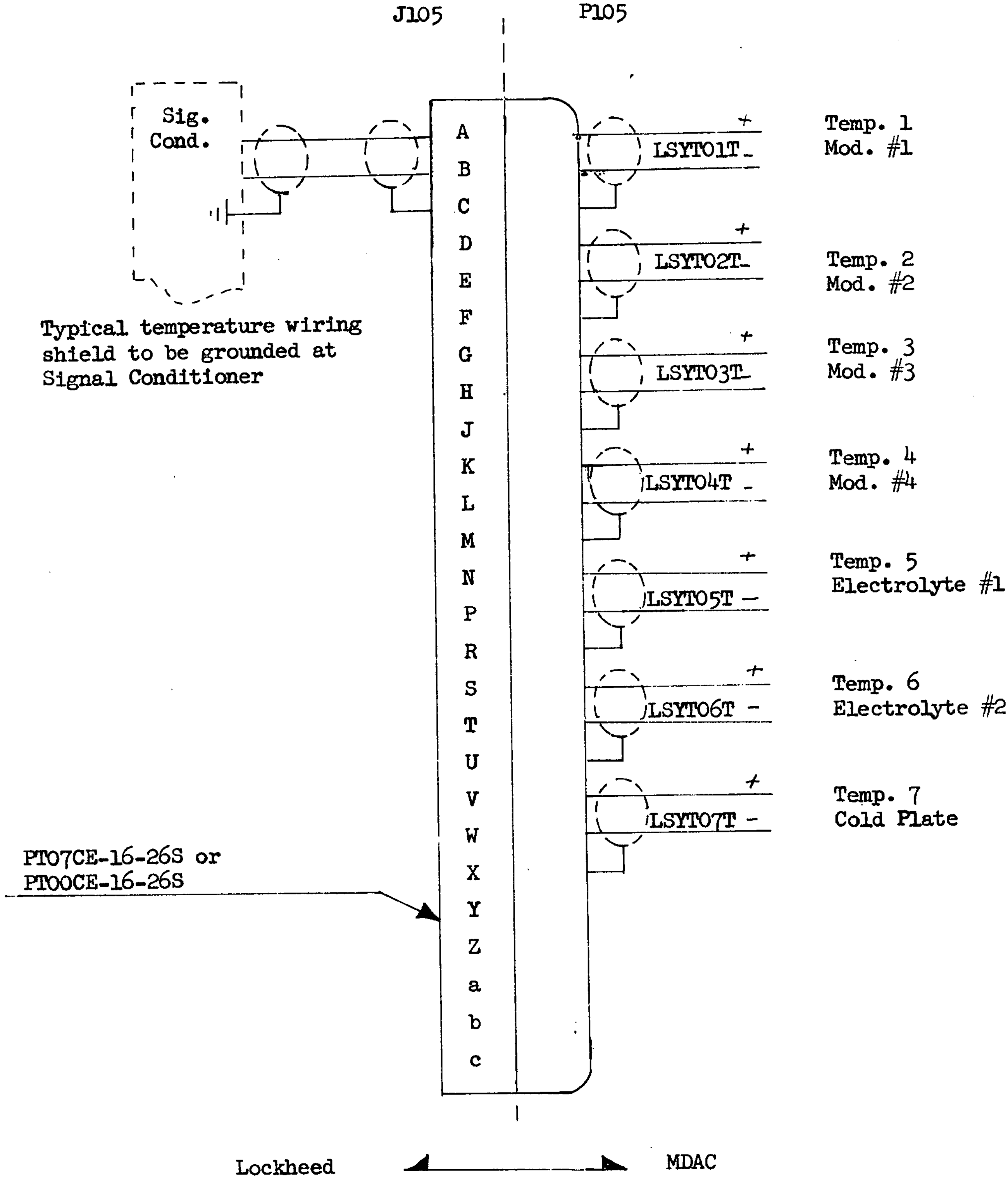

Figure 11 J105 - P105 Connector

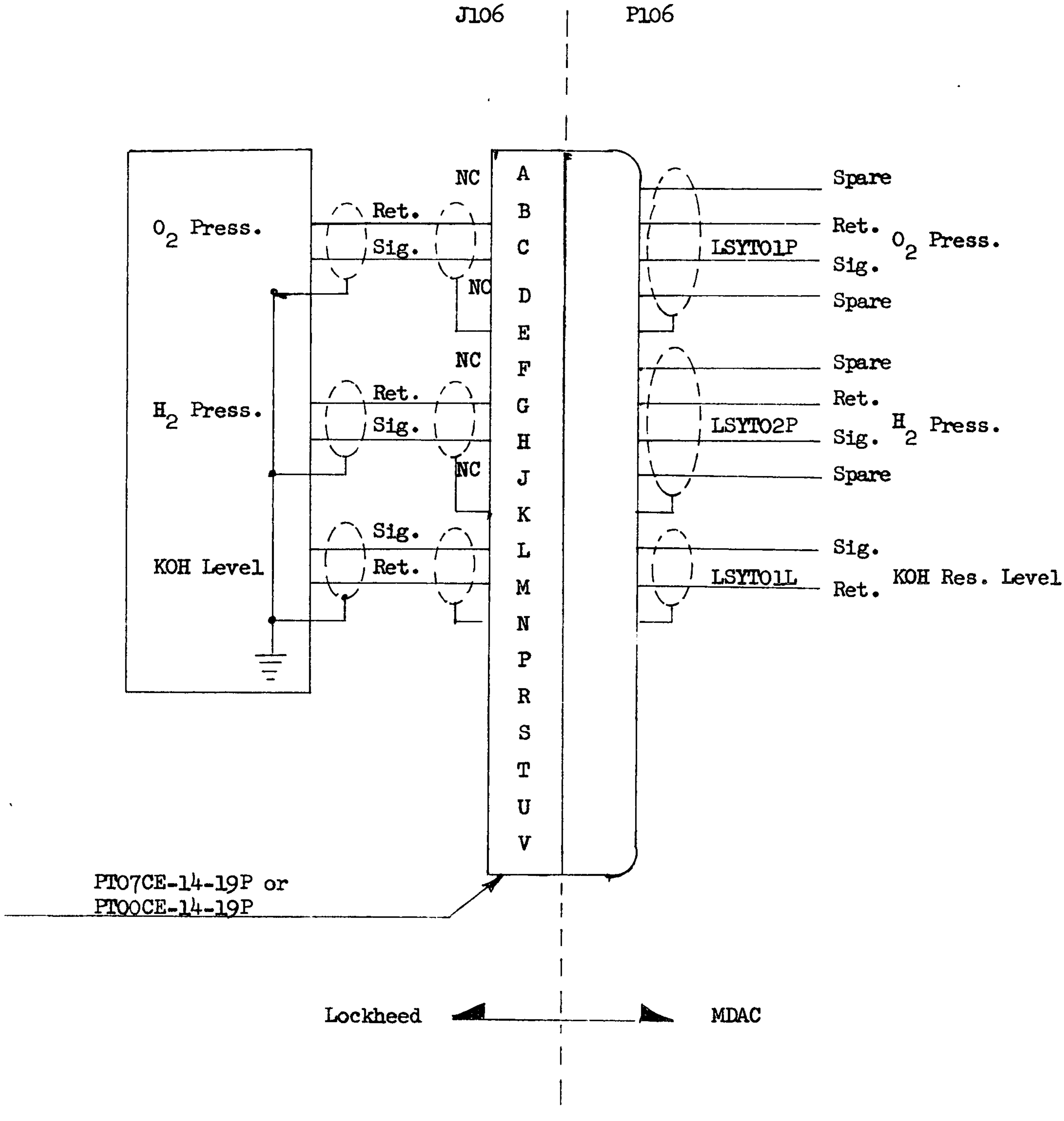

Figure 12 J106 - P106 Connector

The system will deliver oxygen at a nominal rate of 3.63 kg/day (8 lb/day), 4.55 kg/day (10 lb/day) maximum. The hydrogen and oxygen are delivered at approximately ambient pressure.

The water connection and coolant connections are located on the left side at the lower back corner of the unit; elbow fittings pointing toward the back are provided with 6.35×10^{-3} meter (1/4 inch) male AN. The oxygen, hydrogen, nitrogen purge and vent lines are located on the left side at the top and are provided with 6.35×10^{-3} meter (1/4 inch) male Swagelok connections. Gas sampling septum ports are provided in these lines.

The electrical interface is located on the left side near the front of the unit. In addition to the instrumentation connectors described previously, connections P28 - J28 and P400 - J400 are located here. Figure 13 identifies this connection.

2.6 SYSTEM OPERATION

2.6.1 Front Panel & Displays

The controls and displays presented on the front panel are presented in Figure 14.

The controls and displays are provided 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. 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 or non-illuminated switch lights should be visible.

Safety Status

The module temperature indicator displays two different temperature levels for each module. The first level indicated by a yellow lamp is 30°C (86°F). When this lamp is illuminated, the system is not shut down. This indicator serves only to warn of an impending over-temperature condition. The second temperature level is 40°C (104°F) and is indicated by a red light. If any of these indicators are illuminated, the system automatically shuts down.

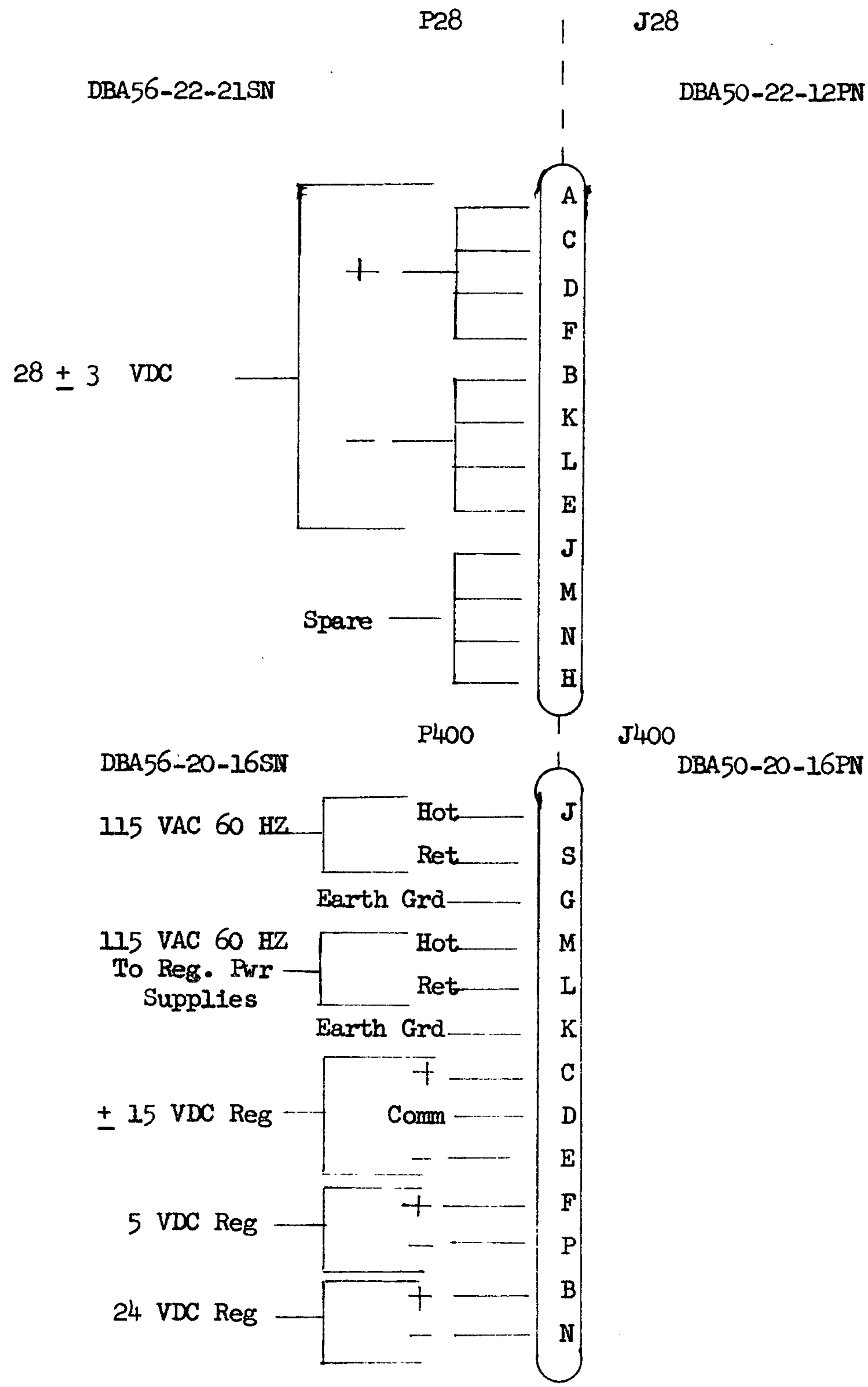

Figure 13 Plug Pin Assignments (Power)

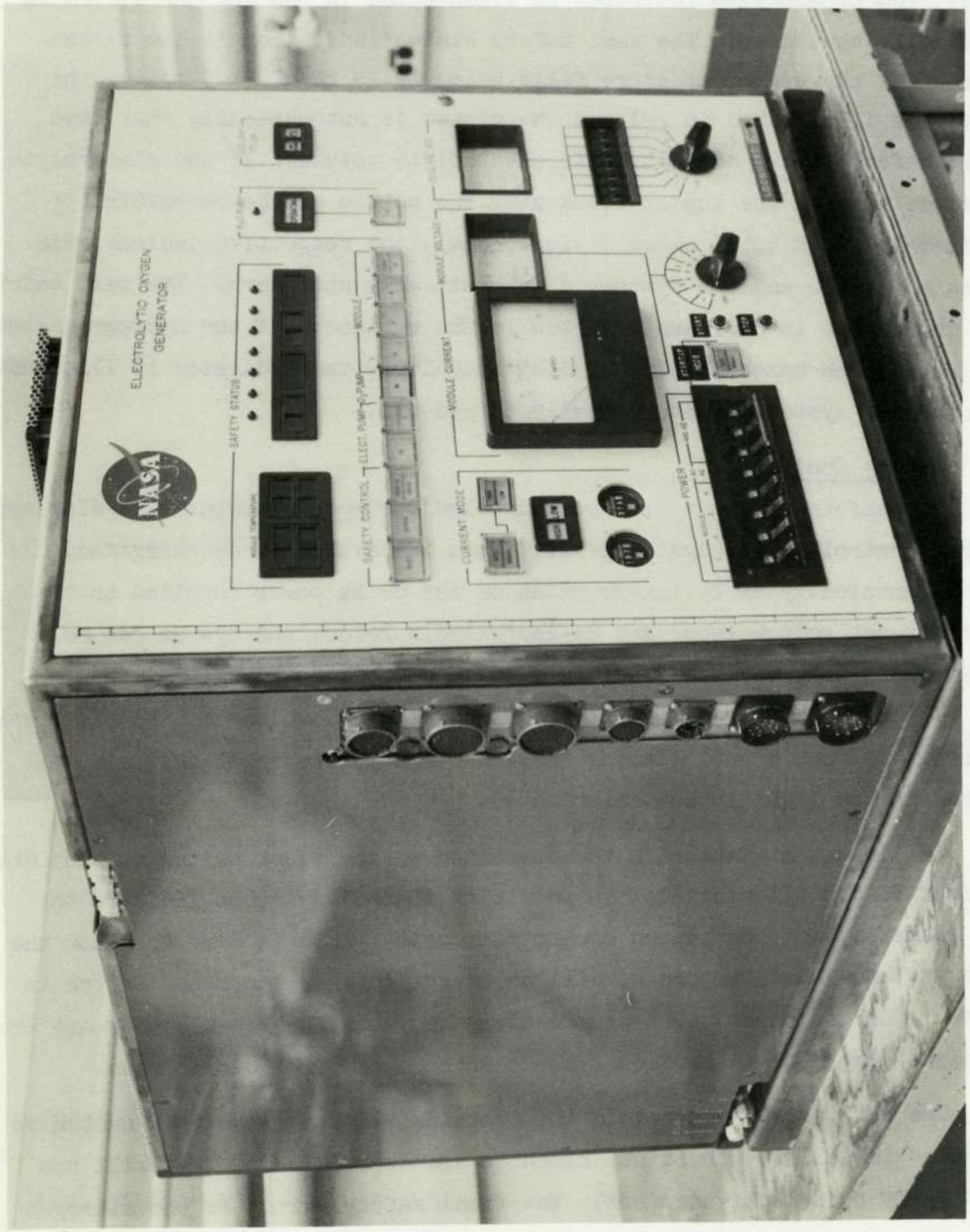

Figure 14 Front Panel Display and Controls

The next safety status indication is excess hydrogen or oxygen gas pressure. If either gas pressure in the discharge manifold exceeds 20.7 kN/m^2 (3 psig), the appropriate indicator is illuminated in red and the system is automatically shut down. The next safety status indication is low system pressure. If the system pressure falls below 10.35 kN/m^2 (1.5 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 near the bottom of the reservoir ($\pm$ approximately 3% of total electrolyte volume), the respective 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% by volume, the indicator is illuminated in red and the system is automatically turned off.

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 manually 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. 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. The components that are de-energized when the reset is off are the electrolyte pump, the water feed system, and the electrolysis modules.

The next safety control is the override switch. When this switch is illuminated in yellow, the safety circuits are overriden and they will not automatically turn the system off. The final safety switch is the nitrogen purge. The upper half of the switch is illuminated when the nitrogen purge solenoids are open. The lower half of the switch is illuminated when manual purge is selected.

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, modules, water feed system and coolant supply to the heat exchanger. The electrolyte pump switch operates the pump that is selected by the adjacent switch. 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 which are off, standby, and on. The function of the standby mode will be discussed when the current mode selector is discussed. The next control and indicator is for the water feed system (H_2O pump). The water feed system has two modes of operation. These are automatic and off. The indicator located above the switch indicates when the water feed system is operating and feeding water to the system.

The indicators of coolant flow to the electrolyte heat exchanger and the cold plate are located adjacent to the water feed system control. These are entirely automatic functions with no front panel control.

Below the safety control switches are located 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 an external electrical stimulus. 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, and in addition, it has a standby mode which selects a fixed low current that is not controlled by the current mode controls.

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 & B. The voltage and current for banks A & 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.

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 D.C. power to the electrolysis cell modules. The next circuit breaker controls the 115 volt, 60 Hz power for the electrolyte pump and all controls and displays. All D.C. power required by the unit is supplied from external power supplies.

Startup Mode

The switch located next to the circuit breakers is the startup mode selector. In the auto mode, the push button switches to the right of the selector switch are used to start and stop the system. In the manual mode, the start-stop buttons are deactivated.

2.6.2 Internal Controls and Displays

The displays and the internal controls which can be manually adjusted are described in Table 3 and portrayed in Figures 15 through 18.

2.6.3 Normal Operation

During normal automatic operation, no operator adjustments are required. The unit can be switched to manual operation in either the low or high modes. Either the continuous or cyclic operation mode can be selected and the time in high mode can be adjusted as necessary.

Table 3

SYSTEM CONTROL AND DISPLAYS

CONTROLS	DISPLAYS	LOCATION
ELECTROLYTE CIRCULATION SYSTEM		
Flow Control Valves (4)		In front of modules 1 & 2 and at left-front
Discharge Valves (4)		On top of modules
Fill Valve		Upstream of electrolyte pump
Drain Valve		Downstream of electrolyte pump
	Electrolyte Flow Meters (4)	In front of reservoir
NITROGEN PRESSURIZATION SYSTEM		
Module Purge Flow Control Valve		Above electrolyte flowmeter
Module Isolation Valves (8)		Left side of cabinet
COOLANT SUPPLY SYSTEM		
Heat Exchanger Flow Control Valve		Below ion canister
Cold Plate Flow Control Valve		Below ion canister
WATER FEED SYSTEM		
Water Flow Control Valve		Downstream of water solenoid valves
Manual Feed Switch		Connector panel - left side
PRODUCT GAS		
Discharge Valves (8)		Left side of cabinet

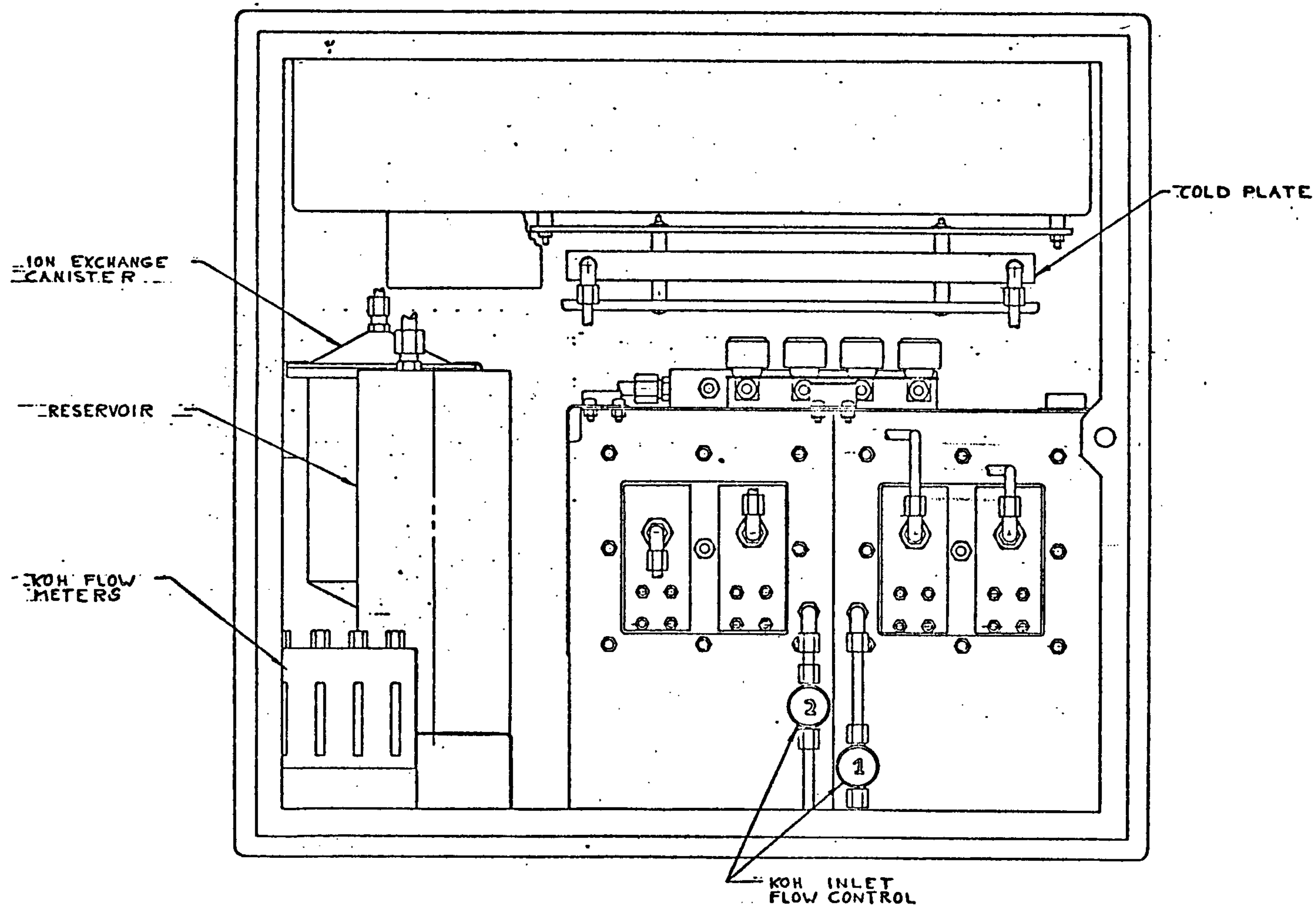

Figure 15 Front Internal View

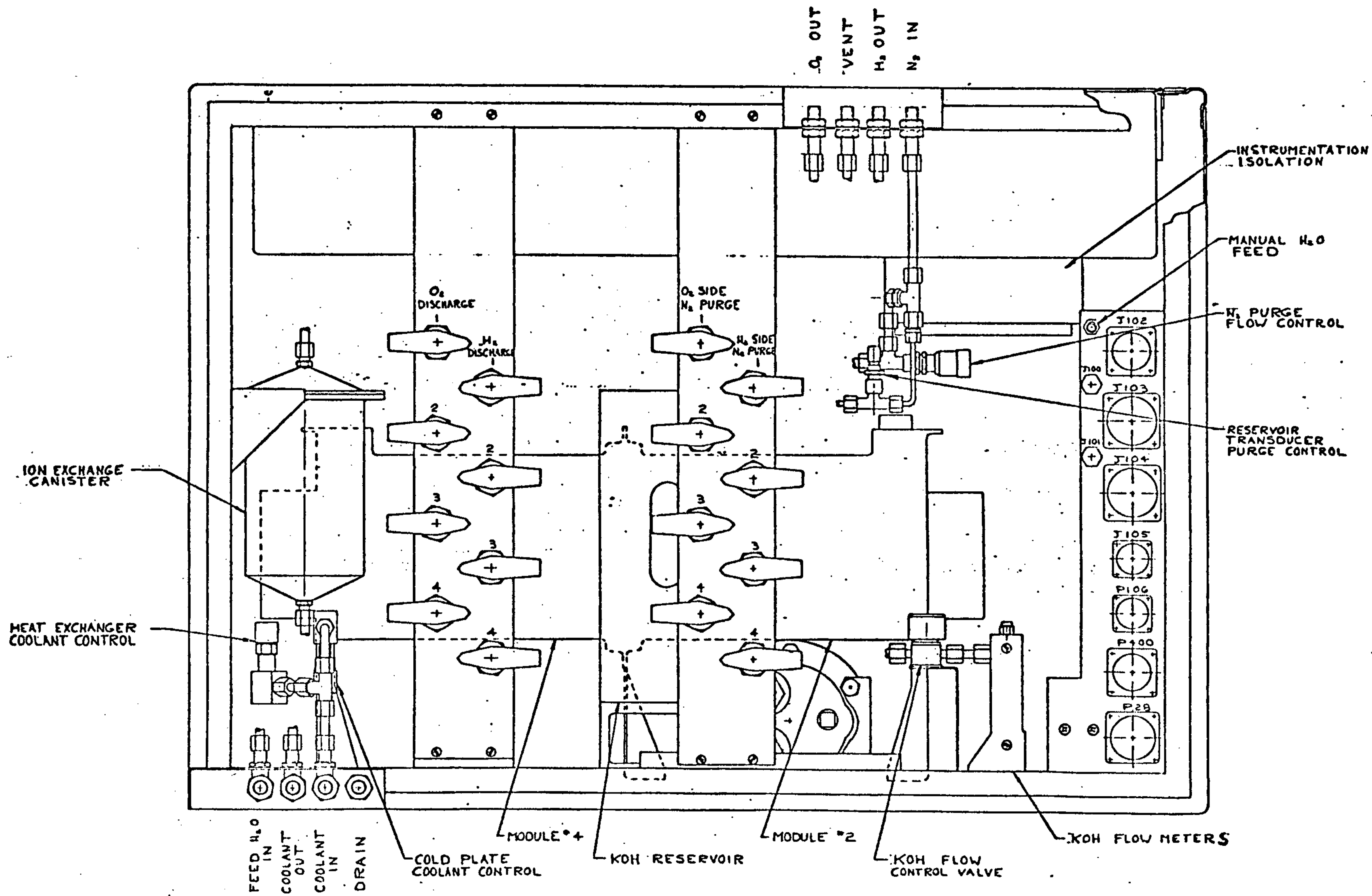

Figure 16 Left-Side View

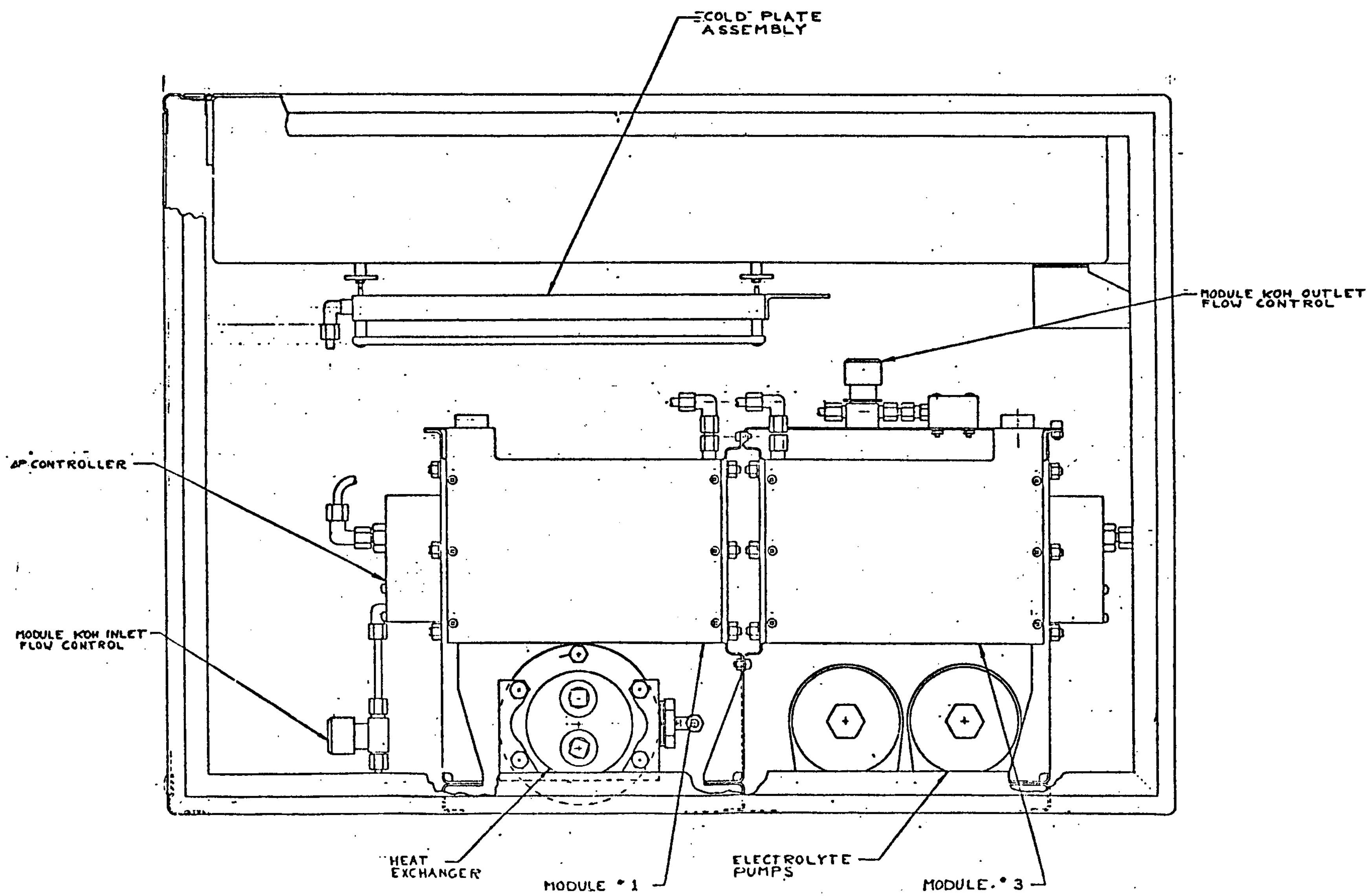

Figure 17 Right-Side View

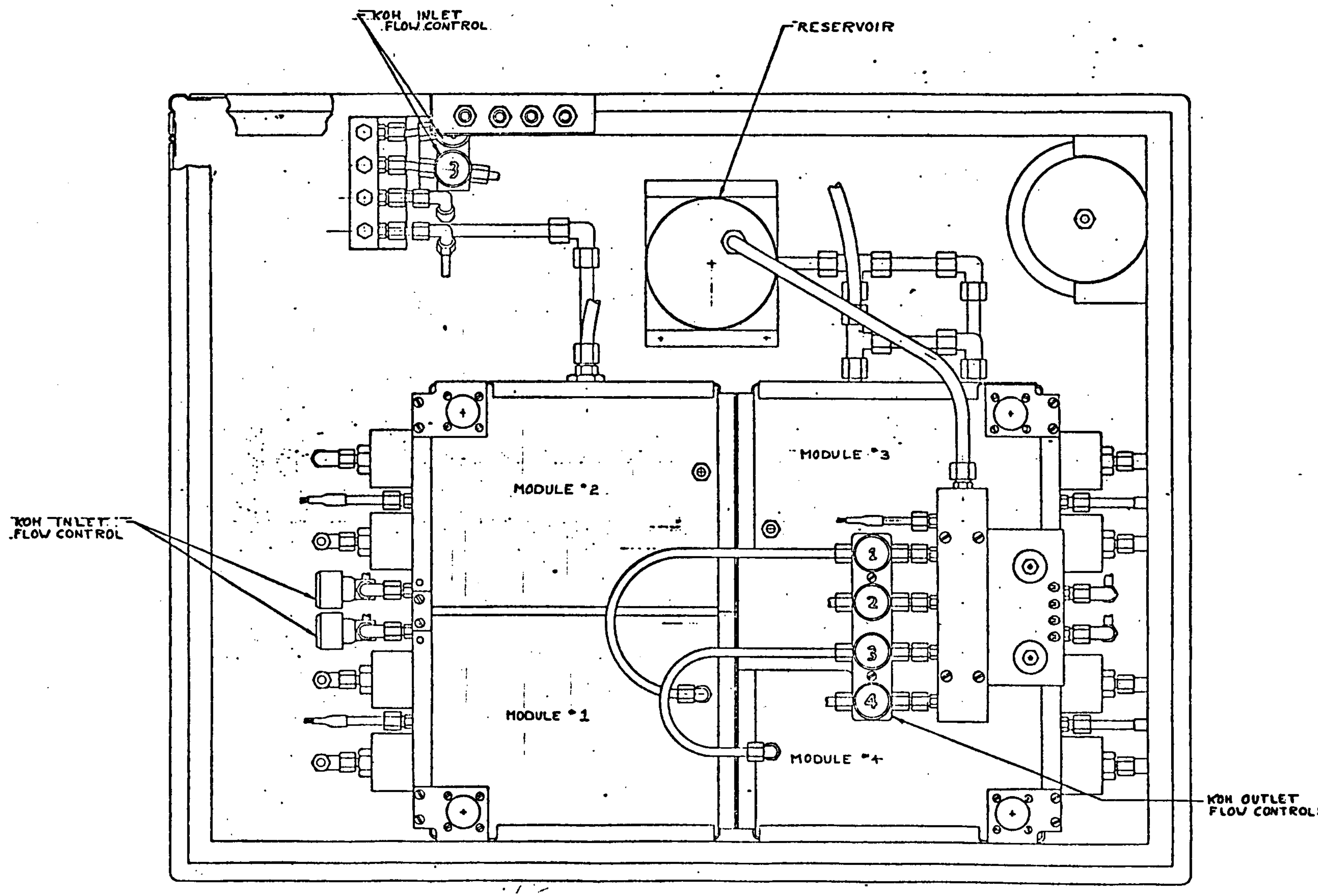

Figure 18 Top Internal View

In the continuous mode of operation, the high/low mode timer operates on a 100-minute cycle. Within this cycle, the time in high current mode can be selected using the digiswitch. The oxygen production rate is determined by the equation:

$$\dot{W}_{O_2} \text{ (lb/day)} = .05664 t_H + 4.536 \qquad (1)$$

where

t_H = time in high (digiswitch setting)

The time in high mode is selectable to the nearest whole minute. For example, to obtain 8 lbs/day of oxygen, solve equation (1) for t_H:

$$t_H = \frac{\dot{W}_{O_2} - 4.536}{.05664} = \frac{8.0 - 4.536}{0.5664}$$

$$t_H = 61.2$$

The nearest setting to provide a minimum of 8.0 lbs/day of oxygen is $t_H = 62$, which provides 8.048 lbs/day.

In the cyclic mode of operation, the on/off timer operates on a 94-minute cycle. The on-time during each cycle is fixed at 55 minutes. (Electrolysis power is off for 39 minutes of each cycle). Within the on-portion of the cycle, the time in high current mode is selected using the digiswitch.

The rate of oxygen production during the on-portion of the cycle is determined by the equation:

$$\dot{W}_{O_2} \text{ (lb/day) rate} = 0.1030 t_H + 4.536 \qquad (2)$$

The total oxygen produced in a 24-hour period is determined by the equation:

$$\dot{W}_{O_2} \text{ (lb/day)} = .0603 t_H + 2.654 \qquad (3)$$

2.7 COMPARISON OF 90-DAY AND 182-DAY TEST SYSTEM CONFIGURATION

At the conclusion of the 90-Day Test, the Electrolytic Oxygen Generator was completely disassembled (excluding electronics) and all components were inspected for evidence of corrosion or wear. The program of rebuilding and refurbishing the unit in preparation for the 182-Day Test required certain changes in internal configuration to (1) incorporate design improvements recommended as a result of the 90-Day Test experience, (2) correct malfunctions evidenced in the 90-Day Test and replace worn components, and (3) provide for the new interface requirements of the 182-Day Test which differed from those of the 90-Day Test.

2.7.1 Design Improvements

A summary of the design improvements which were implemented for the 182-Day Test is presented in Table 4.

2.7.2 Refurbishment

The following changes were made to correct known malfunctions and to replace worn components:

- Positive temperature control was added for the electronics cold plate to prevent moisture condensation.
- The internal 28 VDC power supply which had failed due to excessive operating temperature was removed. An external 28 VDC supply connection was provided as a replacement.
- The high current elapsed time meter, all solenoid and check valves, and the water feed timers were replaced.
- A fan was installed in the electronics chassis because of the additional heat loads of the new electronics circuits.
- Plastic N_2 purge lines were replaced with stainless steel to prevent gas diffusion.
- Holding current was provided for all solenoid valves to reduce their operating temperature.
- The plastic heat exchanger was replaced with a Kynar-coated stainless steel unit.
- The anodes in Module 1 were replaced with experimental electrodes of the type under development under Contract NAS-10405.[5]

Table 4

DESIGN COMPARISON

CONCLUSIONS DRAWN FROM 90-DAY TEST	DESIGN IMPROVEMENTS FOR 182-DAY TEST
o Improve electronics by additional filtering and shielding.	o Capacitance filtering of critical circuits and shielded-twisted-pair signal leads.
o Use solid-state sensors for increased reliability.	o Solid-state temperature, pressure, and water feed control and readout sensors.
o Incorporate auto startup to reduce operator interface.	o Automatic "pushbutton" startup and shutdown.
o Reduce gas interface sensitivity.	o Safety shutdown limits set close to operating pressures.
o Utilize modular maintenance concept to eliminate electrolyte plumbing.	o Manual isolation valves for all fluid connections to each module. **(Partially achieves maintenance objective.)**

2.7.3 Interface Requirements

The following changes were made for the new test conditions:

- The oxygen pump, gages and reservoir pressurization system were removed because ambient gas discharge pressure was acceptable for the 182-Day Test.
- Interface instrumentation of all system temperatures, pressures, currents, and cell/module voltages was incorporated to provide test data to the MDAC data logging system.
- The operating mode was modified to permit continuous high/low current mode or cyclic on/off mode operation on command from an external signal. The external device which provided the signal allowed selection of operating mode and high current duty cycle.

Section 3

CHECKOUT TESTING

3.1 INTRODUCTION

This section contains the results of the checkout test program conducted to verify the operational status of the NASA-LMSC Electrolytic Oxygen Generator prior to delivery of the unit to the McDonnell-Douglas Astronautics Company (MDAC) facility in Huntington Beach, California. Testing was performed by Bioengineering personnel in the LMSC facility in Sunnyvale, California. Test results for bench testing of critical components, a 50-hour test period to demonstrate startup, shutdown, and restart capabilities in the new automatic mode, and a final 100-hour acceptance test are included in the following paragraphs.

3.2 PRE-TEST PARAMETERS

3.2.1 Electrolysis Modules

External Leakage

Conditions. Each module was plumbed with a common manifold for both gas discharge ports and an electrolyte port; all other ports were sealed. The module was submerged completely in water and the manifold was pressurized to 34.5 kN/m^2 (5 psig). Visual inspection for gas bubbles was the external leakage criterion.

Data Recording Requirements. Log book entry: Pass or fail. No data sheet.

Values and Tolerances. No visible leakage was acceptable at 34.5 kN/m^2 (5 psig).

Results. Modules 2 and 4 passed on first assembly. Module 1 leaked on first assembly due to a defective O-ring. The O-ring was replaced and Module 1 passed on second assembly. Module 3 leaked on first assembly due to a missing O-ring. An O-ring was installed and Module 3 passed on second assembly.

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Cross-Leakage

Conditions. Each electrolysis module was installed in a test station in the electrolysis test facility. Water was first circulated through the electrolyte circulation loop and visual inspection was made for gas leakage into the electrolyte by observing the liquid discharge for entrained gas bubbles. Liquid leakage into the gas passages was measured by visual inspection of the liquid level in the reservoir and observing a liquid level change. The test was then repeated with KOH.

Data Recording Requirements. Log book entry; pass or fail. No data sheet.

Values and Tolerances. No visible cross leakage was acceptable.

Results. All four modules passed this test.

Electrical

Conditions. Each module was operated on a test station in the electrolysis test facility using a single constant current power supply to power the two electrical banks of the module in parallel. The total current was set to approximately 9 A; individual bank currents and all cell voltages were measured. The test duration was four hours. Visual inspection for internal shorting was made by observing the electrolyte discharge for entrained gas bubbles.

Data Recording Requirements. Log book entry; internal shorting pass or fail. Cell voltages were read on a digital voltmeter, currents on ammeters (0-10A scale). Data sheets with the following column headings were utilized:

Date, time, elapsed time

Cell voltages: A1 through A8; B1 through B8

Bank current: A and B.

Data were recorded once an hour.

Values and Tolerances.

Total Current	9.0 ± 1.0A
Bank Current	4.5 ± 0.5A
Cell Voltage	1.7 ± 0.2 Vdc

Instrument Calibration.

Ammeter	Weston, Model 931 0-10A MSL 71068 Calibrated 7-2-71 Due 12-31-71
Voltmeter	Non-Linear Systems Model 481 MSL 45993 Calibrated 7-31-71 Due 10-22-71 Accuracy ± (0.04% I.V. +0.01% F.S.)

Results. Modules 2, 3, and 4 were subjected to and passed this test. Final currents and cell voltages were as follows:

	2A	2A	3A	3B	4A	4B
Current	4.7	4.4	4.7	4.4	4.6	4.5
Cell 1	1.631	1.611	1.623	1.635	1.609	1.635
Cell 2	1.606	1.635	1.614	1.626	1.601	1.608
Cell 3	1.604	1.623	1.597	1.637	1.605	1.607
Cell 4	1.604	1.609	1.622	1.619	1.594	1.600
Cell 5	1.621	1.609	1.621	1.607	1.593	1.600
Cell 6	1.604	1.596	1.594	1.599	1.584	1.599
Cell 7	1.628	1.630	1.609	1.609	1.598	1.607
Cell 8	1.637	1.648	1.622	1.623	1.615	1.597

Module 1 operated at 12 Amps for 48 hours with the cell performance shown in **Table 5 and Figure 19.**

3.2.2 ΔP Controllers

Set Point

Conditions. Each controller was installed on a manifold block and tested at gas flow rates of 400, 800, and 1600 cc/min N_2 flow rates

Table 5

MODULE 1 CHECKOUT TEST RESULTS

	Elapsed Time (hr)	Cell Voltage at 12 Amp. 1	2	3	4	5	6	7	8
Module 1A	0	1.749	1.779	1.749	1.762	1.749	1.780	1.749	1.759
	1	1.810	1.826	1.800	1.819	1.790	1.819	1.770	1.791
	3	1.809	1.849	1.800	1.820	1.789	1.820	1.779	1.789
	6	1.794	1.869	1.789	1.819	1.779	1.819	1.769	1.779
	*22	1.799	2.019	1.799	1.839	1.779	1.829	1.769	1.779
	24	1.819	2.059	1.809	1.879	1.802	1.869	1.800	1.810
	27.5	1.839	2.079	1.839	1.910	1.829	1.929	1.839	1.849
	48	1.809	2.089	1.809	1.899	1.801	1.929	1.829	1.826
Module 1B	0	1.760	1.760	1.739	1.750	1.753	1.790	1.749	1.799
	1	1.829	1.809	1.769	1.776	1.761	1.839	1.779	1.839
	3	1.830	1.819	1.770	1.776	1.761	1.831	1.779	1.859
	6	1.809	1.802	1.759	1.762	1.749	1.819	1.769	1.859
	*22	1.799	1.799	1.749	1.740	1.729	1.789	1.749	1.881
	24	1.829	1.839	1.770	1.770	1.749	1.809	1.769	1.939
	27.5	1.859	1.869	1.806	1.800	1.779	1.849	1.803	2.009
	48	1.829	1.849	1.789	1.780	1.769	1.829	1.789	2.009

* Temperature above 27°C control point.

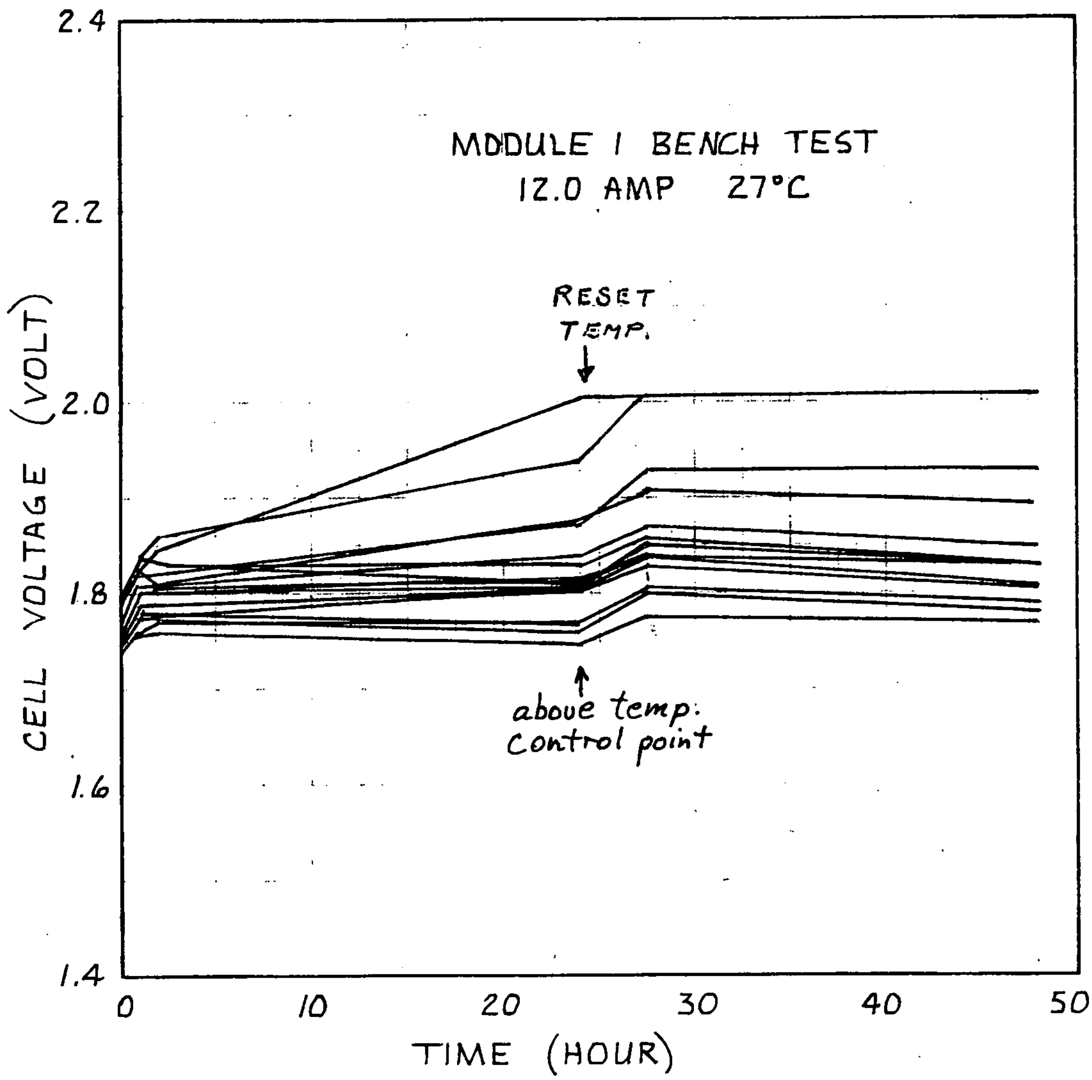


Figure 19 Module 1 Checkout Test Results

and liquid pressures of 6.9 and 13.8 kN/m^2 (1 and 2 psig).

The controller set point was adjusted by means of the valve seat position to read 6.22 ± 0.7 kN/m^2 (25 ± 3 inches of water). Differential pressure was measured with a Magnehelic gage (0 - 50 inches of water). Liquid pressure was measured with a 0 - 15 psig gage. Flow rate was measured with a Brooks rotameter.

Data Recording Requirements. Entries were made in a log book of ΔP at each flow rate and pressure.

Values and Tolerances. Differential pressure was required to be 6.22 ± 0.7 kN/m^2 (25 ± 3 inches of water).

Results. The measured set points for the ΔP controllers were the following:

	O_2 kN/m^2 (in. H_2O)	H_2 kN/m^2 (in. H_2O)
1.	5.97 - 6.72 (24.0 - 27.0)	6.05 - 6.85 (24.3 - 27.5)
2.	6.10 - 6.72 (24.5 - 27.0)	6.10 - 6.85 (24.5 - 27.5)
3.	5.97 - 6.85 (24.0 - 27.5)	6.10 - 6.97 (24.5 - 28.0)
4.	5.97 - 6.72 (24.0 - 27.0)	6.10 - 6.85 (24.5 - 27.5)

External Leakage.

Conditions. Inlet liquid and gas ports were manifolded, exit gas port was sealed and the unit was submerged in water with 34.5 kN/m^2 (5 psig) N_2 pressure on the manifold.

Data Recording Requirements. Log book entry; pass or fail. No data sheet.

Results. All of the ΔP controllers passed this test.

3.2.3 Water Feed Controller

Conditions. The water feed controller was installed in a bench reservoir containing water. End to end signal output vs H_2O head in inches, control band, hysteresis, level safeties, and timing circuits were monitored.

Data Recording Requirements. Log book entries were made of voltage signal vs H_2O head, control band, repeatability on at least ten water feed cycles, level safety signal set points and timing circuit functions. No data sheets.

Values and Tolerances.

Signal Voltage	Digital readout ± 1 mV
Range	0-2.69 kN/m^2 (0.32 psi) 0-5 Vdc
Accuracy	± 25 N/m^2 (0.036 psi)
Hysteresis	± 62 N/m^2 (0.09 psi)
Control Band	1.12 - 1.25 kN/m^2 (0.15-0.18 psi)
Low Level Safety	0.75 kN/m^2 (0.11 psi)
High Level Safety	1.5 kN/m^2 (0.22 psi)
Feed Time Limit	12 ± 1 sec.
Feed Cycle Limit	10 ± 1 min.

Results. The range calibration of the reservoir transducer is shown in Figure 20 as signal voltage of the transducer versus static head pressure. This figure shows the hystersis to be approximately 0.008 psi or 55 N/m^2. The values of control and safety set points are those given above.

3.2.4 Temperature Controls, Indicators and Safeties

Conditions. Each thermistor probe was calibrated by immersion in a controlled temperature water bath. End to end voltage signal vs. temperature was measured and all set points verified.

Data Recording Requirements. Log book entries were made of temperatures, voltages, and set points. No data sheets.

Values and Tolerances. Temperature measurements were made with calibrated mercury thermometers and voltages with a ± 1 mv digital voltmeter. The following is a list of values and tolerances for the individual temperature sensors.

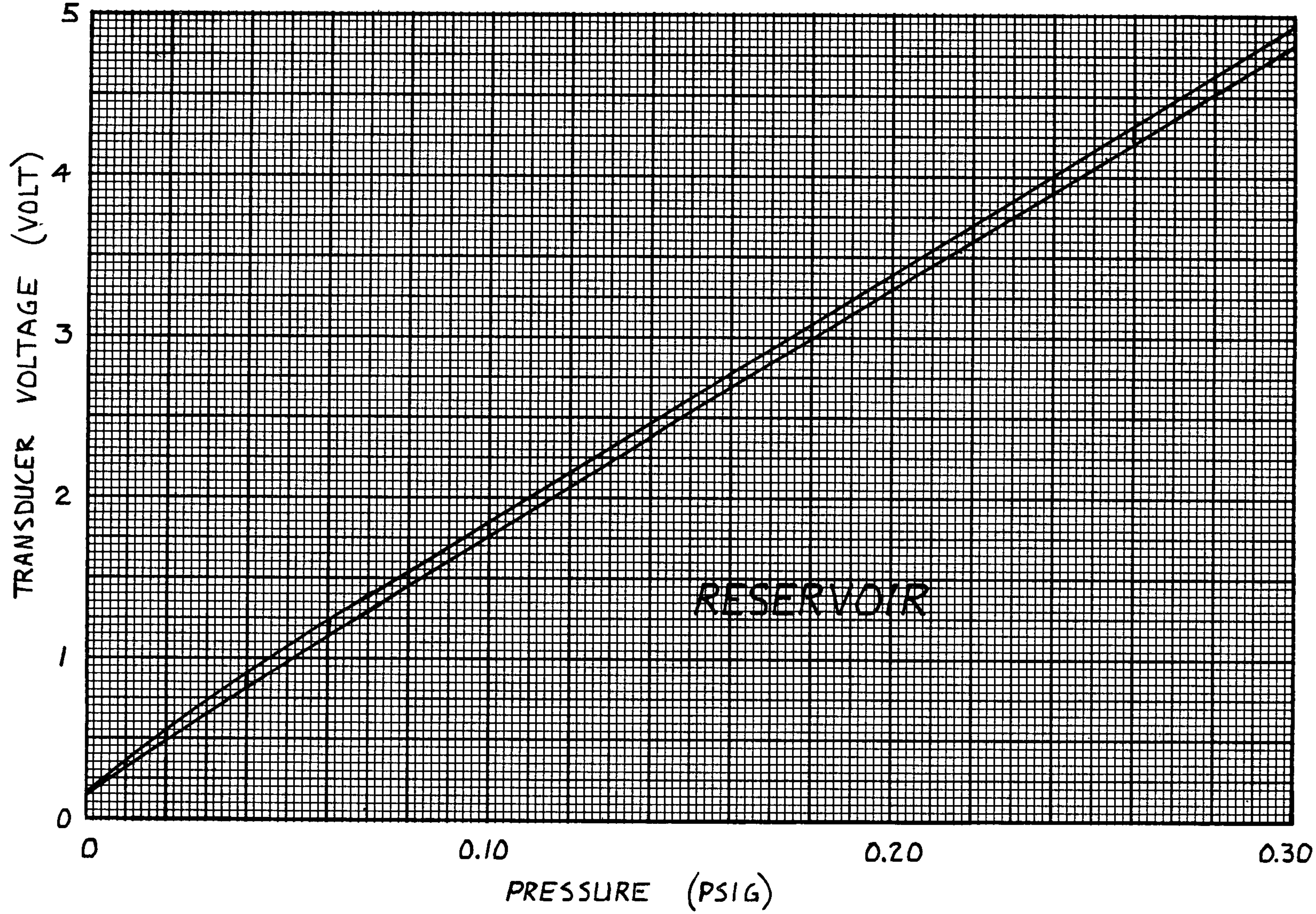


Figure 20 Reservoir Transducer Calibration Curve

Module Overtemperature (4)

end-to-end	18 - 44°C 0-5 vdc
accuracy	± 1.0°C
range	18 - 44°C
limits set	warn 30°C
	shutdown 40°C

Temperature Control and Indicator - Electrolyte #1

end-to-end	20 - 30°C
accuracy	± 1.0°C
range	18 - 44°C
set point	30 ± 2°C

Temperature Control - Coldplate

end-to-end	18 - 44°C
accuracy	± 1.0°C
range	18 - 44°C
set point	25 ± 5°C

Temperature Indicator - Electrolyte #2

end-to-end	18 - 44°C
accuracy	± 1.0°C
range	18 - 44°C

Results. The set points given above were achieved. Calibration curves for the thermisters are shown in Figures 21 through 24 .

3.2.5 O_2 and H_2 Pressure Transducers

Conditions. Pressure vs signal output end-to-end was tested by pressurizing with N_2 and using a Wallace-Tiernan gage for pressure indication and ± 1 mv digital voltmeter for signal measurement.

Data Recording Requirements. Log book entries of range and set point. No data sheets.

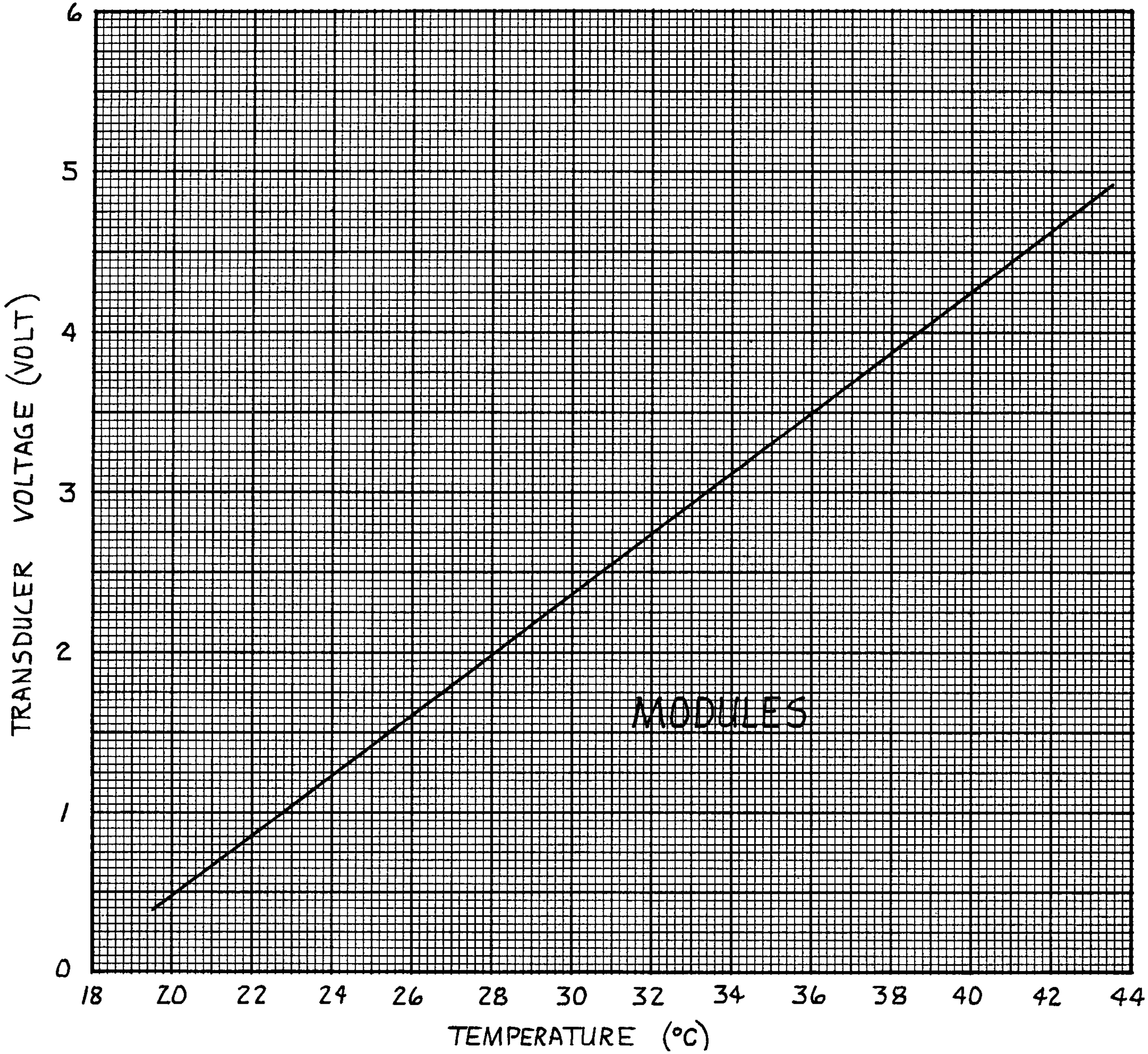


Figure 21 Module Temperature Sensor Calibration Curve

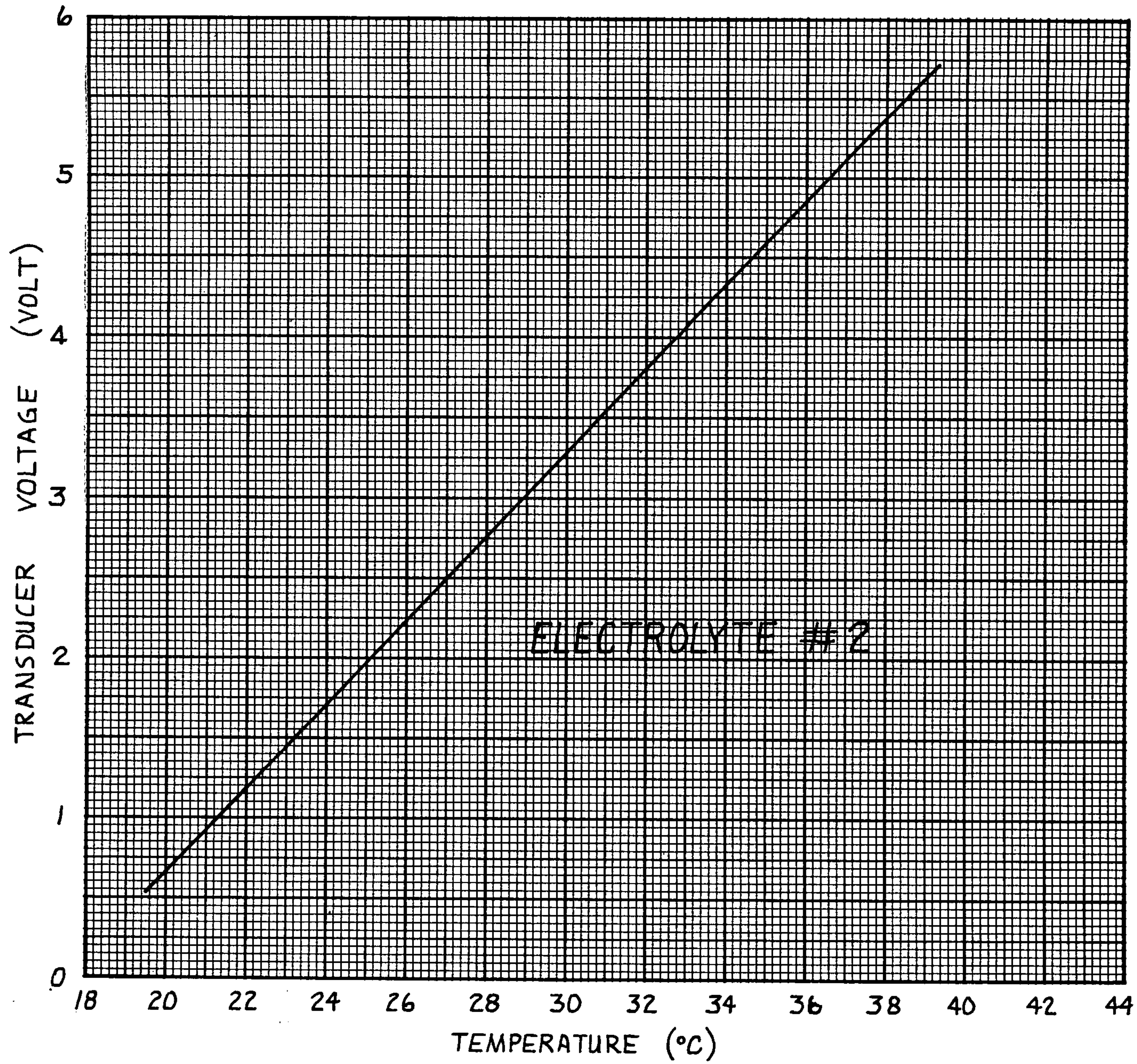


Figure 22 Electrolyte Temperature Indicator Calibration Curve

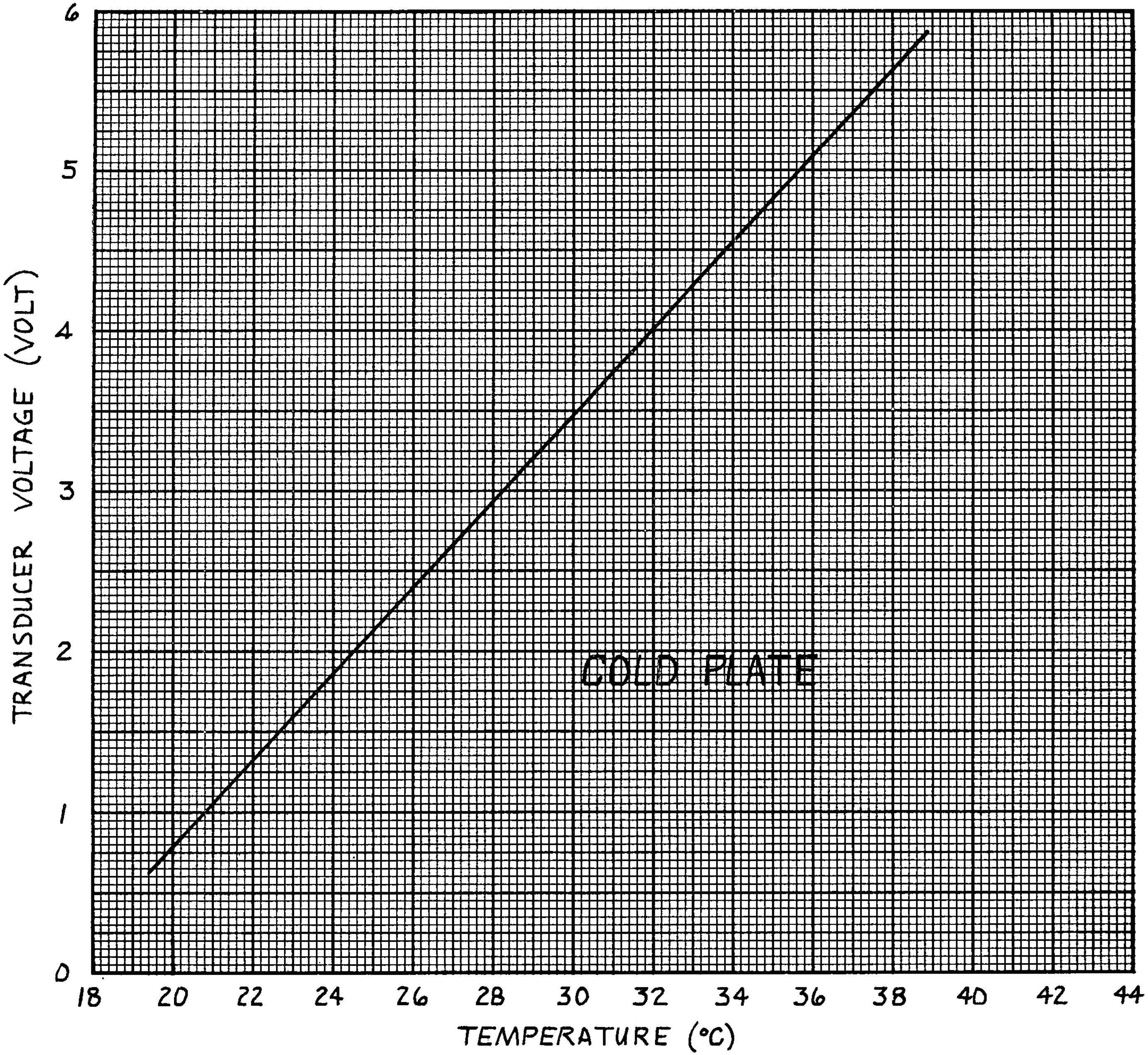


Figure 23 Cold Plate Temperature Sensor Calibration Curve

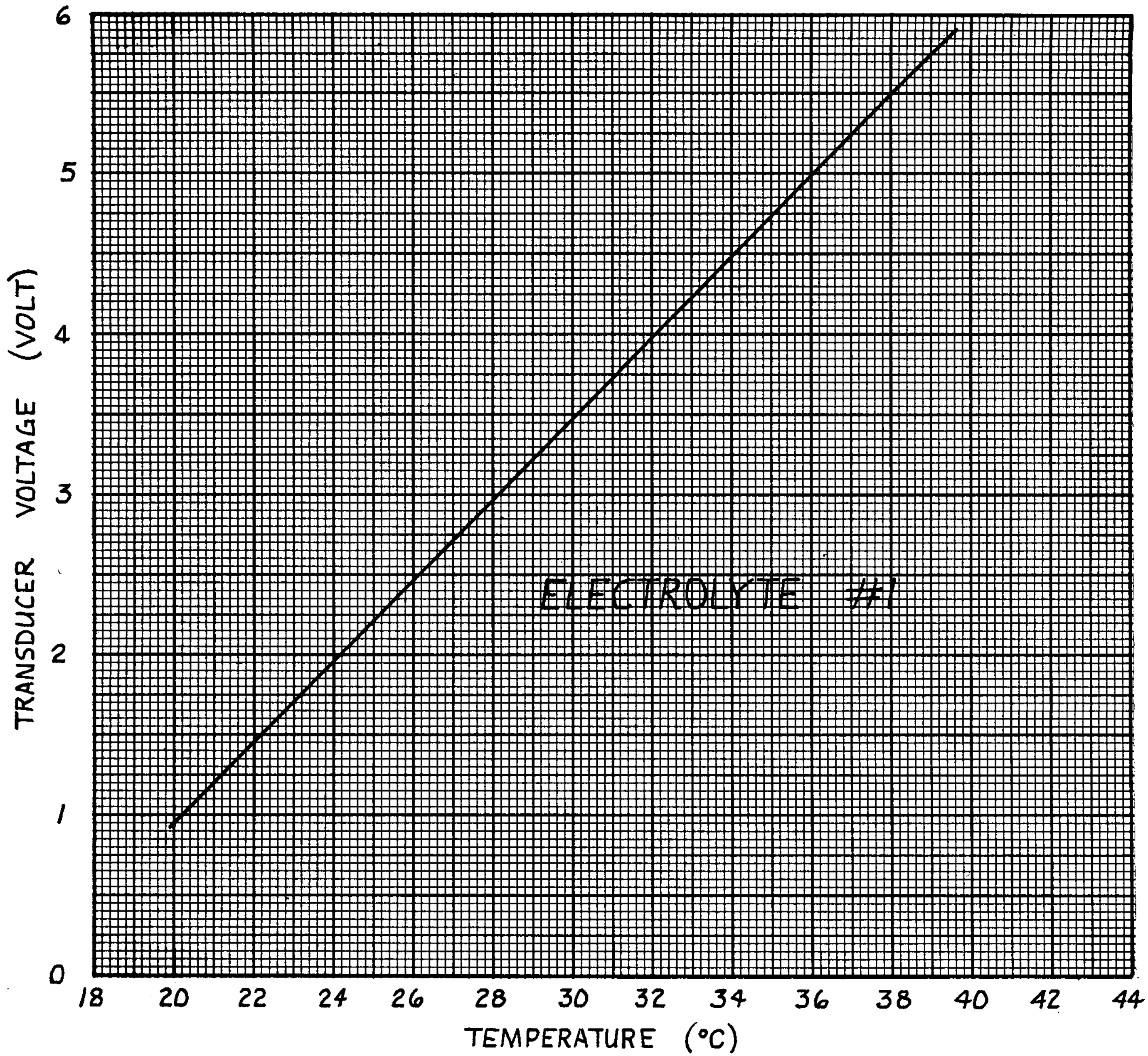


Figure 24 Electrolyte Temperature Control Sensor Calibration Curve

Values and Tolerances.

range	0 - 34.5 kN/m^2 (0 - 5 psig)
accuracy	± 0.34 kN/m^2 (± 0.05 psi)
set points	9.0 kN/m^2 (1.3 psi) low O_2 pressure
	17.7 kN/m^2 (2.57 psi) O_2 overpressure
	16.7 kN/m^2 (2.42 psi) H_2 overpressure

Results. The calibration curves for these transducers are shown in Figures 25 and 26. Some hysteresis was noted; values given above are for decreasing pressure for low O_2 and increasing pressure for overpressure.

3.2.6 Auto Start-up Sequence

Conditions. Sequential command signals were monitored as a function of time. The units to which the command signals were directed were deactivated during this test.

Data Recording Requirements. Log book entries were made of command signals vs time. No data sheets.

Values and Tolerances. 0 - 60 sec. ± 2 sec. total.

Results. The auto startup sequence was verified to be within tolerances.

3.2.7 Shutdown Signal Sources

Conditions. Each shutdown signal was either stimulated or simulated and the command to shutdown was monitored.

Data Recording Requirements. Log book entries: Pass or fail for each safety sensor. No data sheets.

Values and Tolerances.

Overtemperature	warn 30 ± 1.0°C shutdown 40 ± 1.0°C
Overpressure (O_2) (H_2)	17.7 kN/m^2 (2.57 psig) 16.7 kN/m^2 (2.42 psig)
Low O_2 pressure	9.0 kN/m^2 (1.3 psig)
Electrolyte volume (high and low)	1.5 and 0.75 kN/m^2 (6 and 3 "H_2O)
H_2 in cabinet	0.8%
Loss of power	-----

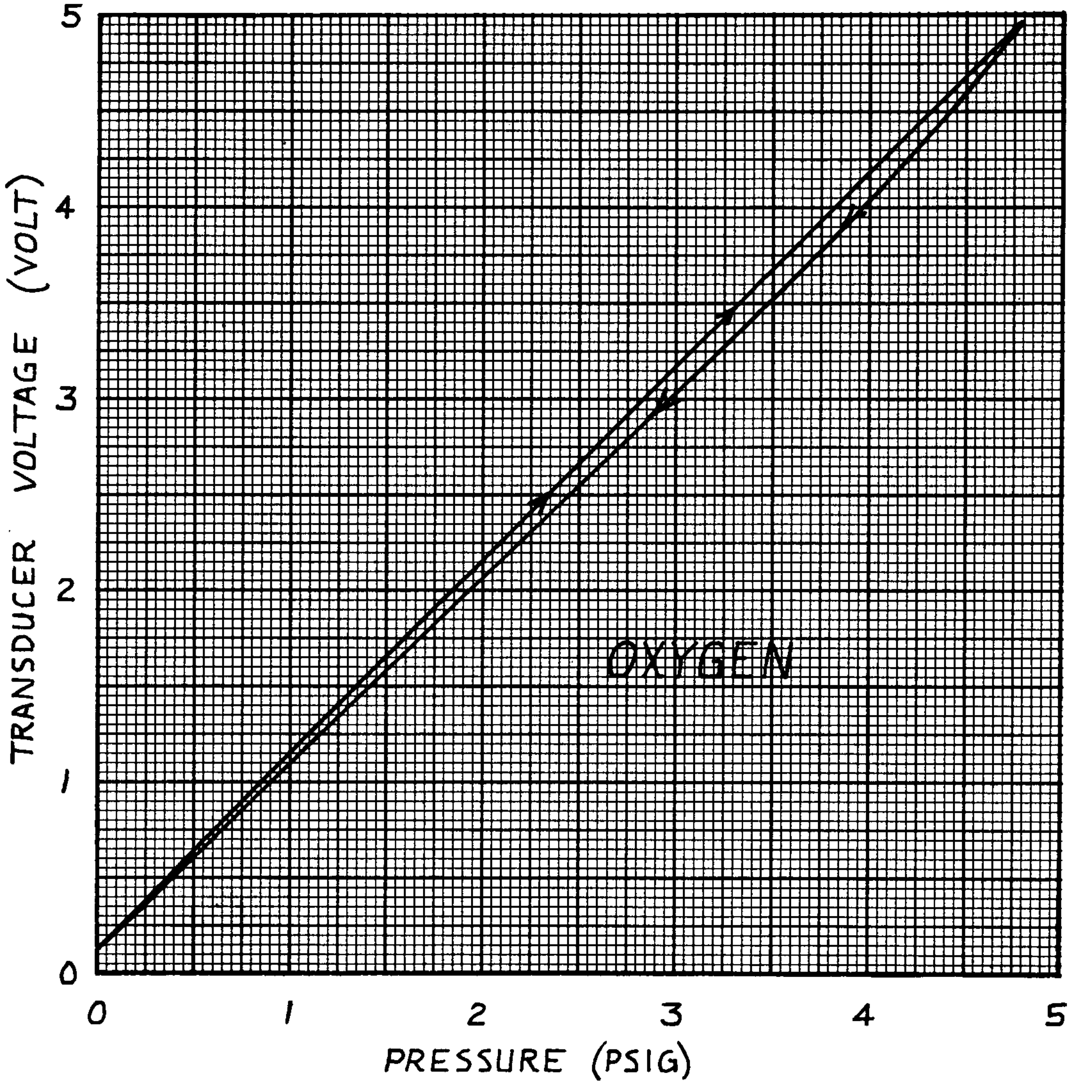


Figure 25 Oxygen Pressure Transducer Calibration Curve

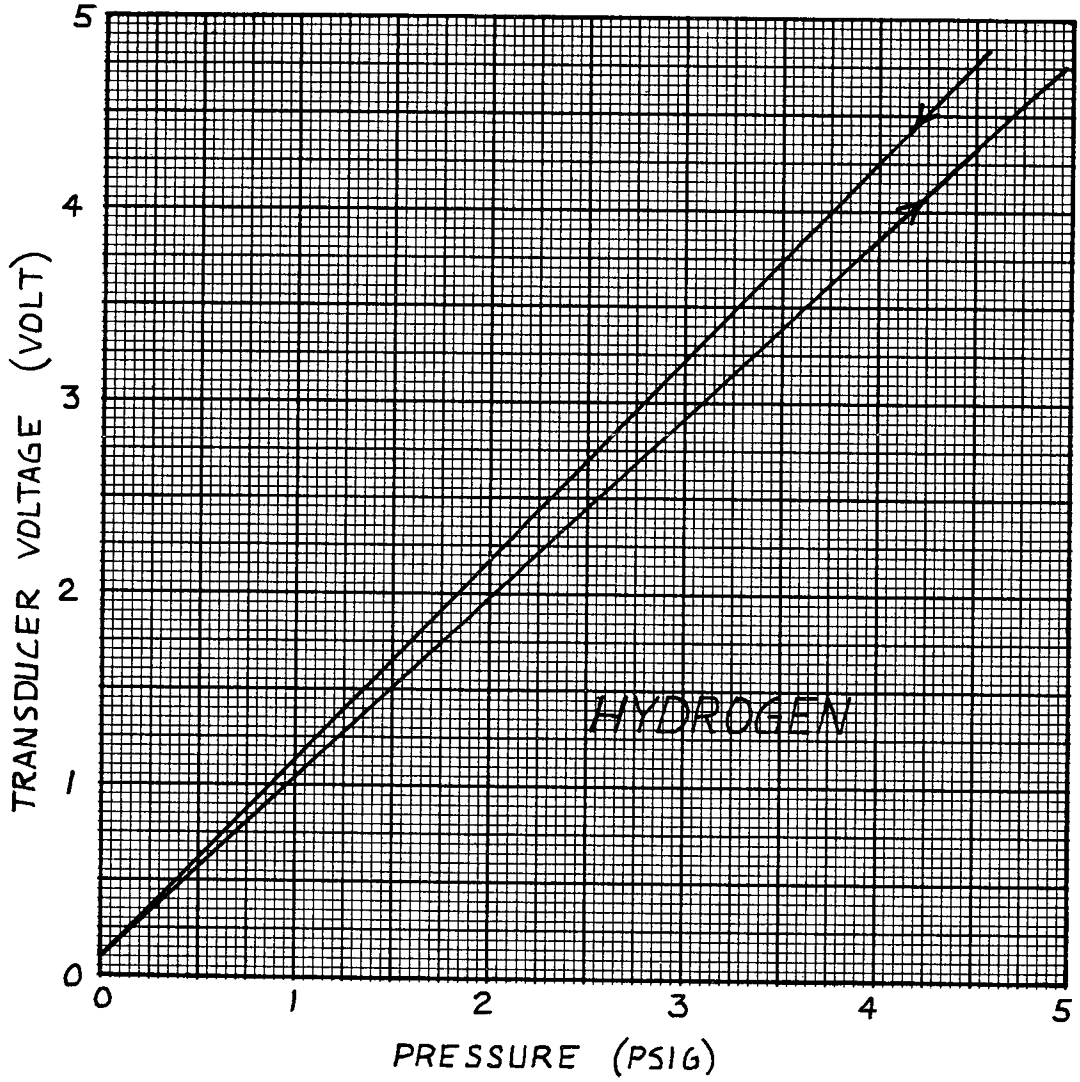


Figure 26 Hydrogen Pressure Transducer Calibration Curve

Results. Values given above were verified for the safety signal sources.

3.2.8 Hi/Lo and On/Off Signal Circuits

Conditions. Timing and duty cycles were measured.

Data Recording Requirements. Log book entries; no data sheets.

Values and Tolerances.

Timing	± 1.0 min.
Duty Cycle	variable

Results. Timing verified to be within ± 1.0 min.

3.2.9 Interface Instrumentation

Conditions. Continuity measurements were made of all signal interfaces at the connector.

Data Recording Requirements. Log book entries: pass or fail. No data sheets.

Values and Tolerances. None

Results. Continuity was verified.

3.3 FIRST FIFTY HOURS - SYSTEM TEST

The Electrolytic Oxygen Generator was operated for a total of fifty (50) hours in a shakedown test in preparation for the one hundred (100) hour acceptance test. All of the safety shutdown features were exercised twice. The automatic startup/shutdown feature was exercised a total of eighteen times. The test log is summarized in Table 6.

A number of minor problems in the wiring and circuitry were identified and corrected. Excessive cell voltages toward the end of testing were traced to a decrease in the KOH concentration. An additional twenty-four (24) hours of testing, starting with a fresh charge of the correct KOH concentration was conducted to investigate the cause of the problem. It was found that the all plastic heat exchanger was leaking from the tube to the shell side. A new Kynar-coated development model stainless steel heat exchanger was installed prior to the start of the 100-Hour Acceptance Test.

TABLE 6 - TEST LOG - FIRST FIFTY HOURS

Date	Time	Event/Action
9/8/71	1400	Auto-startup; operating with manual stimulus of high/low mode command.
	1605	Auto shutdown by simulating overtemperature on Module 1.
	1609	Auto startup.
	1800	Auto shutdown by simulating H_2 overpressure.
	1815	Auto startup.
	1915	Auto shutdown by stimulating high volume.
	1920	Auto startup.
	2020	Auto shutdown by stimulating low volume.
9/9/71	1525	Auto startup; operating with automatic high/low mode control.
	2200	Auto shutdown by stop switch to investigate problem in timer circuit.
9/10/71	0230	Auto startup; operating with automatic high/low mode control.
	0440	Auto shutdown by stimulating low volume.
	0445	Auto startup.
	0450	Auto shutdown by stimulating high volume.
	0455	Auto startup.
	0524	Switch to on/off control mode.
	1100	Auto shutdown by stop switch to correct water feed timer circuit problem.
	1101	Auto startup.

Table 6 - Test Log - First Fifty Hours (Con't).

Date	Time	Event/Action
(9/10/71 Cont'd)	1352	Auto shutdown by simulating overtemperature.
	1354	Auto startup.
	1400	Auto shutdown by simulating H_2 overpressure.
	1402	Auto-startup.
	1404	Auto shutdown by stop switch to correct problem in N_2 purge logic circuit.
	1619	Auto startup.
	2400	Switched to high/low mode control.
9/11/71	1220	Auto shutdown by stop switch to change temperature control point on heat exchanger.
	1620	Auto startup.
	1715	Auto shutdown by simulating H_2 detector signal. Vendor corrected a circuit problem in H_2 detector controls.
	1900	Auto startup.
	1905	Auto shutdown by stimulating H_2 detector.
	1906	Auto startup.
	2400	Auto shutdown by stop switch.
9/12/71	1445	Auto startup; operating with automatic high/low mode control.
	1520	Auto shutdown by stop switch to connect a loose wire on water feed circuit card.
	1555	Auto startup.
	1737	Auto shutdown by stop switch. Cell voltage high. KOH concentration $\sim$ 25%.

Table 6 - Test Log - First Fifty Hours (Con't).

Date	Time	Event/Action
9/13/71	1200	Replaced KOH with 30% solution.
	1348	Auto startup.
	1700	Auto shutdown by stop switch; 50-hour test completed.

3.4 100-HOUR SYSTEM TEST

3.4.1 Conditions. The final 100 hours were continuous hi/low mode operation. The testing was substantially the same as the acceptance test prior to the NASA-MDAC 90-day test. The hi/low mode timer was set for the nominal O_2 generation rate of 8.0 lbs/day. The test parameters for this run were the following:

System

Oxygen	Production		3.64 kg/day (8 lbs/day) nom.
	Purity (less H_2O vapor)		99.7% min.
	Admixed hydrogen		0.1% max.
	Discharge pressure		11.7 kN/m^2 (1.7 psig) nom.
Hydrogen	Purity		99.3% min.
	Admixed oxygen		0.2% max.
	Discharge pressure		11.7 kN/m^2 (1.7 psig) nom.
Voltage	Cell voltage		2.4 Vdc max.
	Module voltage		19.2 Vdc max.
Current	High mode		12.0 $\pm$ 1.0 A nom.
	Low mode		4.5 $\pm$ 0.5 A nom.
Safety Shutdown			
	Module temperature		40°C (104°F) max.
	O_2 Pressure		17.7 kN/m^2 (2.57 psig) max.
	H_2 Pressure		16.7 kN/m^2 (2.42 psig) max.
	High electrolyte		1.5 kN/m^2 (6 "H_2O) max.
	Low electrolyte		0.75 kN/m^2 (3 "H_2O) min.
	H_2 in cabinet		0.8% max.
	Power loss		----
	Module high current (module only)		20 A max.
Interface	Feed Water:	Temperature	ambient nom.
		Pressure	6.9 kN/m^2 (1 psig) min.
		Quality	commercial distilled nom.
	Coolant:	Fluid	ethylene glycol
		Temperature	7 $\pm$ 3°C
		Flow rate	6.3 x 10^{-5} m^3/sec (1 gpm) max.
	Nitrogen:	Pressure	207 kN/m^2 (30 psig) nom.
	Power:		115 Vac, 60 Hz
			208 Vac, 60 Hz, 3 Phase
	Pressure drop in discharge lines:		10.35 kN/m^2 (1.5 psig) max.

3.4.2 Data Recording Requirements. The interface instrumentation was automatically logged once an hour. The automatic data logging system consisted of an Electro-Instruments Model 881 digital voltmeter, output control, multi-channel crossbar scanner, and a paper tape printout. System status parameters other than those included in the interface instrumentation were recorded on data log sheets every hour.

3.4.3 Values and Tolerances

Interface Instrumentation - Automatic

	Range	Control or Limit
Cell voltage (64)	0 - 2.5 Vdc	
Module voltage (8)	0 - 20 Vdc	
O_2 Pressure	0-34.5 kN/m^2 (0-5 psig)	17.7 kN/m^2 (2.57 psig)
H_2 Pressure	0-34.5 kN/m^2 (0-5 psig)	16.7 kN/m^2 (2.42 psig)
Module temperature (4)	18 - 44°C	40° ± 1°C
Electrolyte temperature	18 - 44°C	25° ± 5°C
Cold Plate temperature	18 - 44°C	25° ± 5°C
Electrolyte temperature Control	18 - 44°C	30° ± 2°C
Reservoir pressure	0-2.07 kN/m^2 (0-0.3 psig)	1.10-1.15 kN/m^2 (0.16 - 0.166 psig)
Total current	0 - 75 A	
Module current (8)	0 - 20 A	20 A
Module on/off (4)	Off - 0/4 - On V	
Hi/low mode	Low - 0/4 - High V	
System On/Off Mode	Off - 0/4 - On V	

System Status - Manual

Feed Water:	Pressure	6.9 kN/m^2 (1 psig)
	Temperature	ambient
	Total quantity	initial-final volume
Coolant Supply Temperature:		7 ± 3°C
	Flow rate	6.3×10^{-5} m^3/sec (1 gpm) max.

H_2:	Volumetric flow rate	wet test meter
	Discharge line pressure	10.35 kN/m^2 (1.5 psig) max
	*KOH carry-over	liquid trap pH
	*Composition	99.3% (min.)
O_2:	Volumetric flow rate	3.64 kg/day (8 lbs/day) wet test meter
	Discharge line pressure	10.35 kN/m^2 (1.5 psig) max
	*KOH carry-over	liquid trap pH
	*Composition	99.7% (min.)
N_2:	Supply pressure	207 kN/m^2 (30 psig)
KOH:	Flow rate	0.63 x 10^{-5} m^3/sec/module (6 gph/module)
Electrolysis Power Input:		
	Volts, amps	panel meters
Low amp mode	Time	elapsed time meter
High amp mode	Time	elapsed time meter

*Water feed and KOH carry-over, total quantity: Gas sampling once every 24 hours.

3.4.4 Results

Operation. The 100-hour test was conducted during the period 1430 September 21 through 1830 September 25, 1971. Operation of the Electrolytic Oxygen Generator was completely automatic and continuous. There were no shutdowns and no operator adjustments of any kind made to the system during the test.

Voltage Current Data. The performance of the electrolysis modules during the test is presented in Figure 27. No significant change in performance was noted. Selected individual cell voltages and voltage ranges in high and low current are shown in Figure 28.

Gas Analysis. Gas samples taken daily were analyzed chromatographically for admixing. In the oxygen stream, no hydrogen was detected within the sensitivity limit of 0.05%. In the hydrogen stream, the oxygen content was measured to be less than 0.1%.

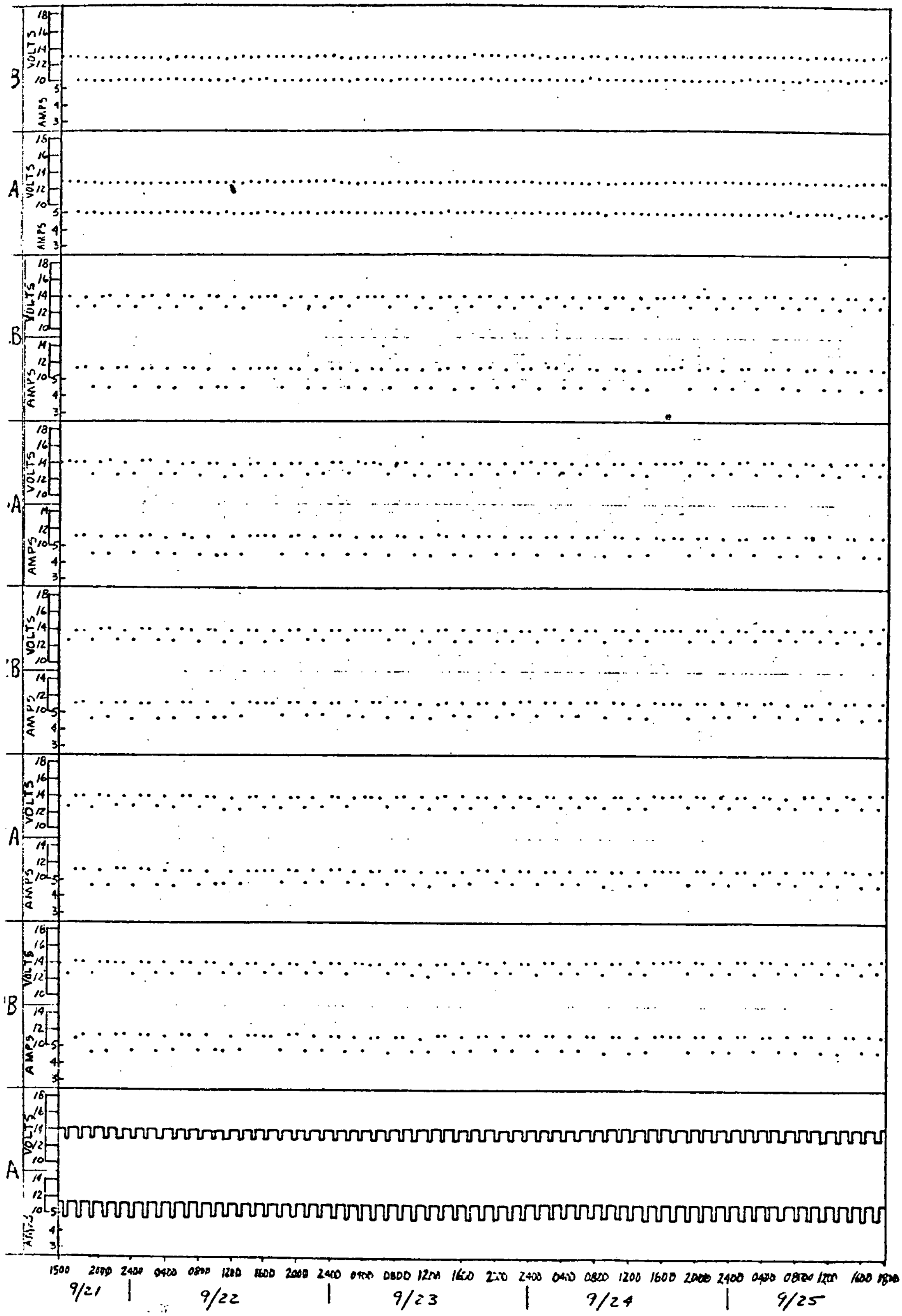


Figure 27 Module Voltage and Current Data
100-Hour Test

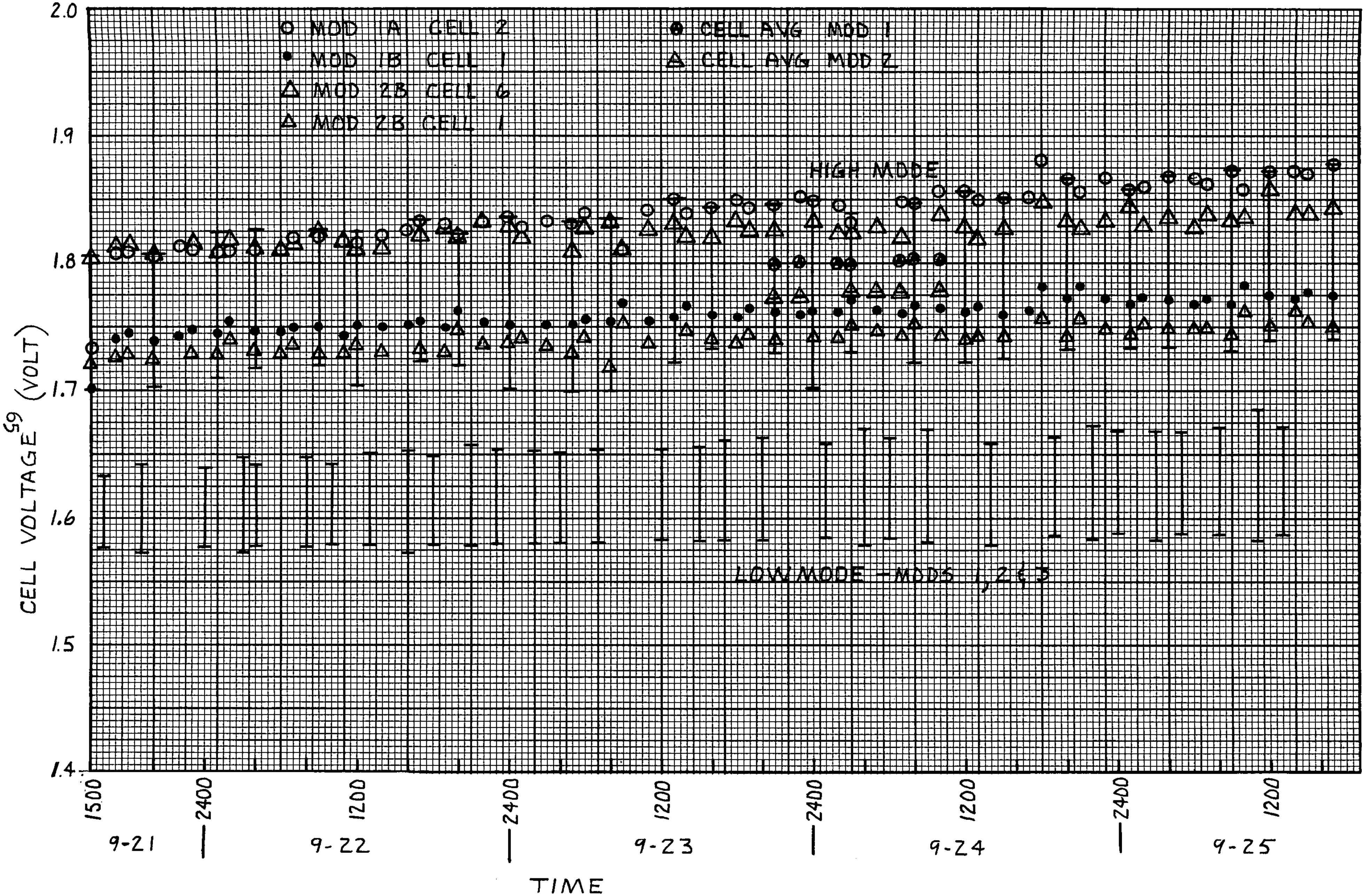


Figure 28 Cell Performance - 100-Hour Acceptance Test

Heat Exchanger Coolant Cycle. Cycle frequency of the coolant to the heat exchanger was monitored through several cycles in high current mode. The cycle was measured to be 1.0 minutes "on" and 4.0 minutes "off", or a 20% duty cycle.

Current Readout. Noise measurement was performed on the current monitors at the interface instrumentation connector with these results:

	At Data Logger	At Unit
Total current (low mode)	60 mv pp	18-30 mV
Module 1A (low mode)	40 mv pp	12-13 mV

The noise on Module 1A current monitor at the interface contains a symmetrical ~ 330 H_z sine wave of ~ 20 mV pp amplitude. Source of this signal is unknown. However, since it is symmetrical, a dc reading meter will average this signal to zero and should have minor effect on the readout measurement.

Water Consumption. The total water consumption was determined by delta volume measurement at the end of the test. A total of 17.2 $\times 10^{-3}$ m^3 of water was consumed in the 100 hours. Without correcting for losses by evaporation in the effluent gases, this value indicates approximately 100% current efficiency for the electrolysis modules. However, the wet test meter data indicate that the current efficiency is closer to 98%.

NOTE: The hydrogen wet test meter readings are 10% low. This was determined in a calibration of the O_2 and H_2 meters after the test was completed.

KOH Carryover. Measurements of pH in the O_2 and H_2 discharge water bubblers before and after the 100-hour test indicated no KOH carryover during the test.

KOH Concentration. A sample of the solution of KOH which was used to charge the system and a sample removed from the system at the end of the test were analyzed with the following results:

	KOH	K_2CO_3
Initial	6.7 M	0.21 M
Final	7.07 M	0.30 M

Data Logger Printout. The data logger used in the 100-hour test to record interface data did not operate completely satisfactorily. Some channels in the printout show random extraneous signals. The current readings were not acceptable because of noise generated in the data logger. Current readings were taken manually once an hour from the front panel ammeter.

3.5 PREPARATION FOR DELIVERY

At the conclusion of the 100-hour acceptance test, the Electrolytic Oxygen Generator was prepared for shipment to McDonnell-Douglas. The following actions were taken:

- The electrolyte was drained from the system.
- Interface plumbing lines for N_2 supply, oxygen and hydrogen discharge, vent, coolant in and out, and water supply were disconnected; the interface connections were capped.
- Manual valves for heat exchanger and cold-plate coolant, and N_2 purge valves were closed.
- Interface electrical connectors were unplugged and the junctions capped.

Section 4

INSTALLATION AND CHECKOUT

The Electrolytic Oxygen Generator was installed in the bench test facility at MDAC, Huntington Beach, California. The system was operated for approximately 160 hours for checkout purposes. The first half of the testing was devoted to preliminary operational and interface checkout. A Test Readiness meeting was then held with the NASA Test Committee to review and document the results and necessary corrective actions. Test Committee approval was obtained to proceed with the 80-hour Checkout Test required before start of the 182-Day Test. At the conclusion of this checkout period, a second Test Readiness meeting was held to define problem areas and corrective actions necessary before formal test start.

The following paragraphs discuss the problems identified in the Checkout Testing and committee meetings, and the corrective actions which were taken.

4.1 TEST READINESS MEETING #1

The first test readiness meeting was concerned with the review of applicable documents, e.g., circuit diagrams, instruction manual, safety review report, and acceptance test report, review of the preliminary testing and interface compatibility and documentation of action items required before proceeding with the final 80-hour checkout test. The following were the items noted and the actions that were taken prior to the final 80-hour checkout run and Test Readiness Meeting #2.

1. The LMSC local representative was designated as the only one authorized to operate and maintain the Electrolytic Oxygen Gemerator.
2. Final as-built and as-tested updating of the Checkout Test Report, Instruction Manual, and Configuration Drawings were prepared.
3. The thermister identified as EL #1 and used to control the coolant supply to the electrolyte heat exchanger was malfunctioning and had to be replaced. Visual inspection of the failed unit indicated that the failure probably resulted from damage to the

thermister element during processing at LMSC.

4. Excessive noise in the LMSC current instrumentation to the MDAC data logger was encountered. Additional filtering was added to the LMSC unit instrumentation, which improved the module current readings but not the total current reading. It was decided to eliminate the total current signal.

Approval was given at TRM #1 to conduct the 80-hour Checkout Run of the LMSC unit.

4.2 TEST READINESS MEETING #2

The Electrolytic Oxygen Generator was subjected to an 80-hour Checkout Run which was accomplished successfully with no shutdowns. Problems identified during the test and corrective actions taken subsequent to the test were the following:

1. Chatter in the heat exchanger coolant solenoid valve was corrected by increasing the hysteresis of the thermister signal.
2. The oxygen 3-way solenoid valve was sticking occasionally. The duration of the current pulse to actuate the valve was increased. Since there are four valves electrically in parallel in this circuit, a mechanical malfunction of the O_2 valve was suspected. The valve was disassembled for inspection; no visible cause for sticking was evident. It was agreed with NASA to replace the 3-way valves later in the testing if the problem re-occurred.
3. Occasional flickering of the current mode indicator lights on the front panel was observed. The problem was attributed to electronic noise; addition of a filtering capacitor to the appropriate circuit eliminated the problem.
4. A slow leak was detected around the threads of a stainless steel reducer bushing on the heat exchanger. When the bushing was installed at Lockheed, excessive torque was required because the tapped hole in the heat exchanger header was out of round. It was, therefore, decided to seal the bushing with epoxy rather than to try applying additional torque.

5. A MDAC power supply was tested and found to be a suitable backup for the Lockheed power supply.
6. When the system was operated at the 10 lb/day rate, it was found that a setting of 97 minutes high mode on the "100 minute timer" did not provide the desired 3 minutes of low mode, i.e., the unit remained in high mode all the time. A minor adjustment to the 100-minute timer circuit was made.

The following were additional items noted at TRM #2.

1. Cell 2 in Module 1A was consistently running at a higher voltage than all other cells. It was agreed that 2.5 volts would be the cell voltage limit at which the Test Committee Chairman would be notified to examine possible operating changes.
2. Some drift in current settings was observed during the 80-hour checkout run. Module 4B in particular drifted from the 4.5 A initial setting and stabilized at 6 A. It was agreed to leave the module at this setting for the 182-Day Test.
3. A digital voltmeter calibration schedule for the panel ammeter and the pressure transducers was established.
4. Updating of documentation was made a requirement to reflect changes made in the electronics.

Approval was given at TRM #2 to start the 182-Day Test of the Electrolytic Oxygen Generator.

Section 5

182-DAY TEST

5.1 TEST OUTLINE

The test program was structured to subject the electrolysis system to the nominal design point load, 3.63 kg/day (8 lbs/day) for the first 13 weeks to approximate the essential conditions and requirements of the 90-Day Test. The second half of the test program was intended to explore off-design conditions. The operating modes of the test are shown in Figure 29.

A major groundrule of the test was a "hands-off" philosophy to approximate NASA operational usage by crewmen or relatively unskilled operators in a remote location. A test committee composed of the contractors involved and three NASA development centers, the Manned Spacecraft Center (MSC), the Langley Research Center (LRC) and the Ames Research Center (ARC), controlled the proceedings of the test program. The committee was chaired by MSC. Test committee management was used to pool capabilities and to allow interchange of ideas in the event that changes in operating conditions or hardware were indicated.

5.2 OVERALL SYSTEM PERFORMANCE

The Electrolytic Oxygen Generator operated for 160 days, cumulative, during the 182-Day Test period. This corresponds to an 88 percent on time. A summary operational status is shown in Figure 30. A detailed system status with explanatory notes is included in Appendix A. The longest period of completely uninterrupted operating time was the last 53 days of the test. When the unit was stopped on the last day of the test, it was operational with no indication of trends toward failure. All of the operating conditions of the test were met. There were no interface problems and no cell or module failures of any kind. Most of the downtime resulted from troubleshooting of electronics problems.

Week of Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Oxygen Production	3.63 kg/day													2.14 kg/day	3.63 kg/day	2.14 kg/day	3.63 kg/day		4.55 kg/day					3.63 kg/day		
Operating Mode	Continuous													Orbital	Continuous	Orbital	Continuous									

Duty Cycles

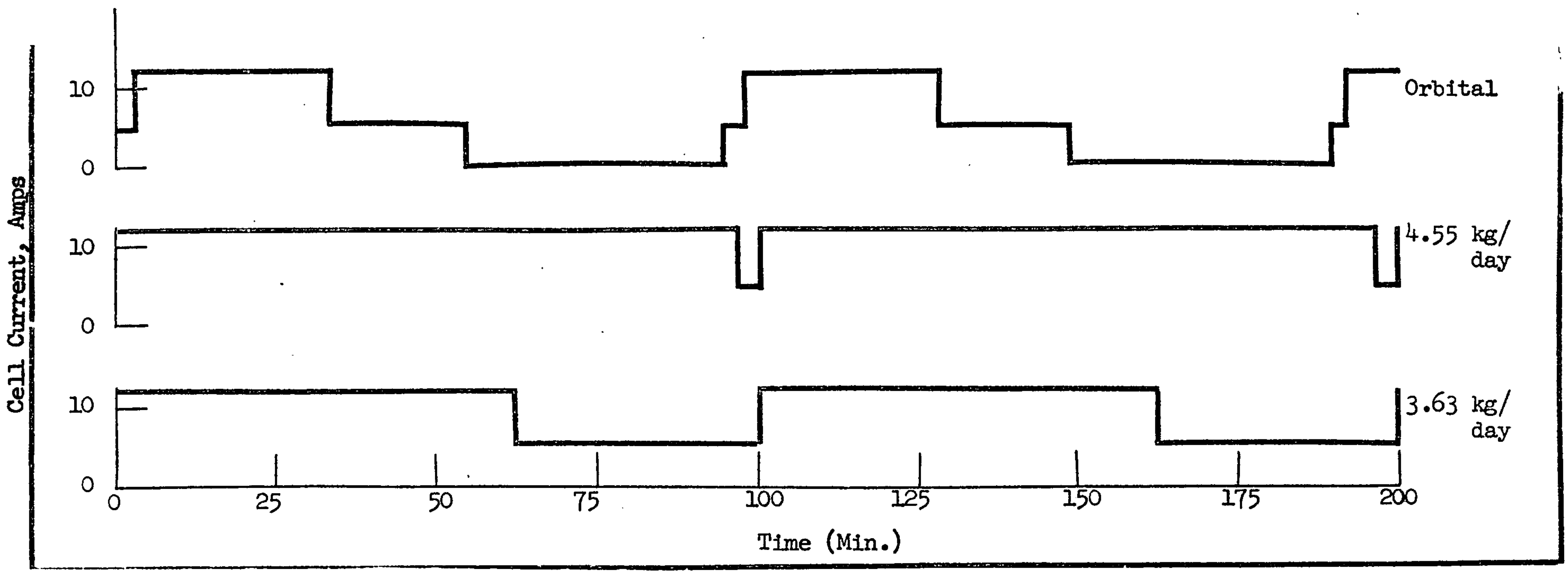


Figure 29 182-Day Test Operating Modes

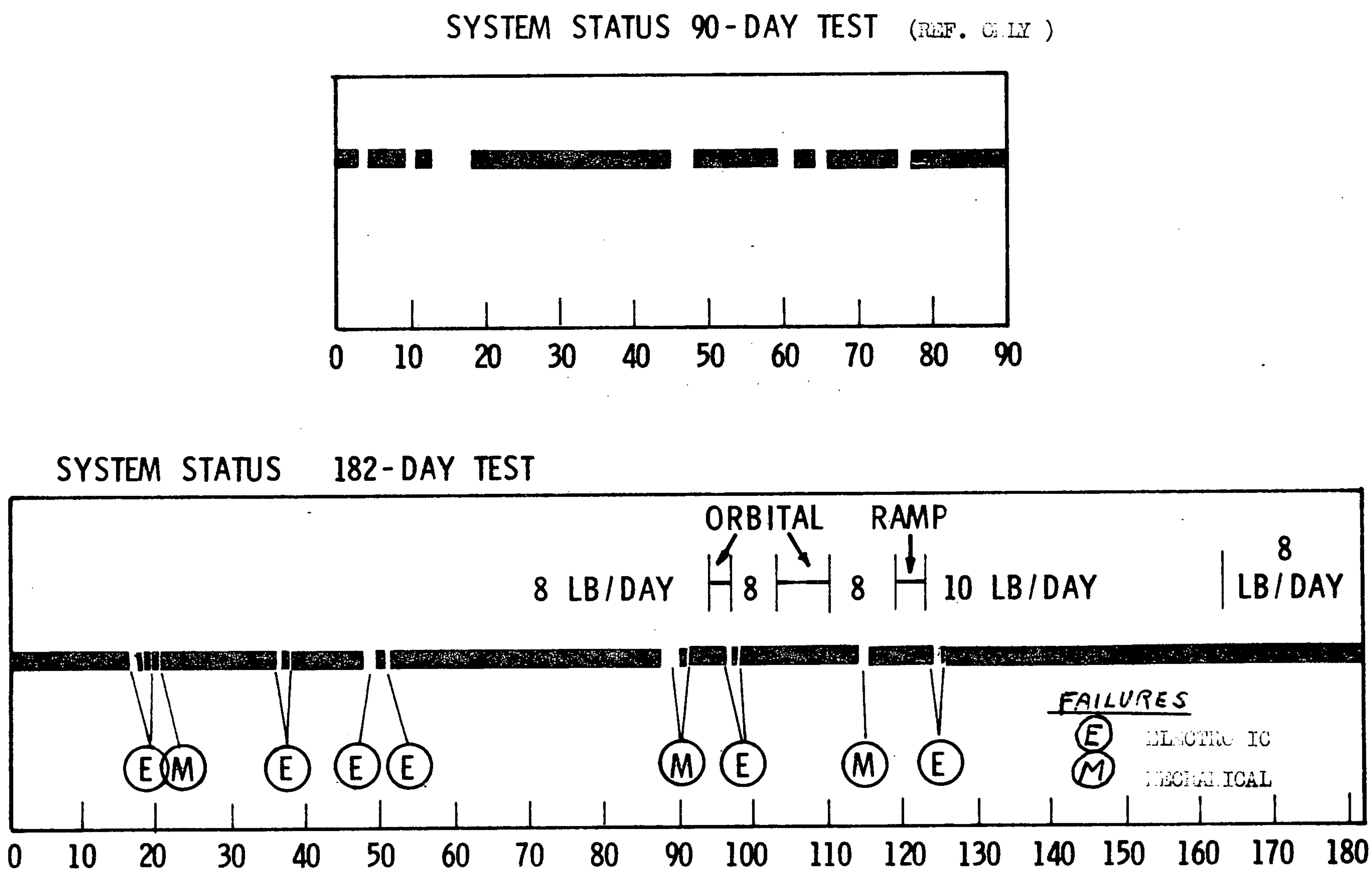


Figure 30 Operational Status - 182-Day Test

5.3 PERFORMANCE DATA AND ANALYSIS

5.3.1 Electrolysis Module Performance

A summary plot of voltage/current data for all of the electrolysis modules is shown in Figure 31. (More detailed plots are included in Appendix A). Values shown are weekly averages in high current mode except for Module 4, which remained in low mode. Note that discrete data points have been spanned with continuous lines for the purpose of illustration of trends; in actual operation, the current was cycling high/low/off (12/45/0 A) depending on the test condition. During the first 13 weeks of the test, the high current mode duty was 62% of a 100-minute cycle. Orbital (on/off) operation occurred from the middle of the 15th to the middle of the 16th week. The oxygen output was ramped from 3.63 to 4.55 kg/day in 0.23 kg/day increments during the 17th week. The 4.55 kg/day rate was maintained for five weeks (19th-23rd). The last three weeks of the test, the oxygen output was reduced back to the nominal 3.63 kg/day.

It is apparent from Figure 31 that the electrical performance of all of the modules was stable, regardless of test conditions. Some fluctuation in current is evident with Module 4B showing the greatest variation, but in no case is the current out of control. All of the module voltages show a slight upward trend. The effect is most pronounced in Module 1 containing the experimental anodes. The effect of the voltage increase on system power requirements is discussed in Section 5.3.2.

The experimental anodes in Module 1 were strictly of development status. Each one was handmade in the laboratory without formal process specifications. Therefore, quality control and uniformity were difficult to achieve. The only standard which was established was an arbitrary maximum of one percent organic extender residue after post treatment, as determined by thermo-gravimetric analysis (TGA).

Processing and performance data for these electrodes are given in Table 7. The electrodes are numbered in the sequence in which they were made. The cell number in Module 1 in which each was used during the 182-Day Test is indicated. Electrical performance at the beginning,

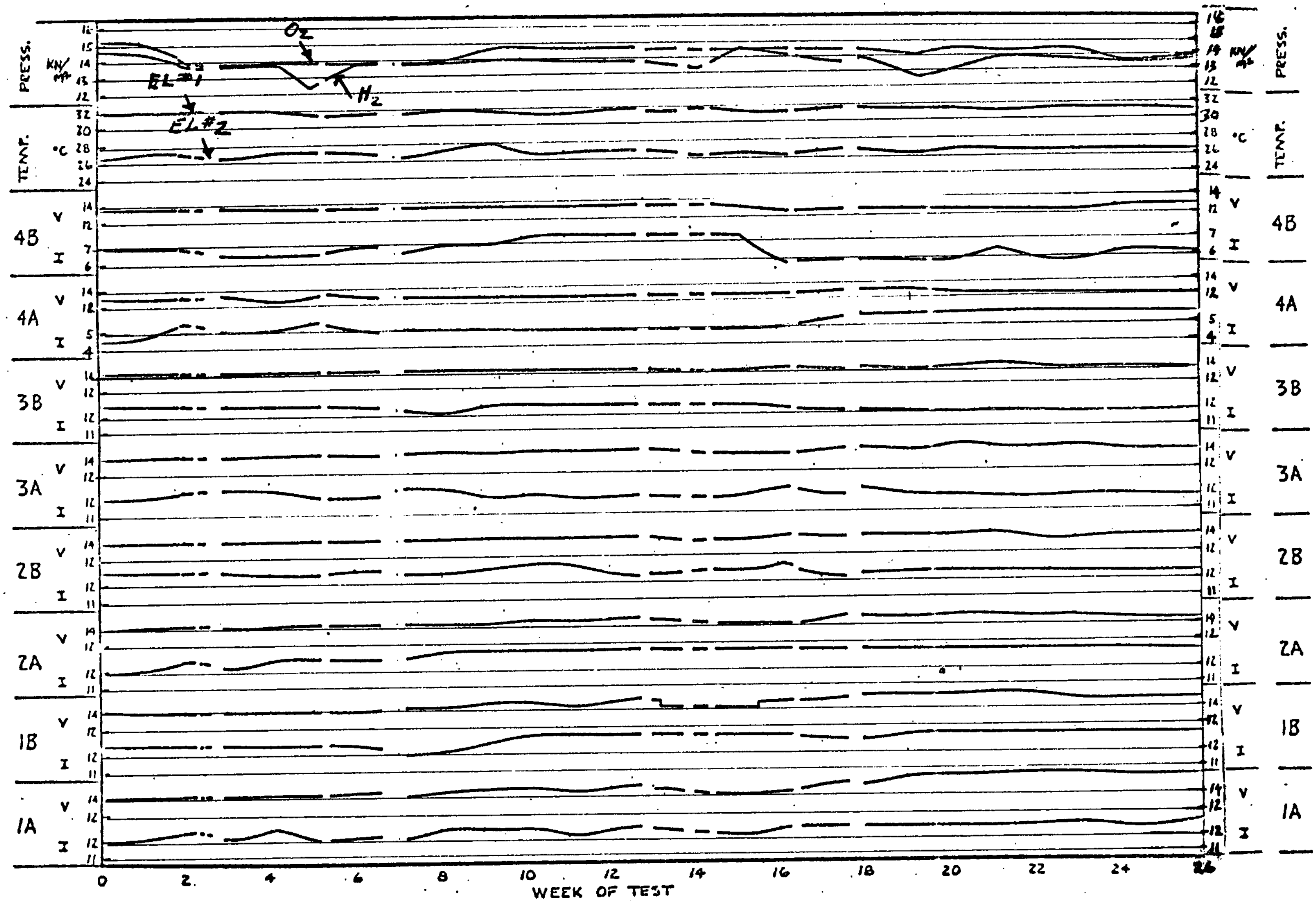


Figure 31 MODULE PERFORMANCE - 182-DAY TEST

Table 7

Experimental Electrode Data

Electrode Number	Cell No.	Cell Voltage: Week 1 (A-12.4 Amp B-12.6 Amp)	Cell Voltage: Week 12 (A-12.6 Amp B-13.0 Amp)	Cell Voltage: Week 26 (A-12.9 Amp B-13.5 Amp)	TGA %	No. Of Leachings
1					1.00	3
2					0.90	3
3	4A	1.799	1.864	1.962	1.00	3
4					0.95	2
5					0.90	1
6	8B	1.825	2.065	2.156	0.60	3
7	7B	1.762	1.839	1.997	0.50	1
8	2A	1.846	2.049	2.399	0.95	4
9					--	-
10					0.50	1
11	7A	1.783	1.856	2.010	0.80	2
12					--	-
13					0.76	1
14	3B	1.774	1.854	1.997	1.00	2
15	8A	1.783	1.862	1.930	0.70	2
16					1.00	3
17	2B	1.813	1.860	1.928	0.95	3
18	5B	1.752	1.803	1.893	0.83	1
19	6A	1.783	1.868	2.108	0.90	3
20	1A	1.801	1.831	1.848	0.98	1
21	6B	1.795	1.841	1.901	0.90	1
22	3A	1.785	1.819	1.829	0.80	1
23	1B	1.819	1.850	1.872	1.00	1
24	5A	1.783	1.823	1.877	0.60	1
25	4B	1.758	1.801	1.854	0.90	1

middle, and end of the test in high current mode is presented. The last two columns of data show the TGA analysis and the number of post-treatment operations that were required to reach the acceptable TGA level of 1.0%. There appears to be no correlation between TGA percent residue and the electrical performance in this range. Cell 2A, containing electrode #8, exhibited the highest voltage, which may have resulted from mechanical degradation in post-treatment. This electrode required 4 leachings, more than any other electrode, to reach the TGA standard.

It is also apparent that a "learning curve" was involved. The last six electrodes in the series showed a very consistent voltage grouping which was probably the result of gradual improvements in the processing and post-treatment techniques.

A summary plot of electrical performance of Cells 2A and 2B is shown in Figure 32. Evident in this Figure is the typical large voltage increase during the first few hundred hours of continuous operation, recovery to approximately the initial voltage after shutdown, and eventual stabilization at a voltage level characteristic to that particular electrode. For Cell 2A, the "stable" voltage was approximately 2.4 volts and for 2B, the stable voltage was approximately 2.0 volts.

5.3.2 Energy Requirements

The energy requirements of the system at various operating conditions and as a function of time, are shown in Figure 33. The lower curve shows the energy per kilogram of oxygen required by the electrolysis modules. The increment added for the power controllers is represented by the middle curve and shows a 70-75 percent conversion efficiency for these devices. The upper curve is the total energy expended per kilogram of oxygen and includes accessory input for solenoid valves, light bulbs, control logic circuits, and the electrolyte pump.

Module performance degradation at 3.53 kg/day showed a rate of approximately 5 percent with Module 1 included and only 2 percent without Module 1. Performance degradation rate at 4.55 kg/day was not substantially different from the 3.63 kg/day rate. However, the specific module energy consumption was approximately 5 percent higher. Module energy requirements

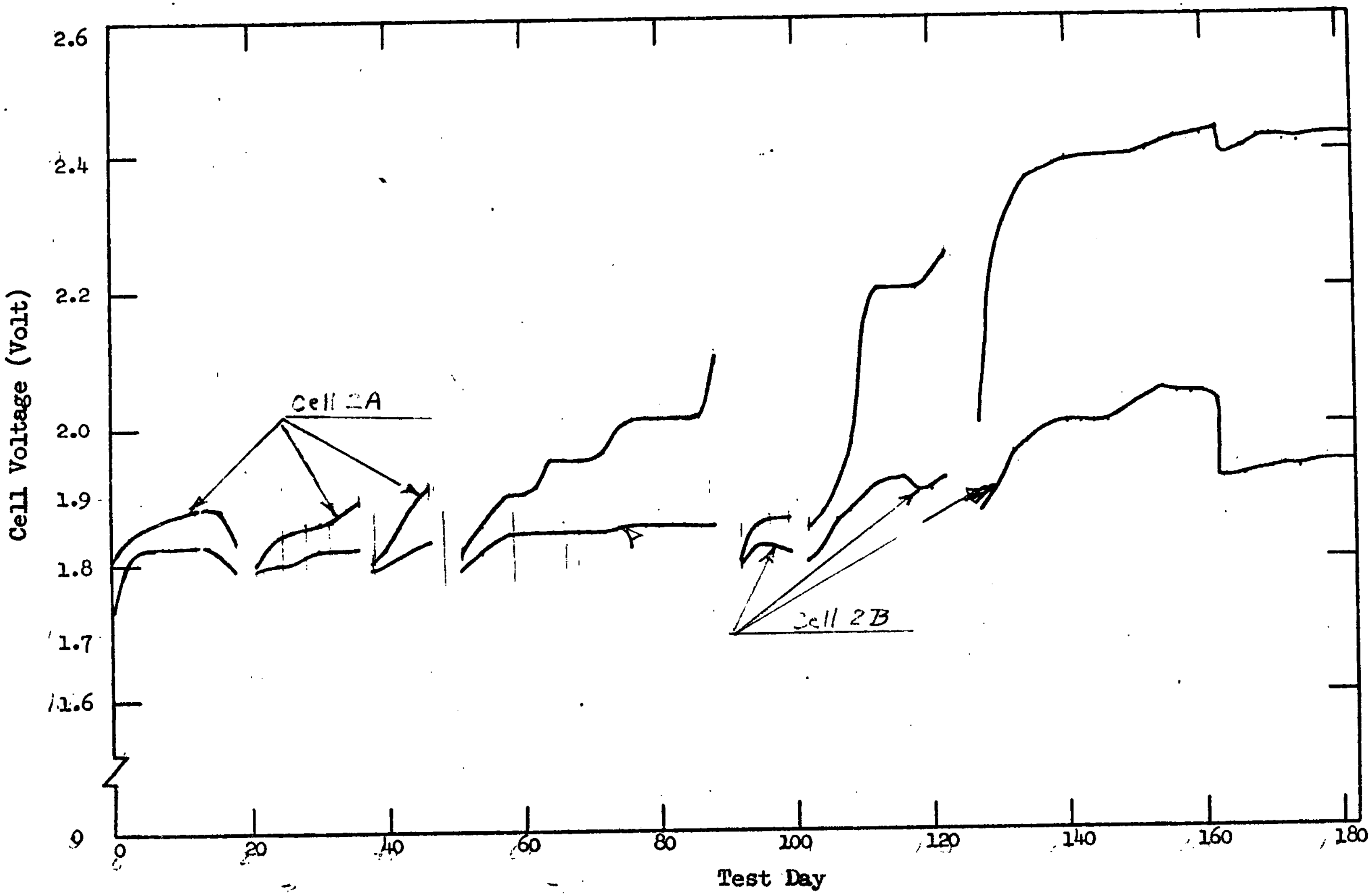


Figure 32 Performance of Cells with Experimental Anodes, Upper Curve Cell 2A, Lower Curve Cell 2B

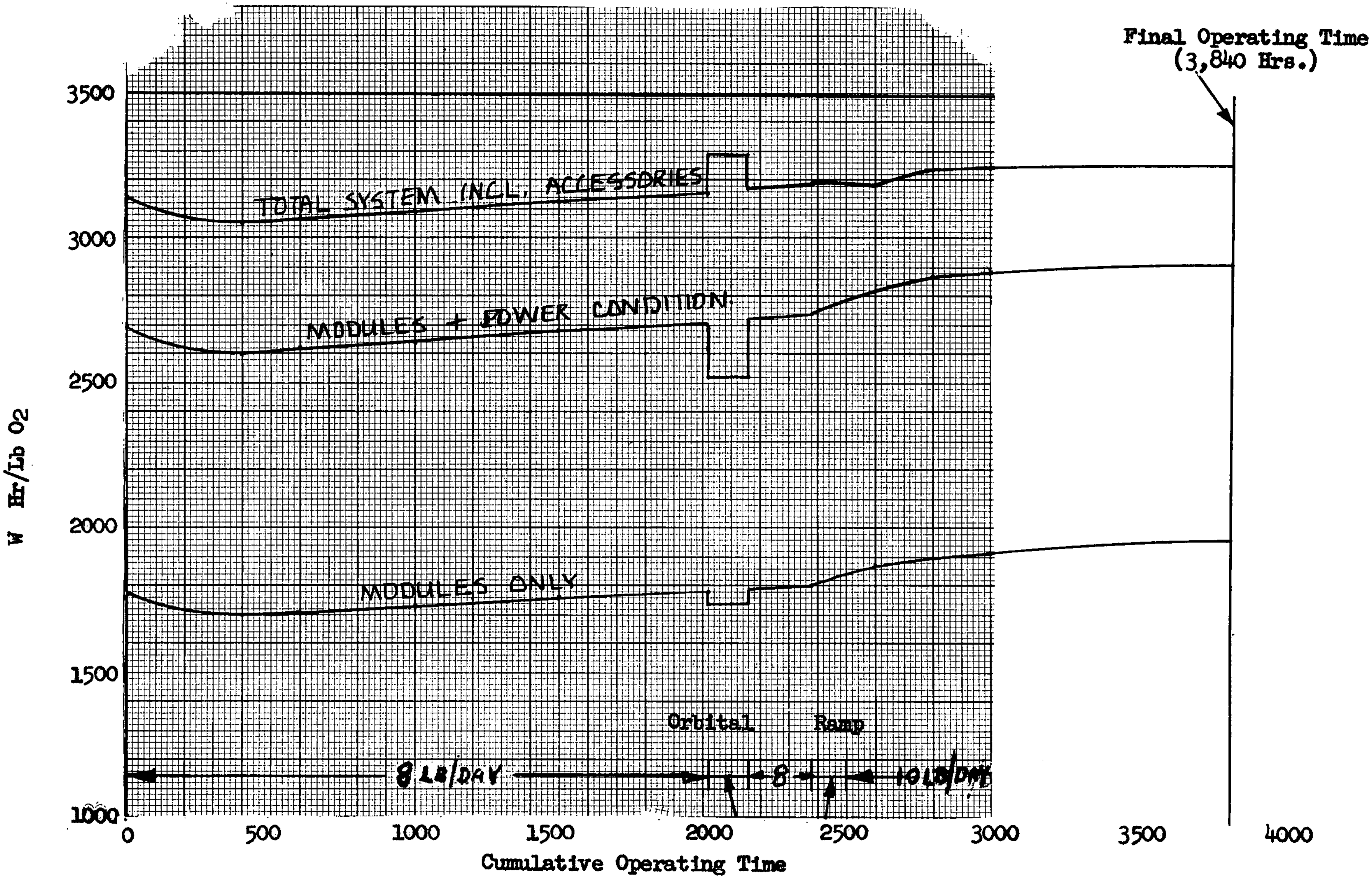


Figure 33 System Energy Requirements

were lowest for orbital operation and no performance degradation was observed. Higher total energy requirements during orbital operation resulted because the system had not been optimized for this mode of operation, i.e., a number of accessories had to be left energized during the off-periods which would not be required in a properly designed spacecraft system.

There was no requirement in the test to accurately monitor accessory power usage. The power contributions of the individual accessory groups shown in Figure 33 are therefore approximate, based on panel meter readings for the 28, 15, and 5 VDC power supplies and merely a "best" estimate for the 115 VAC electrolyte pump motor.

Test data were used to determine the efficiency of the power controllers in converting constant 30 VDC input power to constant current output. The data consisted of weekly average module current/voltage values and 30 Vdc power supply panel meter readings of input voltage and current. The computed power conversion efficiency decreased gradually during the test from early values of 73-75 percent. The power supply panel meters were recalibrated at the conclusion of test and a 4 percent increase in ammeter readings was found. Applying this correction to the final power conversion efficiency values results in corrected values of 73-75 percent. This indicates that there was no significant change in this efficiency as a function of time.

5.3.3 Current Efficiency

Current efficiency is a measure of the percentage of the applied electrolysis current which produces oxygen and hydrogen. The inefficiency is that portion of the applied current which is shunted through the electrolyte manifolds to adjacent cells and does not, therefore, produce the desired electrolysis reaction. The magnitude of the shunt current is a function of the electrical resistance of the shunt path, which is fixed by the cell geometry and the cell voltages, which vary with input current.

Current efficiencies computed from O_2 and H_2 wet test meter data and module currents on a weekly average basis are shown in Figure 34. The module energy requirements shown previously in Figure 33 are co-plotted to illustrate the voltage effect on efficiency. Note that at fixed input current corresponding to a Faradaic 3.63 kg/day of oxygen production, the current efficiency varies inversely with energy required per kilogram of oxygen, i.e., for a fixed oxygen rate, the current efficiency decreases as voltage increases due to the increase in shunt current. It is also evident that, as would be expected, increasing the oxygen output to 4.55 kg/day increases the current efficiency. This results from the fact that the 25 percent increase in total current results in only a 5 percent increase in cell voltages.

5.3.4 Orbital Operation

A significant result of the test program was the simulated orbital operation of the system for one week of the test (weeks 15-16). The external timer provided a simulated orbit duty cycle of 55 minutes on (sunlit portion of the orbit) and 39 minutes off (shadow portion of the orbit). Duty cycles for high/low/off were presented in Figure 29. During the one-week orbital mode test period, 120 orbits were simulated, thereby subjecting the system automatically to 120 changes from zero up to maximum oxygen production and 120 step changes from low mode current to zero. During the off period, nitrogen purge was automatically provided to maintain gas/liquid differential pressure in the modules and power to the accessories and safety circuits was maintained. No module performance degradation during the orbital period was evident. This result is significant in that it is at least a preliminary indication that substantially more stable performance in orbital mode than in continuous mode could be expected for a long duration mission.

The orbital test period successfully demonstrated the instant start/stop capability of the circulating electrolyte type electrolysis cells, a capability which is necessary for orbital operation. A typical orbit cycle is presented for Module 1 in Figure 35, using one-minute data from the MDAC data logger. Complete plots are given in Appendix A.

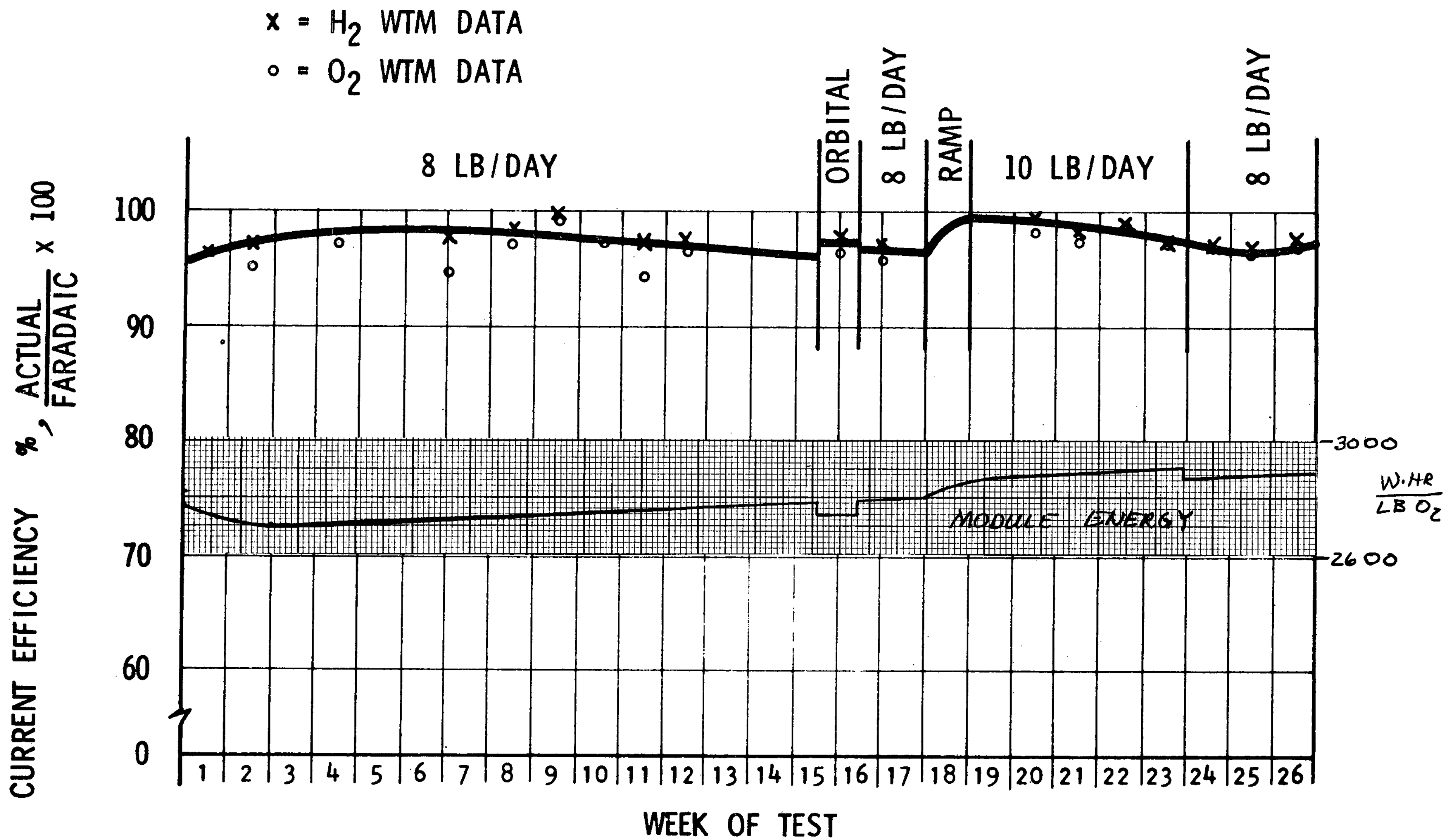


Figure 34 Electrolysis Current Efficiency
Module Energy Co-Plotted

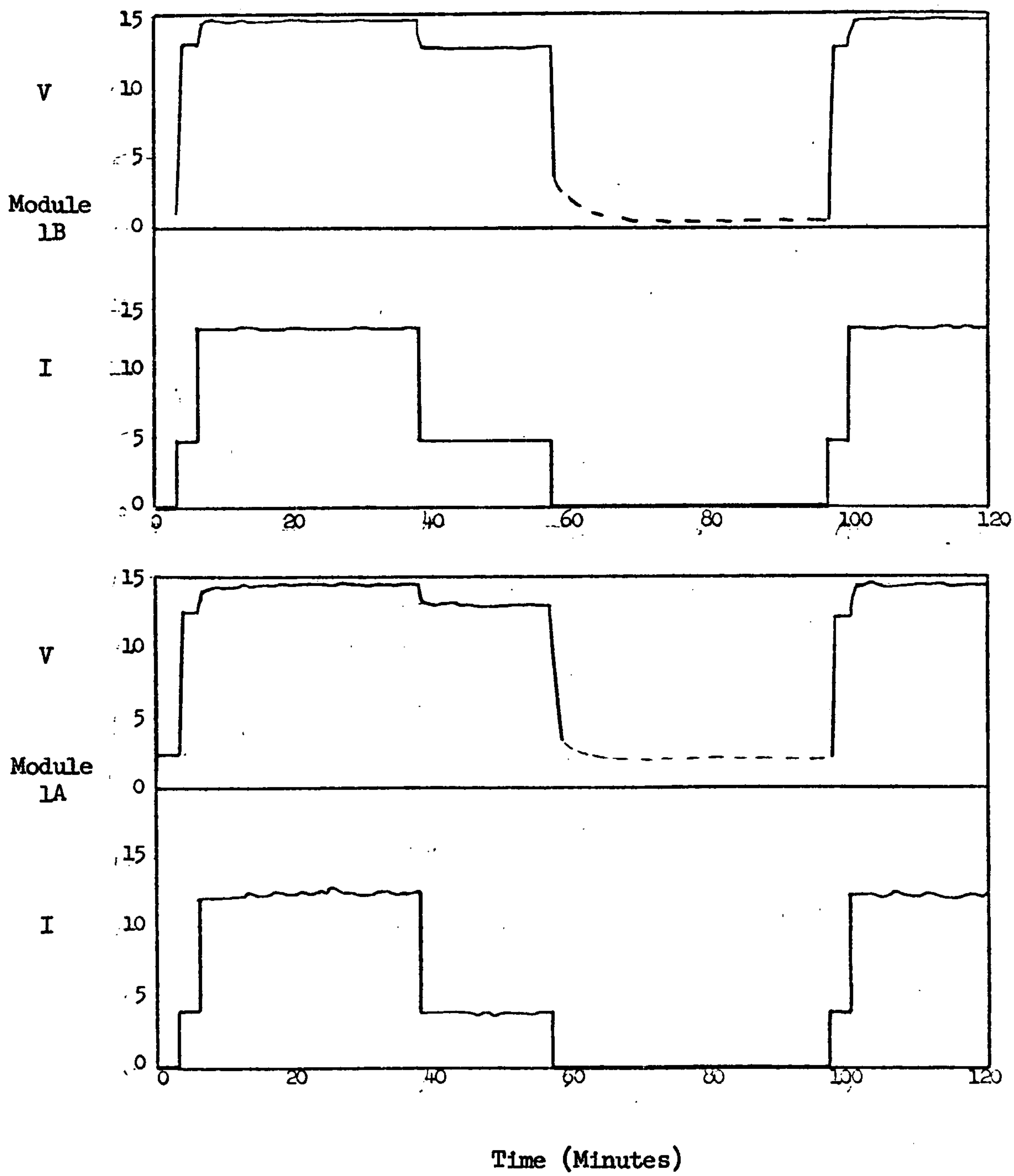


Figure 35 One Minute Data for One Period of Orbital Operation

5.3.5 Gas Bubbler and Analyses

Oxygen and hydrogen gases generated by the system were vented during the test to separate bubblers, each containing approximately 300 cc of water. Because the system was operated slightly above ambient temperature, the oxygen dewpoint was above ambient, and water condensed in the oxygen bubbler as the gas cooled. This necessitated periodic removal of liquid to maintain the 300 cc bubbler liquid volume. The hydrogen gas dewpoint was always below ambient and resulted in evaporation of water from the hydrogen bubbler. This required periodic addition of water to maintain the initial 300 cc bubbler liquid volume.

Samples were taken from each bubbler once or twice a month during the test for pH measurement by MDAC personnel. The results of the analyses are given in Table 8. The initial pH of the water in both bubblers is assumed to have been approximately 7.0. This assumption implies that an initial, large increase in pH occurred during the first two weeks of the test. The pH in both bubblers leveled off after this period with only minor variations apparent for the remainder of the test. The fact that liquid was periodically removed from the oxygen bubbler and water periodically added to the hydrogen bubbler complicates the assessment of these pH data in determining KOH carryover in the generated gases.

The following possible interpretations of the bubbler analyses data appear most reasonable.

Oxygen Bubbler. A total of 1430 cc of liquid was removed from the oxygen bubbler during the course of the test. Assume that, as a worst case, all of the liquid removed was at the highest pH and that the pH in the bubbler was being maintained by continued carryover of KOH in the generated gas. The amount of KOH contained in 1430 cc of water at pH = 12 is approximately 0.8 gm. This would represent a KOH carryover rate of 5 mg/day based on 160 days of operation. The most probable source of this small amount of KOH would be residue left in the gas passages and manifolds of the cell spacers when the module parts were cleaned and re-assembled at LMSC.

Table 8

Gas Bubbler Analysis Results

Date	pH	
	O_2 Bubbler	H_2 Bubbler
9 November 1971	10.50	9.30
15 November 1971	10.60	9.25
22 November 1971	11.40	9.75
23 December 1971	10.70	9.45
18 January 1972	11.80	9.50
31 January 1972	11.85	9.30
15 February 1972	11.60	8.70
13 March 1972	11.05	8.70
12 April 1972	10.50	8.80
25 April 1972	10.50	8.90

Hydrogen Bubbler.- The hydrogen gas, being generated very dry, would be expected to have less tendency than the oxygen to carry over any KOH residue left in the gas manifolds. Assume that all liquid removed from the hydrogen bubbler was, at a worst case, at a pH of 10. A total of 250 cc of liquid was withdrawn for pH measurement during the test. This is equivalent to 1.4 mg of KOH or 0.009 mg/day carryover rate. All of the additions of water to the bubbler to replace that lost by evaporation are assumed to have been distilled water (pH 7). Since these additions always brought the liquid volume back to the original level, they could not have contributed to any change in bubbler pH unless the water used was contaminated.

5.3.6 Gas Analysis Data

Samples of both the product oxygen and hydrogen streams were taken periodically for analysis by MDAC personnel. The analysis data are shown in Table 9. Sampling and analysis techniques were not indicated nor were limits of detectability given. On the hydrogen side, 85 percent of the samples showed O_2 present at less than 0.1 percent, which is in agreement with the results of analyses conducted at LMSC during acceptance testing. The organic contaminant detected in Tests 3 and 4 was identified as mineral oil. Its presence resulted from using new solenoid valves which had not been cleaned. No further evidence of this contaminant was apparent in the December samples, indicating that the valves had purged clean over this period of time.

TABLE 9

PRODUCT GAS SAMPLE DATA

Test Number	Date	Product O_2			Product H_2		
		N_2 %	H_2 %	Organic	N_2 %	O_2 %	Organic
1	3 Nov 71	N [1]	N	N	N	N	N
2	11 Nov 71	N	N	N	N	N	N
3	24 Nov 71	N	N	2	1.75	0.15	2
4	8 Dec 71	0.1	N	3	0.4	0.07	4
5	23 Dec 71	N	N	5	N	N	5
6	6 Jan 72	0.05	N	N	0.71	0.13	N
7	19 Jan 72	N	N	N	0.3	0.04	N
8	2 Feb 72	0.5	N	N	0.65	N	N
9	15 Feb 72	N	N	N	N	N	N
10	1 Mar 72	N	N	N	0.2	N	N
11	15 Mar 72	N	N	N	N	N	N
12	29 Mar 72	N	N	N	0.1	N	N
13	12 Apr 72	N	N	N	N	N	N
14	25 Apr 72	N	N	N	N	N	N

NOTE:

1. No contaminants detected denoted thus "N".
2. Organic peak at 24.5 minutes. ROM estimated at 1 to 2 parts per million.
3. Very small organic peak at 24.5 minutes.
4. Organic peak at 29.5 minutes. ROM estimated at 1 part per million.
5. No discernible organic peak detected.

5.4 FAILURE ANALYSIS

5.4.1 Operational and Failure Summary

The operational status of the system is shown in Figure 36. There were only 10 days (24-hour periods) out of the 182 day total when the system was not operational. All of these days occurred on weekends with no one in attendance or while awaiting parts. This represents 45 percent of the total cumulative downtime. A major portion of the remaining downtime involved diagnosis and troubleshooting of electronics problems. A failure and shutdown summary is given in Table 10.

A total of 24 system shutdowns were identified in the test log (see Appendix B), of which 13 are attributed to primary failure or malfunctions and 11 to start/stop operation required for fault diagnosis and checkout of repairs. There were, in addition, two malfunctions associated with module electronics which did not cause system shutdown. Cumulative primary shutdowns (modules and system) as a function of time are shown in Figure 37.

A total of 11 components either failed, for primary or secondary causes, or malfunctioned during the test. A component was considered failed if it had to be repaired or replaced. A component was considered malfunctioning if modification to the system or operating procedure was required for proper operation. Within these definitions, seven of the eleven components failed and the remaining four malfunctioned.

5.4.2 Component Analysis

The components which failed or malfunctioned during the test are listed in Table 11. They are discussed in the following paragraphs.

Nylon Fittings.- Three nylon fittings in the electrolyte loop (1/4 inch Swagelok unions) failed by breaking in half. In each case, the fitting that failed was being used in an off-design manner, i.e., one end of the fitting with an O-ring against the shoulder was threaded into a 7/16-20, chamfered hole in a plastic block. Each fitting was installed dry and tightened until visible compression of the O-ring was observed. Failure probably resulted from stress fatigue due to the constant pressure of the O-ring pushing against the shoulder. All three fittings broke at the shoulder. (See Figure 38).

SHUTDOWN (ZERO O_2 PRODUCTION) ON WEEKENDS = 5 DAYS
SHUTDOWN (ZERO O_2 PRODUCTION) AWAITING PARTS = 5 DAYS

TOTAL 10 DAYS

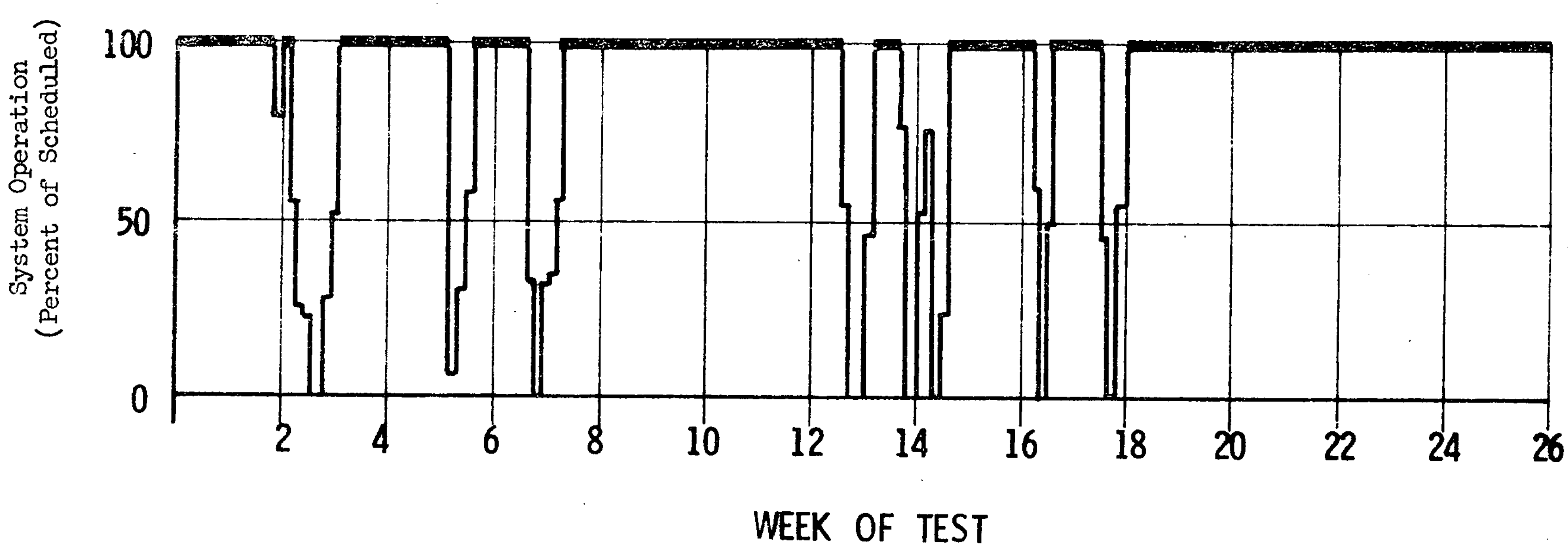


Figure 36 System Operational Status-Percent of Scheduled

Table 10

FAILURE & SHUTDOWN SUMMARY

Day of Test	Date	Time	Shutdown	Failure ** Indication	Cause	Corrective Action	Repair Time
14	11/8	0745-1214	*Auto	Low sys. press.	Electronic noise.	None - restart.	-0-
		1213	Manual	None (diagnosis)	--	None - restart.	-0-
16-17	11/10-11/11	1443-1112	*Auto	High pO_2.	Electronic noise.	None - restart.	-0-
17-18	11/11-11/12	1644-1540	*Manual	KOH leak.	Broken fitting.	Replaced fitting.	1.0
		"	Manual	None (diagnosis)	--	None - restart.	-0-
18-21	11/12-11/15	2153-1003	*Auto	Low sys. press.	Electronic noise.	None - restart	-0-
		"	No	False Mod. 4 "On" Command.	?	Turn Mod. 4 off at night and on weekends.	-0-
		"	Manual	None (checkout)	--		
21-22	11/15-11/16	1730-0803	Manual	None (diagnosis)	--	Replaced I.C. Z1 and Z2	0.1
		"	Manual	None (diagnosis)		Card W3 and Z5 on W2.	
22	11/16	1021-1053	Manual	None (diagnosis)	--		
37-38	12/1-12/2	0206-1152	*Auto	Low sys. press.	Electronic noise.	Increased low pO_2 setting.	0.3
39	12/3	0752-1620	*Auto	Low sys. press.	Electronic noise.	Added test monitor points.	
47-49	12/11-12/13	0858-1521	*Auto	High pO_2.	Electronic noise.		
50-51	12/14-12/15	0755-0839	*Manual	No gas flow in bubblers.	Momentary power loss. Purge valves not re-set.	None - restart.	-0-
89-92	1/22-1/25	1404-0952	*Auto	Low sys press.	Broken fitting.	Replaced fitting.	1.0
92	1/25	1004	No	Mod 3 temp warning.	Temp sensor failed.	Disconnected until replacement obtained.	-0-
		1119-1513	Manual	Pump 2 motor hot.	KOH on pump motor from failure on Day 89.	Switched to Pump 1.	
93	1/26	1300-1427	Manual	None	--	Installed new motor on Pump 2.	0.3
96-99	1/29-2/1	1837-1021	*Auto	Low sys. press.	Pressure decay in cyclic mode, off-to-on.	None - restarted in continuous mode during diagnosis.	0.1

Table 10 (Continued)

Day of Test	Date	Time	Shutdown	Failure**		Corrective Action	Repair Time
				Indication	Cause		
100-102	2/2-2/4	1821-1743	*Auto	Test pt 3 noisy.	Electronic noise.	Replaced Chip Z1-W2. Installed new temp sensor (see Day 89). Modified purge ckt for cyclic mode (see Day 93).	4.0
101	2/3	1461	Manual	Mod 4 would not turn on.	Loose coaxial cable.	Tightened cable.	
114-116	2/16-2/18	1600-1139	*Manual	KOH leak.	Broken fittings.	Replaced all O-ring type plastic fittings with Teflon-coated stainless steel.	2.0
124	2/26	0400	No	Mod 3 breaker tripped.	Regulator failed.	Installed spare regulator.	0.1
124-127	2/26-2/29	1100-0947	*Auto	None	Electronic noise.	None - restart.	
127	2/29	1325-1545	Manual	None	--	Added test point and filter to shutdown gate.	0.5
130	3/3	0850	No	None	--	Noise check.	
		1302-1311	Manual	None	--	Add additional filtering.	0.1
133	3/6	0755	No	Mod 4 would not turn on.	?	None - problem corrected itself.	-0-
154	3/27	1632	No	Mod 4 switch not working.	?	Started using breaker to turn Mod 4 on and off.	
						Total	9.5

* Shutdowns for primary failures (not including diagnostic shutdowns = 13
** Total failures (counting intermittent failure as one) = 11

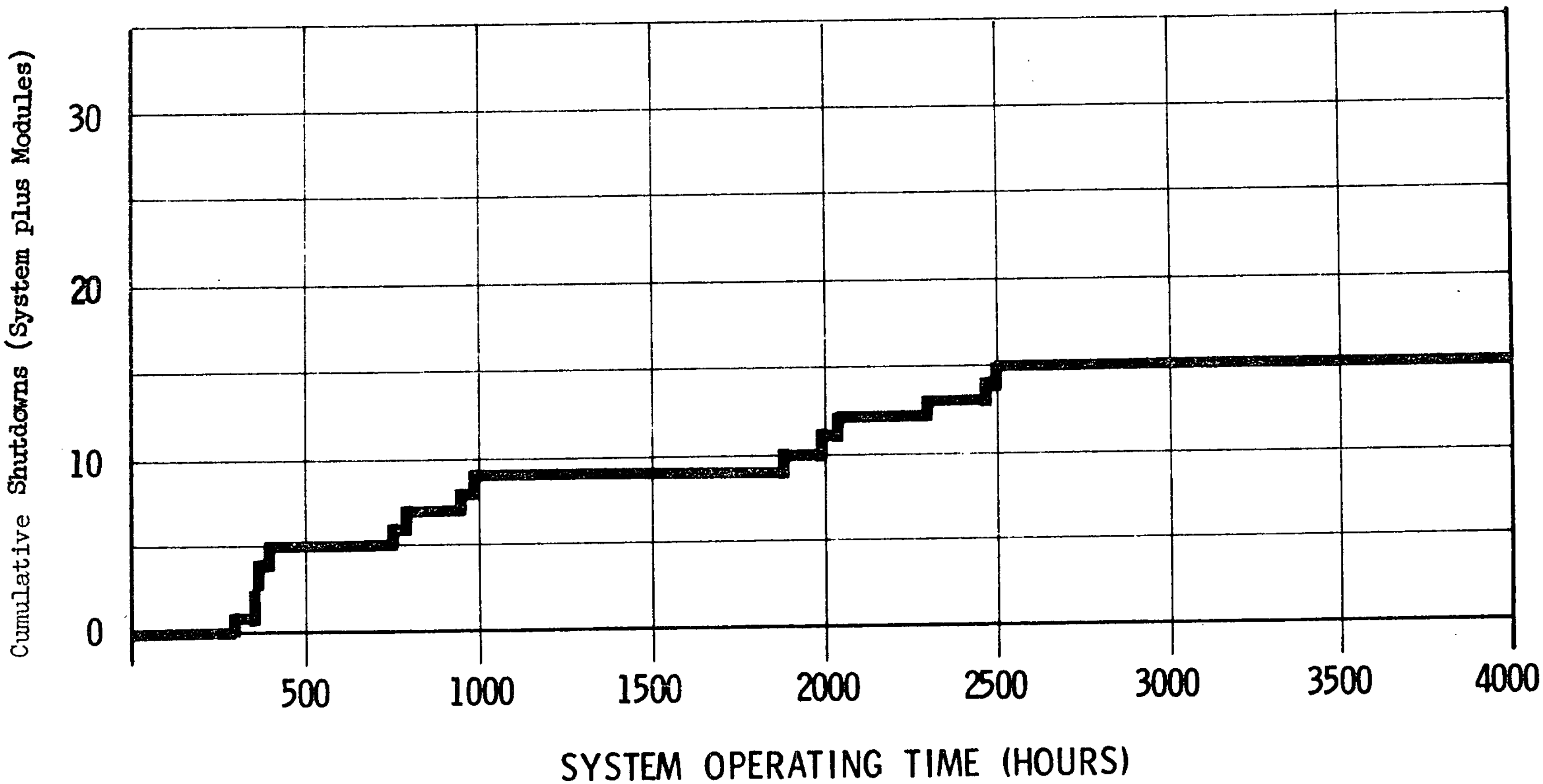


Figure 37 Cumulative **Shutdowns (System plus Modules)**

Table 11

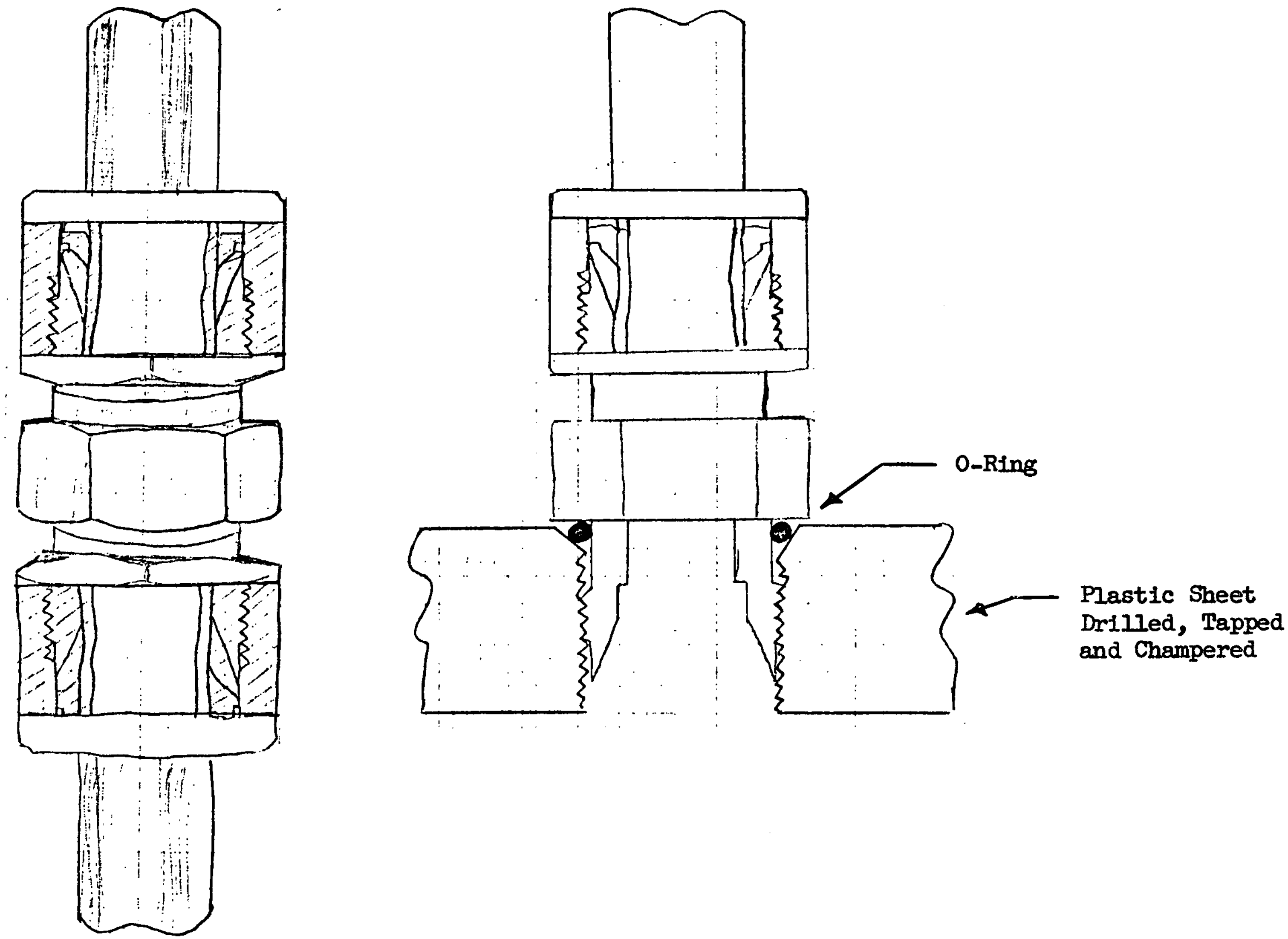
Component Failure and Malfunction Summary

Failure

No. of Components	Failure Description	Cause
3	Broken nylon fittings.	Incorrect use with O-ring seal.
1	Electrolyte pump motor stopped.	Leakage of KOH onto armature after a fitting failure above.
1	Temperature sensor failed open.	Damage to thermistor during assembly.
1	Module 3 current regulator failed to max current.	Not determined.
1	No current to Module 4B.	Loose coax connector.

Malfunction

No. of Components	No. of Occurrences	Malfunction Description	Cause
1	8	Master shutdown Chip Z1 emitting false shutdown signals.	Missing capacitor allowed intermittent noise to reach chip.
1	Approx. 7	False on commands and no response to manual on/off commands.	Not determined.
1	1	Orbital operation pressure decay.	Not determined.
1	1	Solenoid valves de-energized.	Momentary power supply voltage decay.



Normal Configuration

182-Day Test Configuration

Figure 38 Nylon Fitting Configuration

These failures represented a design deficiency. The corrective action that was taken after the third failure occurred was to replace all nylon fittings which were being used with O-rings with Teflon-coated stainless steel fittings. No further escape of KOH from the electrolyte loop occurred after this action.

Electrolyte Pump Motor.- Failure of the electrolyte pump motor was a secondary failure resulting from one of the nylon fitting failures noted above. KOH leaked onto the motor armature causing an internal short. The corrective action consisted of replacing the motor with a spare.

Temperature Sensor.- The temperature sensor on Module 3 failed open which resulted in an erroneous high temperature signal. This was the second sensor to fail: sensor EL #1 failed during checkout prior to the start of the test. Cause of both failures was an incorrect assembly procedure. The sensor probes were prepared by epoxy-plotting the small (1/32" dia.) thermister beads in 3-inch long, 1/4" diameter stainless steel tubing. The positive meniscus which was formed by this process was then filed off. The thermistors were supposed to be positioned just inside the end of the tubes. However, inspection of the two units which failed indicated that in these two cases, the bead had been exposed and probably scored or cracked by the file. The corrective action was installation of spares.

Current Regulator.- Module 3 current regulator failed to high current, allowing maximum current as limited by the external power supply (100 A) to be applied to the module. A 30-Amp breaker opened to prevent sustained high current. Cause of failure was not determined. Corrective action consisted of installing a spare regulator card.

Coaxial Cable Connector. A loose coax connector to Module 4B resulted in no current to this module. This was a secondary failure resulting from a problem in the module electronics that is discussed in a later paragraph. The connector is of a type which is fragile and not designed for the repeated connect/disconnect operations to which it was subjected. Corrective action consisted of tightening the connector.

Master Shutdown I.C. Chip.- The malfunction of this chip (Z1 on Card W2) consisted of random, erroneous automatic system shutdown signals. This was an intermittent malfunction which triggered 8 automatic shutdowns and was responsible for another 5 manual shutdowns for diagnosis, constituting a total which is more than half of all system shutdowns during the test.

Diagnosis of the problem was made difficult by its intermittent nature. It was eventually traced to a missing capacitor which had been included in the design of the circuit to protect against electronic noise but which had been omitted during fabrication of the circuit card. Corrective action consisted of installing the needed capacitor.

Module 4 Electronics.- Early in the test, Module 4 received several false "on" commands while the system was shut down. The cause of the problem was not determined at that time, but rather the procedure was changed to turn Module 4 off on nights and weekends for the remainder of the test. For several months, the module was turned off as scheduled by disconnecting the coax cable which provides current to the module and allowing the command electronics to remain active. This was a diagnostic measure to see if the false on-command would re-occur during a shutdown. The procedure was modified after the coax connector problem noted previously, so that Module 4 was turned off and on with the switch and breaker. During the last two months, there were a number of occasions when the module electronics failed to change state, either from off-to-on or from on-to-off, when the switch was actuated. In these instances, the breaker was used to achieve the desired condition. It is assumed that the problems associated with Module 4 command electronics, both the false on commands and failure to respond to commands, were the result of a single intermittent malfunction. The source of the problem was not identified and the only corrective action taken was to use the module breaker to effect the required commands.

Orbital Operation.- An automatic shutdown, caused by low system pressure, occurred during the first segment of the orbital simulation because the startup sequence had not been fully optimized. The numerous off-on cycles during the orbital simulation made the problem evident. The low gas pressure was found to occur at the point in the off-to-on sequence where nitrogen purge was turned off and current was applied to the modules simultaneously. With a momentarily no-flow condition existing, the pressure decay could have been caused by leakage from the differential pressure controllers, although this has not been verified. Corrective action consisted of adding a ten-second electronic delay to the nitrogen purge off-signal to maintain nitrogen flow until gas production was underway.

Solenoid Valves.- On one occasion, the nitrogen purge and vent solenoid valves de-energized while the system was operating. Since only one vent had been provided by MDAC, the generated oxygen and hydrogen and the nitrogen purge were being mixed in the single vent when the valves opened. The problem was attributed to a momentary voltage decay of the 30 Vdc power supply. The power supply voltage was put on a strip chart monitor for diagnosis but the problem never re-occurred. As a safety measure, MDAC installed a second vent. No corrective action was taken on the system itself.

Section 6
RELIABILITY ANALYSIS

The 182-Day Test of the water electrolysis system was intended to be an engineering evaluation test; hence, a formal reliability program was not required by the contract. Other than the reliability inherent in good engineering judgment, there was no attempt to invoke the reliability principles that would be normal for a flight article. The hardware itself was refurbished from that used in an earlier development test. No attempt was made to conduct parts application studies, failure mode and effects analyses, quantitative reliability analysis, or design reviews. Similarly, there was no formal quality assurance program performed either during the original fabrication, the refurbishment, or the test itself. Most of the electronic components used were commercial off-the-shelf, received without acceptance testing. The mechanical components were either standard commercial or specially fabricated devices produced in a laboratory environment without quality control procedures.

The purpose of the program, to conduct a 182-day feasibility test, was achieved under the controlled conditions evidenced in other sections of this report. However, since quality assurance procedures were not required, there was neither formal failure documentation nor Material Review Board disposition of the failed hardware. With these limitations, the brief failure analysis that follows is more inductive than deductive. Since the preceding failure analysis in Section 5.4 of this report is related more to the general problems encountered during test operation than to the specific diagnosis of the failed hardware, reference was made to the Test Log in Appendix B for this reliability analysis.

Of the several shutdowns listed in the Appendix, only one instance can be found of a failure due to incorrect design. This was the use of nylon fittings in the KOH lines. A more recent program for the design of an electrolysis system (intended for operation in a Space Station) provided that fittings such as the above would be stainless steel with areas in contact with the electrolyte coated with Teflon. Double O-ring seals of ethylene propylene were also specified. It is reasonable to assume that a design review of the 182-Day Test system would have revealed the improper use of nylon.

It is noted that the causes of two failures, viz., a short in a current regulator card and the false start-up of Module 4, were not determined. Both failures appear to have been related to the electronics. It is unlikely that these failures are related to a design deficiency since, in both cases, similar circuits are to be found in other modules. It is much more reasonable to assume that these problems were either the result of a part failure or of an error during fabrication. Reliability parts application, together with controlled receiving inspection, would have prevented the first alternative; quality control procedures during fabrication would prevent the second.

A recurrent problem with a temperature sensor, noted during the initial checkout as well as during the test, was traced to an incorrect manufacturing procedure, as described in Section 5.4.2. Normal inspection methods for encapsulated devices would have detected the fault. Similarly, the cause for nine of the automatic shutdowns, eventually traced to the missing capacitor on the master shutdown I/C, would have been prevented by normal inspection and box level acceptance testing. At the very least, replacement with a spare module would have restricted the number of shutdowns to one. The failure of the electrolyte pump motor at Day 89 and the module 4B connector failure at Day 101 were both secondary failures as indicated in Section 5. The KOH leak in the first case and the repeated disconnect-connect cycles of the connector in the other case would have been precluded in an end-item intended for flight use.

From a reliability viewpoint, this water electrolysis system for producing oxygen appears to be entirely feasible. No problems were seen that could not be prevented by invoking the standard techniques of reliability and quality assurance programs that are normally found in flight articles. This conclusion is based not only on the 182-Day Test, but also on the later programs for water electrolysis systems in which the Reliability Organization participated.

Failure mode and effects analyses, parts application, maintainability analyses, and fault detection/isolation analyses have been performed in these later programs, indicating that high reliability systems with a minimum life of two years are entirely within the present state-of-the-art.[6] [7]

Section 7
SAFETY ANALYSIS

A safety review of the Electrolytic Oxygen Generator was presented to the LMSC Space Systems Division Safety Review Board prior to delivery of the hardware to the MDAC test site. Based on the data presented, the Board deemed adequate the safety considerations which were being taken in the program and the design safety features which were incorporated in the system. They recommended that the interface nitrogen supply pressure be noted daily by the resident LMSC representative to assure that an adequate supply would be available in case of an automatic safety shut-down.

The test results indicated that three potentially hazardous conditions occurred during the test program. In each case, a modification in equipment or test procedure was accomplished to prevent re-occurrence of the condition.

In one case, a system malfunction resulted in opening of the nitrogen purge and vent solenoids valves while the system was operating. This resulted in mixing of the product hydrogen and oxygen with nitrogen purge in the single vent which had been provided by MDAC. Only one vent had been provided in spite of a strong recommendation by LMSC before the start of the test that two vents be provided for safety purposes. After the system malfunction which allowed mixing of the product gases in the single vent, MDAC installed the second vent to preclude reoccurrence of this problem.

The second potentially hazardous condition occurred as the result of improper use of nylon fittings in the potassium hydroxide electrolyte loop. Fitting failure on three occasions allowed the electrolyte to escape into the system enclosure. This problem was corrected by installing Teflon-coated stainless steel fittings as replacements.

The third condition which could have been potentially unsafe was the occurrence of false "on" commands to Module 4 during a period when the system was shut down. No attempt was made to correct the problem, but rather, the test procedure was modified to require that Module 4 be turned off on nights and week ends.

Section 8

INTERFACE REQUIREMENT FOR SPACECRAFT APPLICATION

8.1 ELECTROLYSIS SYSTEM CONFIGURATION

The first consideration in adapting the circulating electrolyte type of electrolysis system to spacecraft application is an appropriate maintenance concept which would preclude breaking into the electrolyte circuit for any maintenance or repair tasks. This could be achieved by configuring the system to contain individual, self-contained hydraulic assemblies with no external electrolyte connections. The optimum size and number of these individual assemblies could then be selected for the particular crew and cabin leakage makeup requirements, and spares could be provided to meet the particular reliability requirement. An individual electrolysis module assembly is shown conceptually in Figure 39. The appropriate number of these assemblies, with sealed covers, would be installed with quick disconnects in a cabinet in the spacecraft, as shown in Figure 40. A failed module could be unplugged from the cabinet and replaced with a spare.

Also shown in Figure 40 are replaceable modular electronics assemblies, one for each electrolysis module. The 182-Day Test results, indicating that a majority of the system shutdowns were associated with electronics problems, emphasize the need for individual electronics assemblies. These individual electronic units should be provided with voting circuits on all critical functions and should utilize the spacecraft computer system for additional fault diagnosis. Equipment should also be provided for checkout of an electronics module to isolate the problem source in the event of an electrolysis module shutdown.

8.2 SYSTEM INTERFACES

The following paragraphs describe the system interfaces required for spacecraft use. The interface descriptions are necessarily qualitative where they depend on spacecraft requirements rather than electrolysis system requirements.

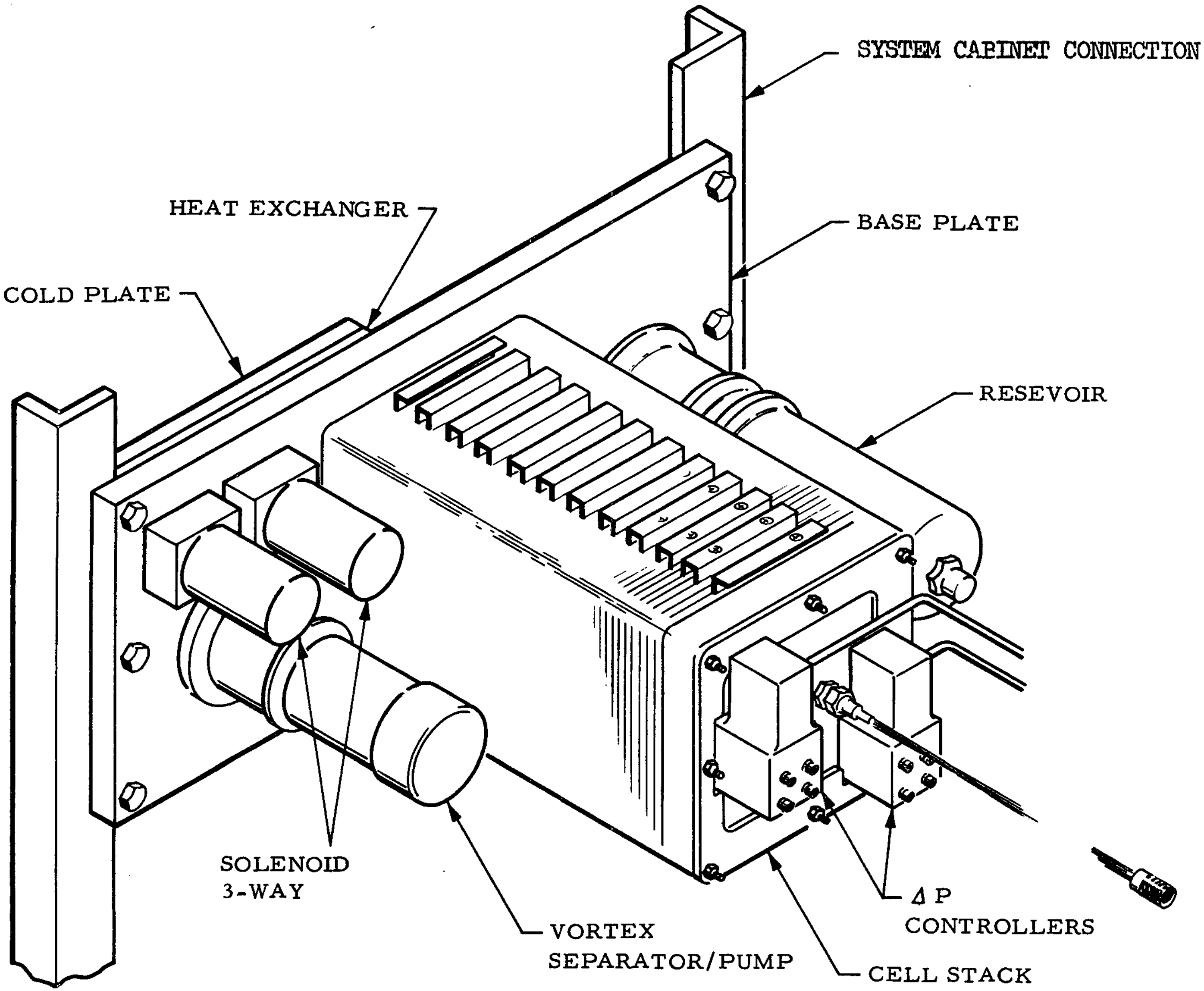


Figure 39 Electrolysis Module Conceptual Configuration
(Shown without Cover)

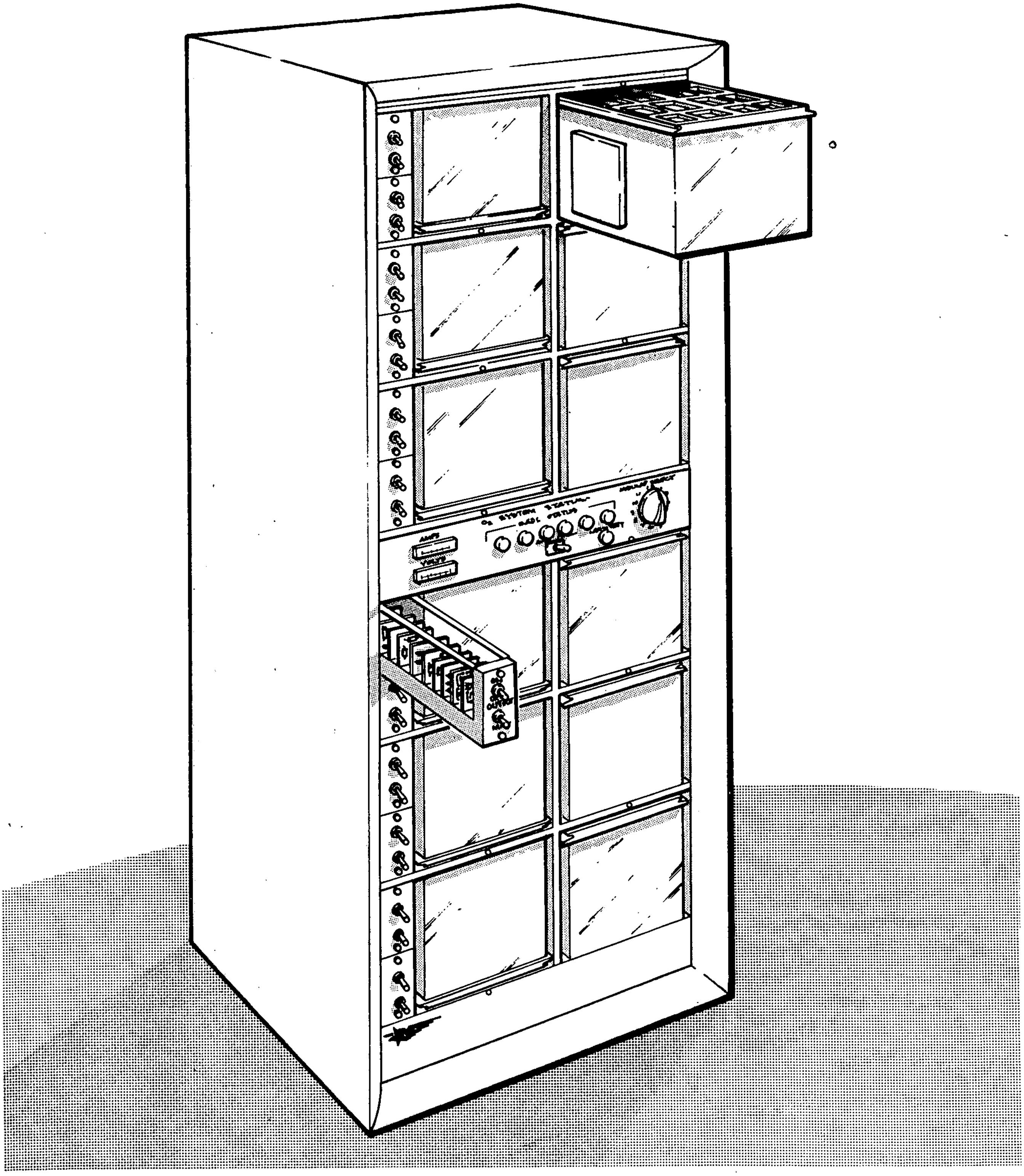


Figure 40 Spacecraft Electrolysis System Configuration

8.2.1 Power Supply

The power conditioners in the system should be designed to utilize unregulated solar array power to minimize power penalty. Regulated 28 Vdc would be required for the electronic logic circuits and accessories.

8.2.2 Coolant Supply

The electrolysis system cabinet would contain a fixed cold-plate through which spacecraft coolant would flow continuously. Each electrolysis module would contain a contact heat exchanger to mate with the cold plate by contact only (no fluid inter-connections).

8.2.3 Water Supply

The system would utilize the processed water from the spacecraft water and waste management system. Ionic contaminants in the water would be removed in an ion-exchange canister mounted inside the electrolysis system cabinet.

8.2.4 Nitrogen Supply

Nitrogen supply would be required by the electrolysis system for system pressurization and safety shutdown purge.

8.2.5 Oxygen Discharge

Oxygen produced in the electrolysis modules could be discharged directly to the spacecraft cabin if no oxygen accumulator is provided in the cabin.

8.2.6 Hydrogen Discharge

Hydrogen would be discharged to an accumulator for subsequent use in the spacecraft CO_2 reduction system.

8.2.7 Bubble Separator Discharge

Gas removed from the feed water in the electrolysis modules would be discharged directly to the spacecraft cabin. The composition of this gas would be expected to be oxygen and nitrogen.

Section 9

CONCLUSIONS

This program was successful in demonstrating the soundness of the basic concept of circulating electrolyte water electrolysis as evidenced by the following:

- No cell or module failures of any kind occurred during the test program.
- All critical functions, i.e., temperature control, water balance control, phase separation, and gas generation rate control, were maintained throughout the test.
- The system successfully operated at all of the conditions planned for it in the test program.

The capability of the system to operate in an orbital (on/off) mode was demonstrated. The scheduled period of operation in this mode was too brief for an exact determination of long-term performance benefits, but the lack of any measurable performance degradation in the one-week period is indicative of improved performance stability to be gained from orbital operation in a spacecraft application.

Control logic for this system is highly developed as demonstrated by the completely "hands-off" operation, the automatic start/stop feature, and the automatic safety shutdown capability.

Problems encountered during the test program were primarily due to electronics malfunctions which were difficult to diagnose because they were intermittent, but simple to correct once they had been identified. All the problems fell in one or more of the categories of (1) design deficiency due to the accelerated nature of the refurbishment program, (2) commercial component failure; no high reliability components were used, (3) inadequate quality control due to the development nature of the program. In no case was a problem identified which indicated an inherent deficiency of the system concept.

Section 10
RECOMMENDATIONS

Further development of the circulating electrolyte water electrolysis system, which is now at the prototype level, is warranted. Flight prototype hardware development will be necessary to advance this system concept to flight hardware readiness. The following areas require development emphasis to achieve this goal:

- Improve electronics. Convert from commercial to high-reliability flight-type electronic components. Increase quality assurance effort in circuit design and fabrication.
- Improve power conditioning. Redesign the electrolysis power conditioning units to achieve higher conversion efficiency.
- Incorporate Modular Maintenance Concept. Eliminate external electrolyte plumbing by redesigning the system to contain replaceable electrolysis module assemblies, each having completely internal manifolding of electrolyte.
- Incorporate Zero-Gravity Hardware. Utilize zero-gravity compatible components in the electrolysis module assemblies.

In future programs where testing to determine long-term performance characteristics of prototype or development grade hardware is an objective, the duration of the checkout run prior to start of the actual test should be increased. The experience with the NASA-LMSC Electrolytic Oxygen Generator in the 90-Day Manned Test and with the refurbished and modified unit in the 182-Day Test substantiates this need. In the 90-Day Manned Test, after 100 hours of checkout testing, 12 of a total of 14 system component malfunctions became apparent in the first 22 days of the test. In the 182-Day Test, after 300 hours of checkout testing, the problems associated with 11 of the 13 primary failures/malfunctions first occurred in the first 16 days of the test. These results indicate that as much as 30 days of pre-test checkout would be reasonable to assure a successful long-term test.

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LIBRARY CARD ABSTRACT

The NASA-LMSC Electrolytic Oxygen Generator, based on the circulating electrolyte water electrolysis concept, was refurbished and improved after the NASA-McDonnell Douglas 90-Day Manned Test and subjected to a 182-Day bench test. The system operated successfully for 160 cumulative days, demonstrating the soundness of the basic concept and the capability of orbital operation, long-term operation at design maximum oxygen output, and automatic, completely "hands-off" operation. Specific design improvements were recommended as a result of the test experience to advance the concept to flight worthiness for application in a manned spacecraft regenerative life support system.

APPENDIX A

PERFORMANCE PLOTS

Performance data, voltages, currents, pressures and temperatures were obtained from the MDAC data logger. The plots of these data contained herein are the following:

Figures A-1 through A-54.
Daily Performance Data. Data plotted at 4-hour intervals; one week to a page.

Figures A-55 through A-82
Module Summary Performance Data. Data plotted at 1-day intervals, highest and lowest reading for each 24-hour period; one month to a page.

Figures A-83 through A-86
Module Temperature History. Data for Modules 1, 2, and 3 plotted for a one-week period.

Figures A-87 through A-91
Orbital Simulation Data. Data plotted at 10-minute intervals for 5 hours each day.

Figure A-92
One-Minute Orbital Data. Data plotted at one-minute intervals through one complete orbit for Module 1.

Numbers shown on these Figures along the bottom margin, viz. 3, are referenced in the Condensed Test Log in Appendix B. An X is shown along the bottom margin for periods when the MDAC data logger was not operating and there were no data available to plot.

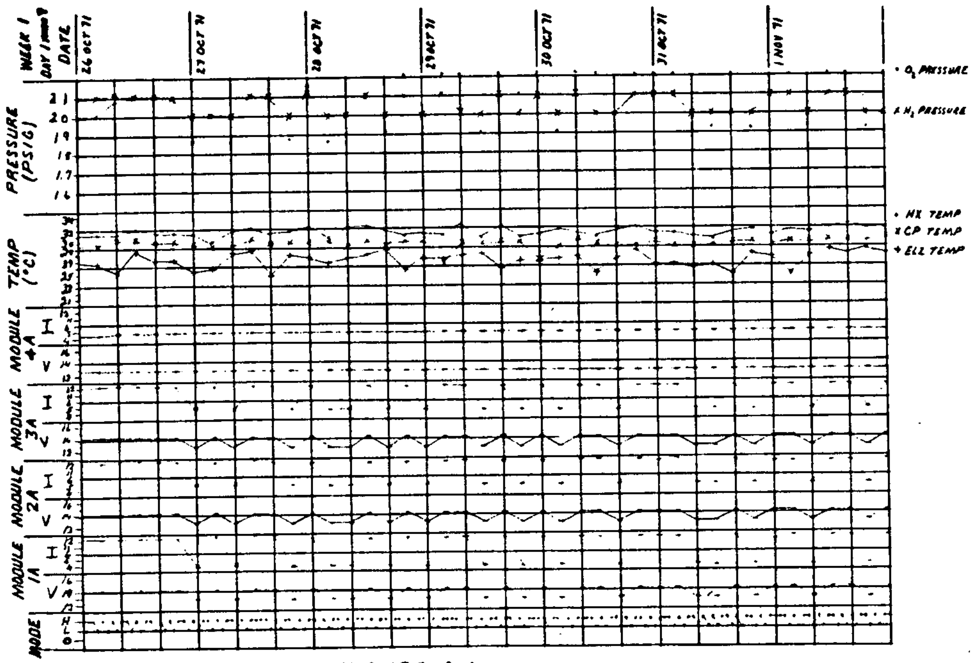


FIGURE A-1
CEU DAILY PERFORMANCE DATA

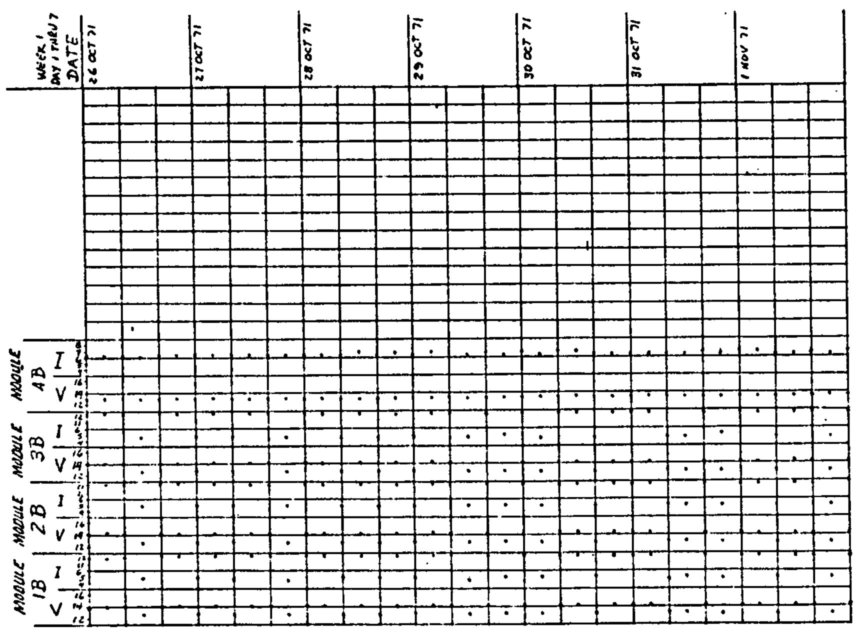


FIGURE A-2
CEU DAILY PERFORMANCE DATA

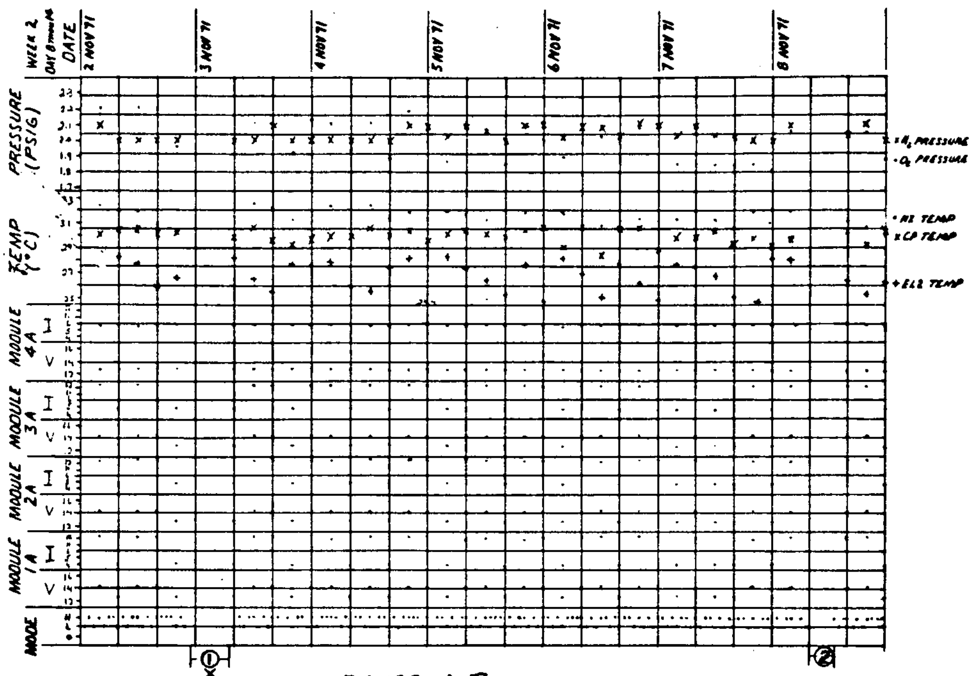


FIGURE A-3
CEU DAILY PERFORMANCE DATA

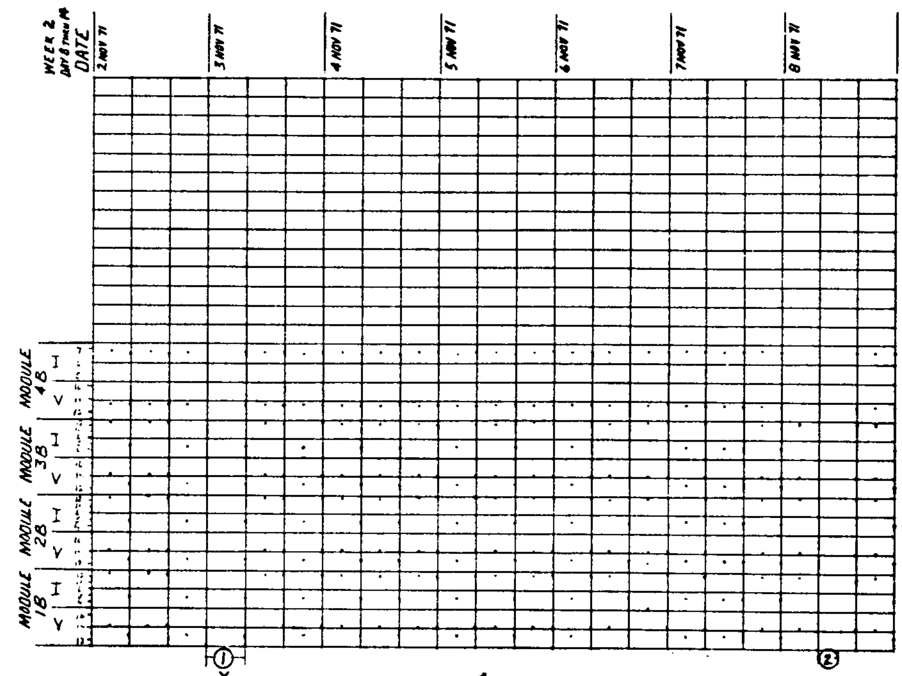


FIGURE A-4
CEU DAILY PERFORMANCE DATA

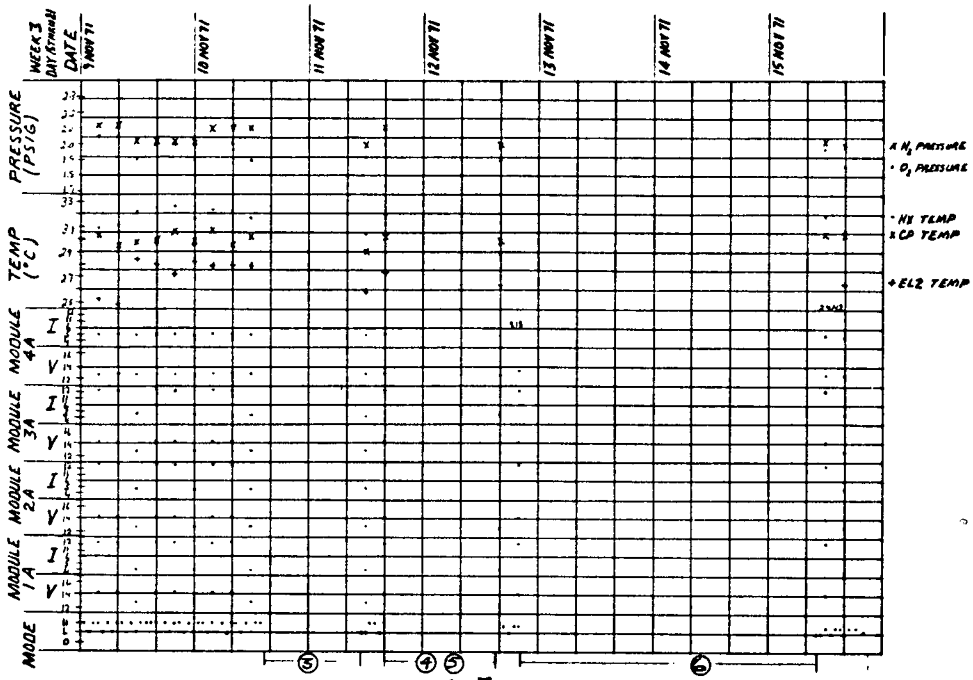


FIGURE A-5
CEU DAILY PERFORMANCE DATA

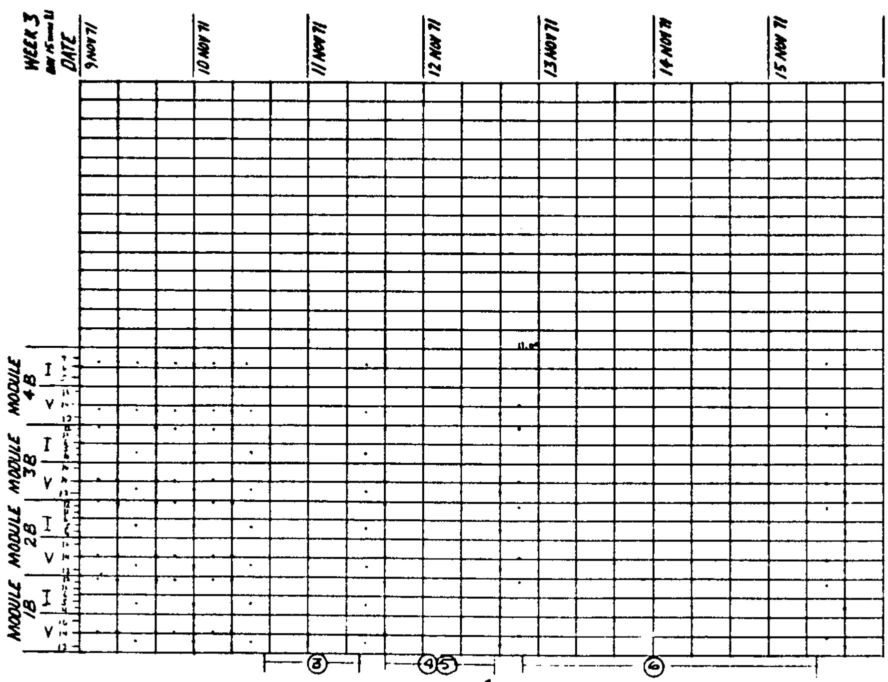


FIGURE A-6
CEU DAILY PERFORMANCE DATA

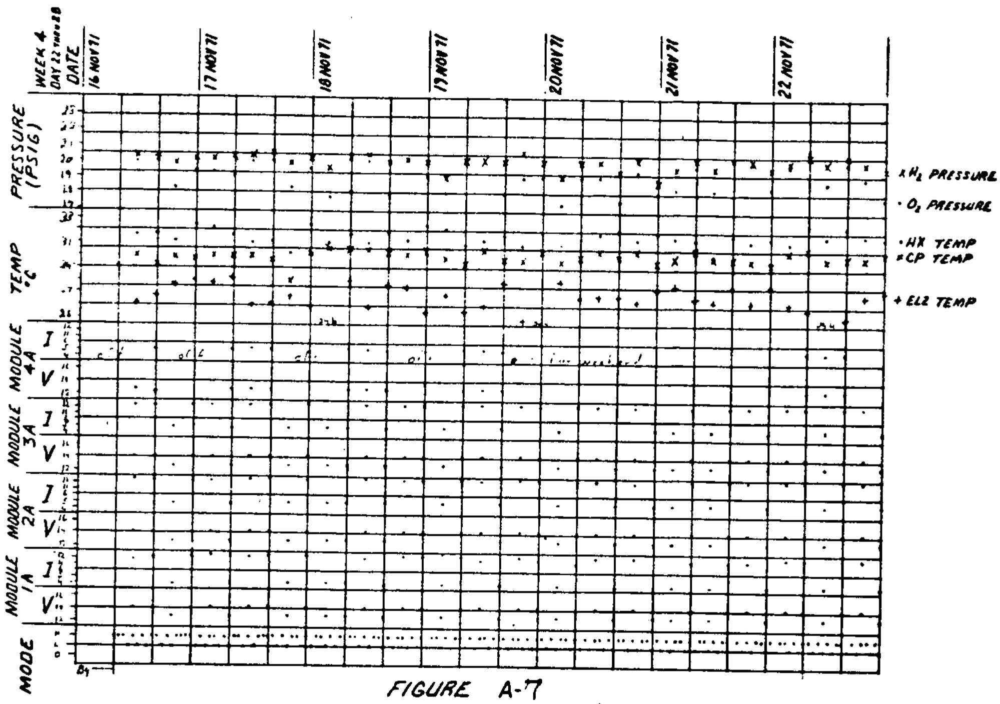


FIGURE A-7
CEU DAILY PERFORMANCE DATA

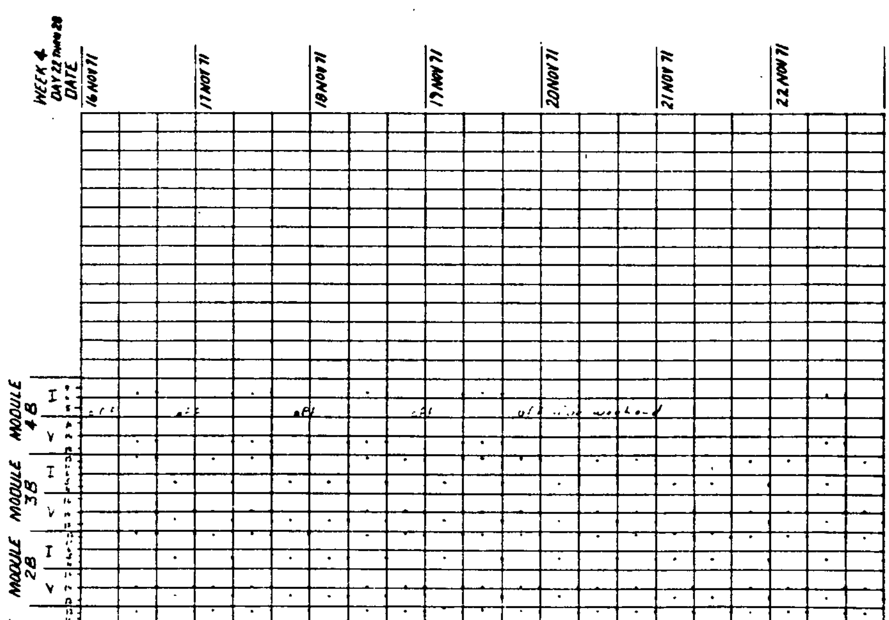


FIGURE A-8
CEU DAILY PERFORMANCE DATA

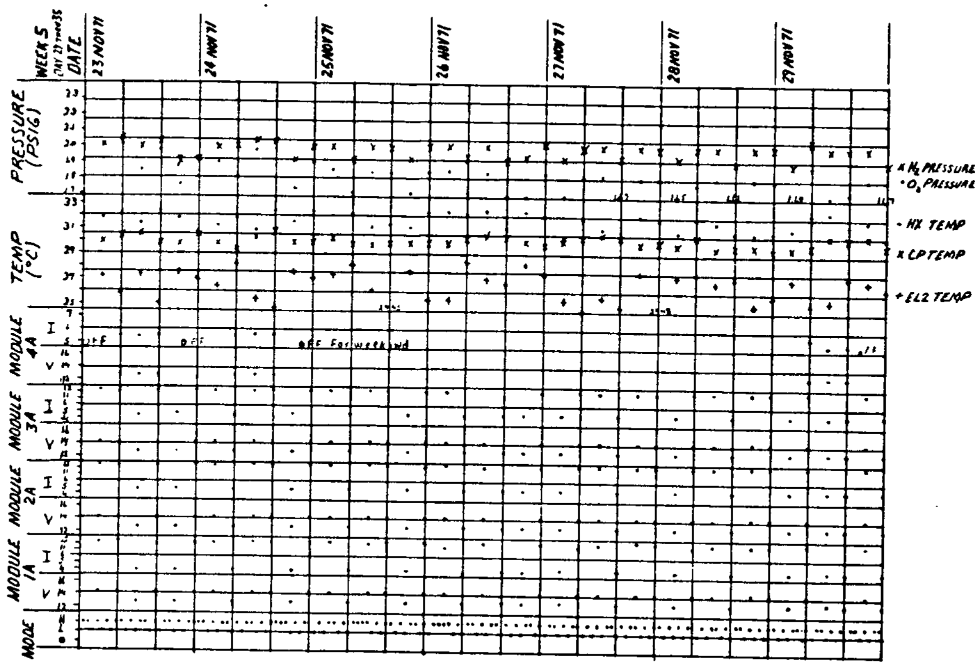


FIGURE A-9
CEU DAILY PERFORMANCE DATA

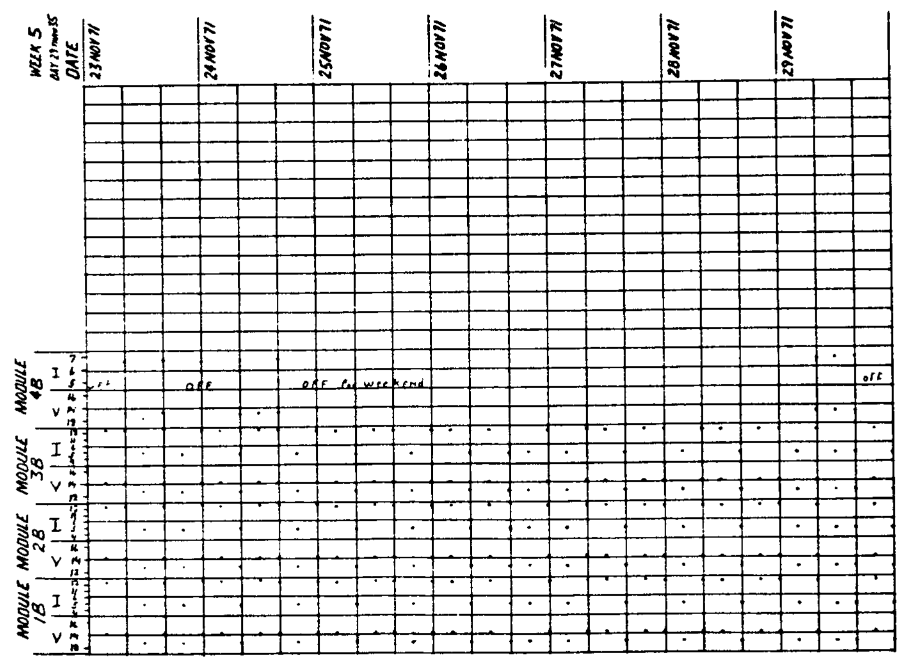


FIGURE A-10
CEU DAILY PERFORMANCE DATA

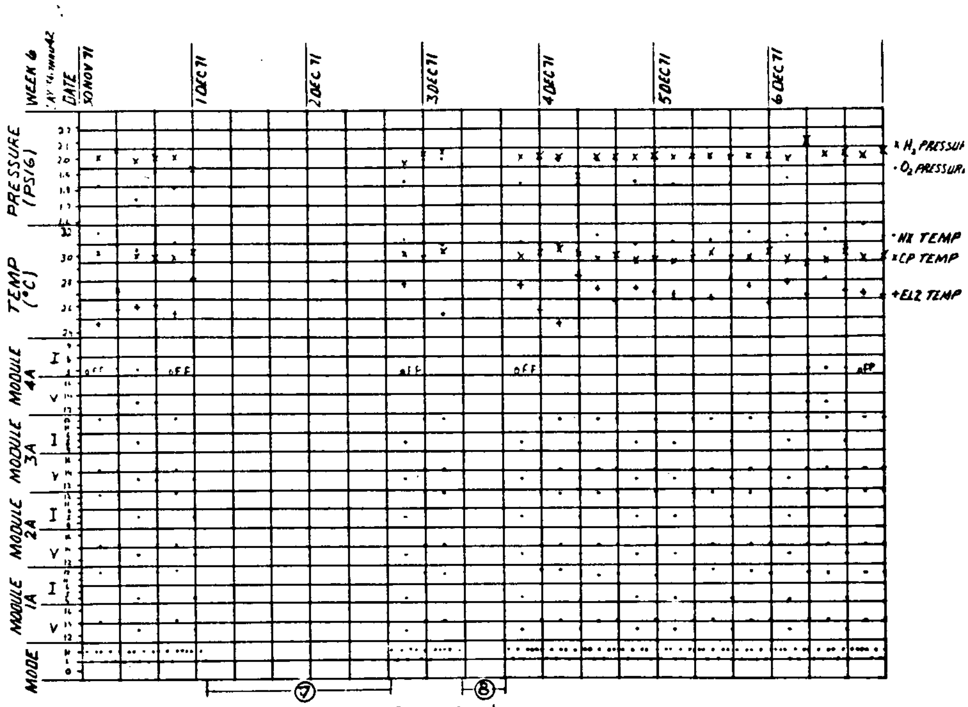


FIGURE A-11
CEU DAILY PERFORMANCE DATA

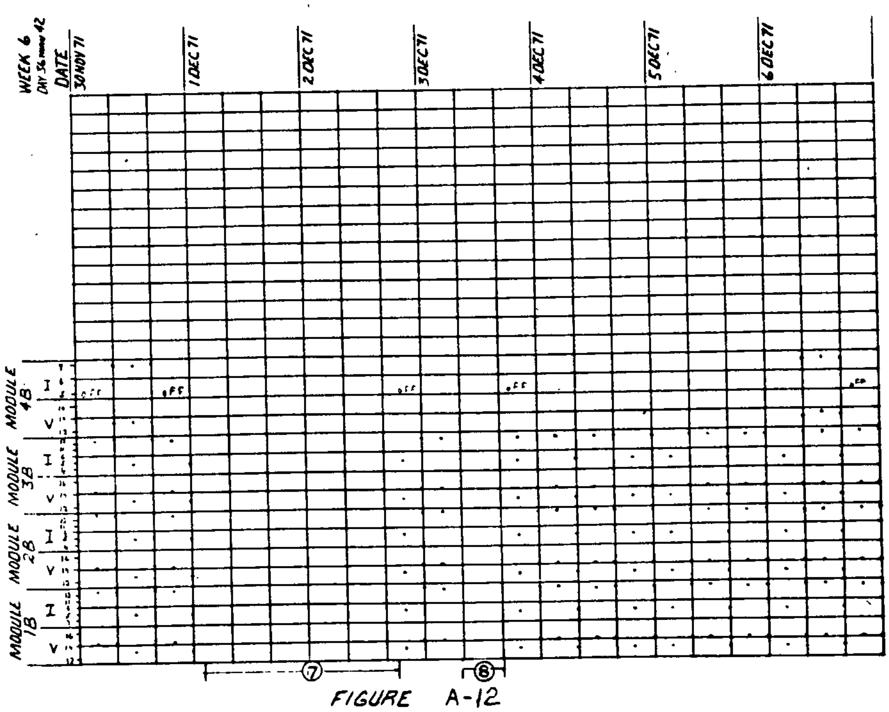


FIGURE A-12
CEU DAILY PERFORMANCE DATA

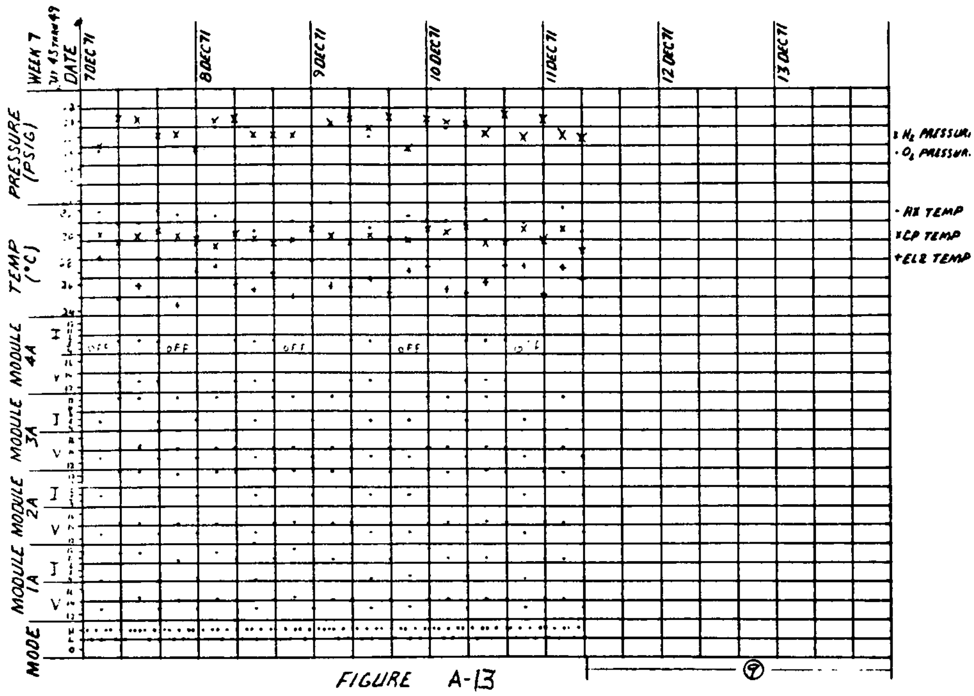


FIGURE A-13
CEU DAILY PERFORMANCE DATA

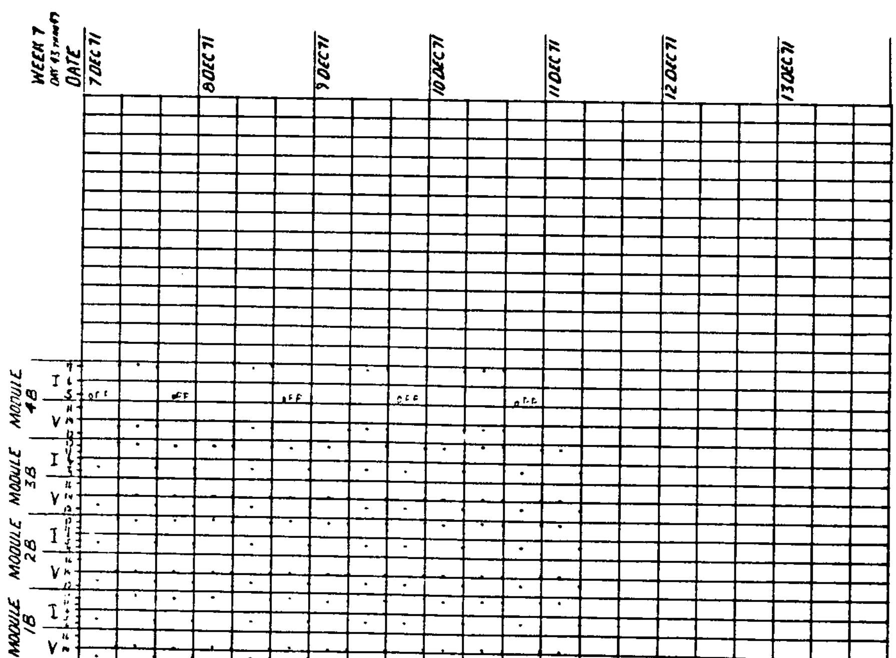


FIGURE A-14
CEU DAILY PERFORMANCE DATA

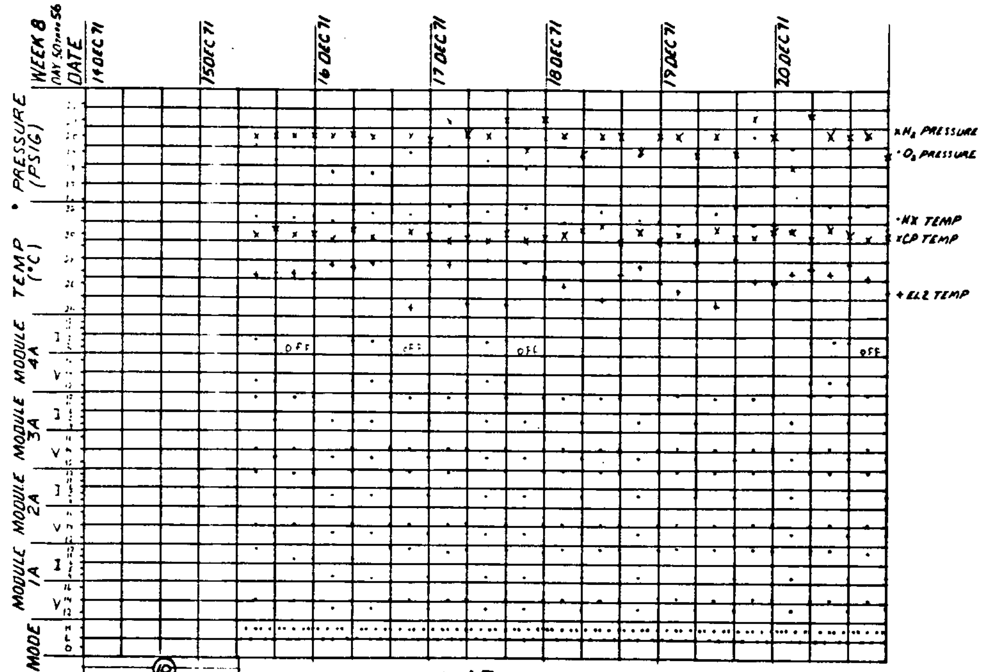


FIGURE A-15
CEU DAILY PERFORMANCE DATA

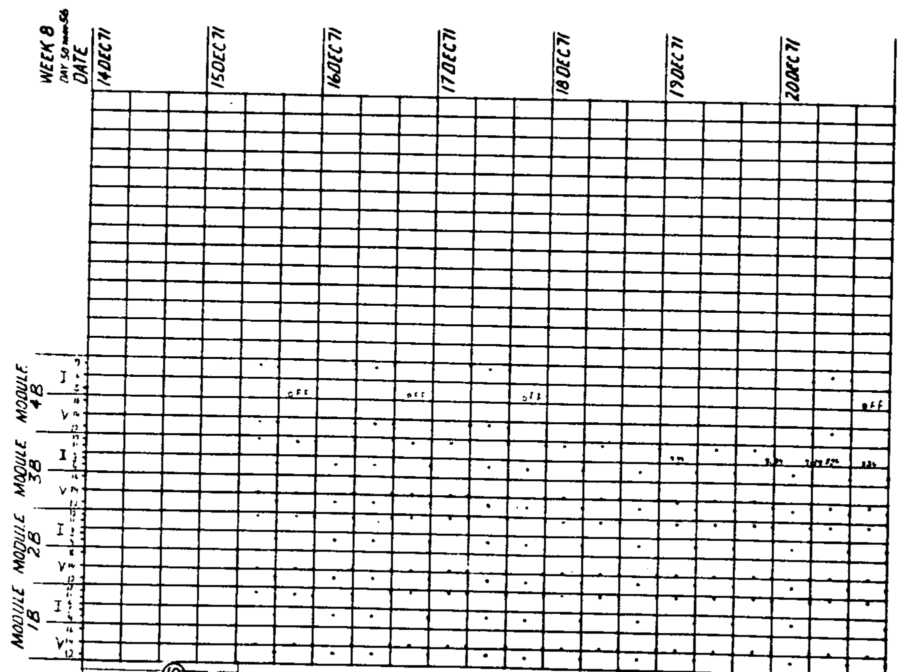


FIGURE A-16
CEU DAILY PERFORMANCE DATA

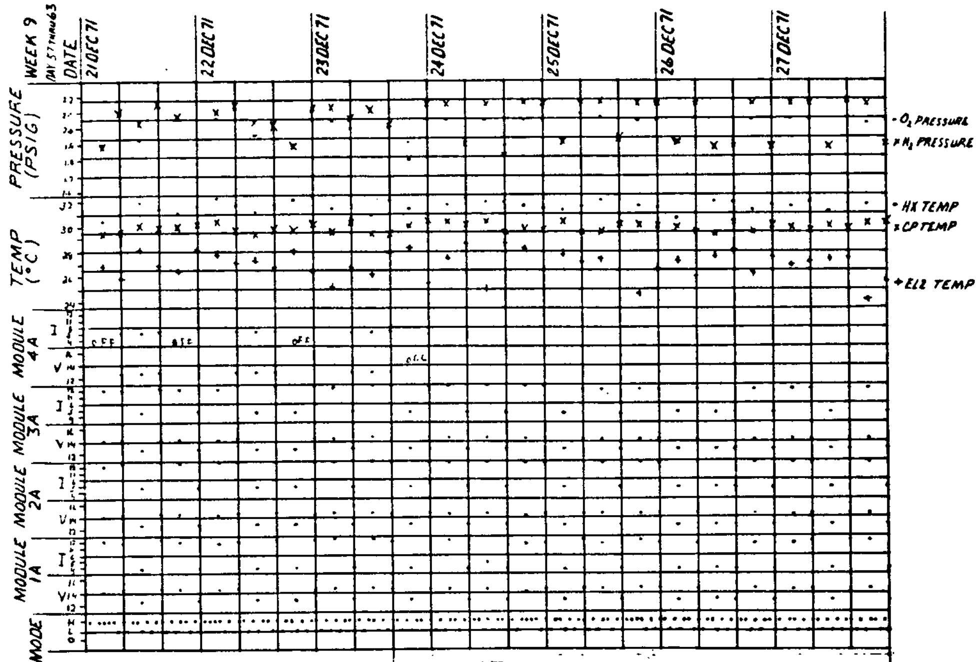


FIGURE A-17
CEU DAILY PERFORMANCE DATA

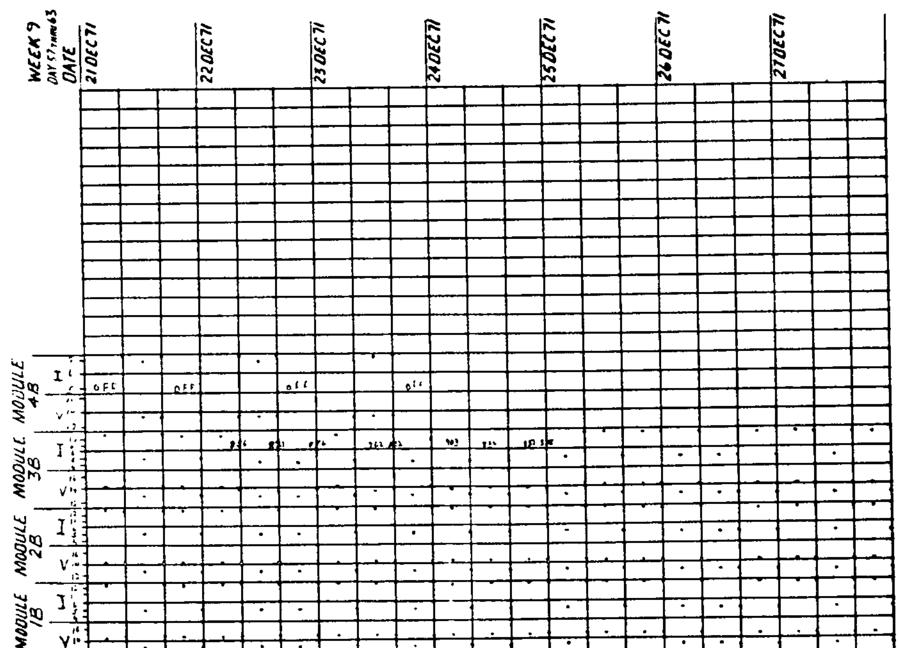


FIGURE A 18
CEU DAILY PERFORMANCE DATA

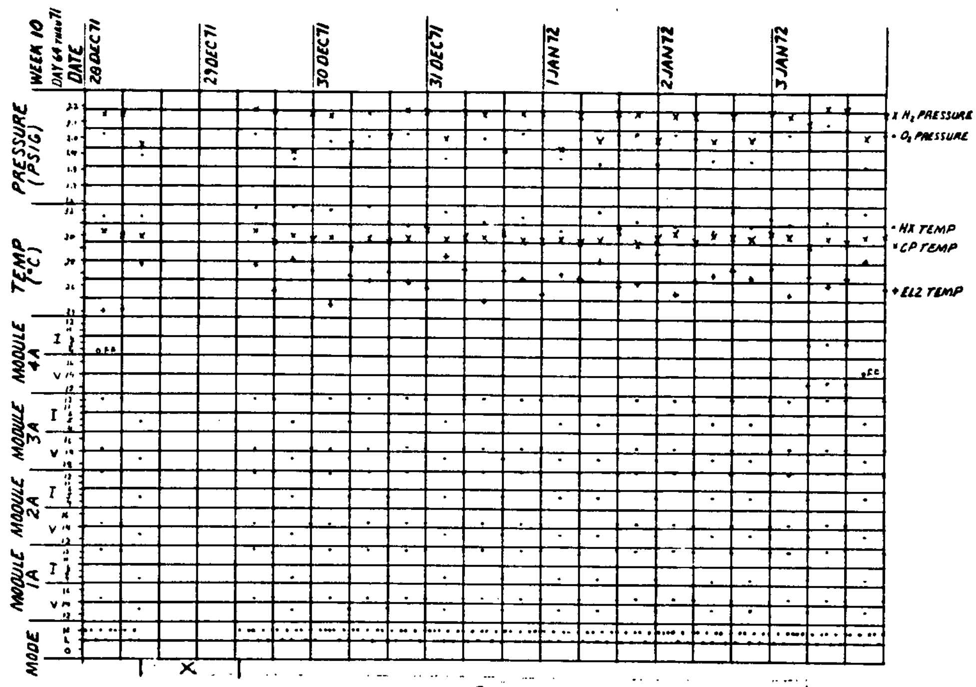


FIGURE A-19
CEU DAILY PERFORMANCE DATA

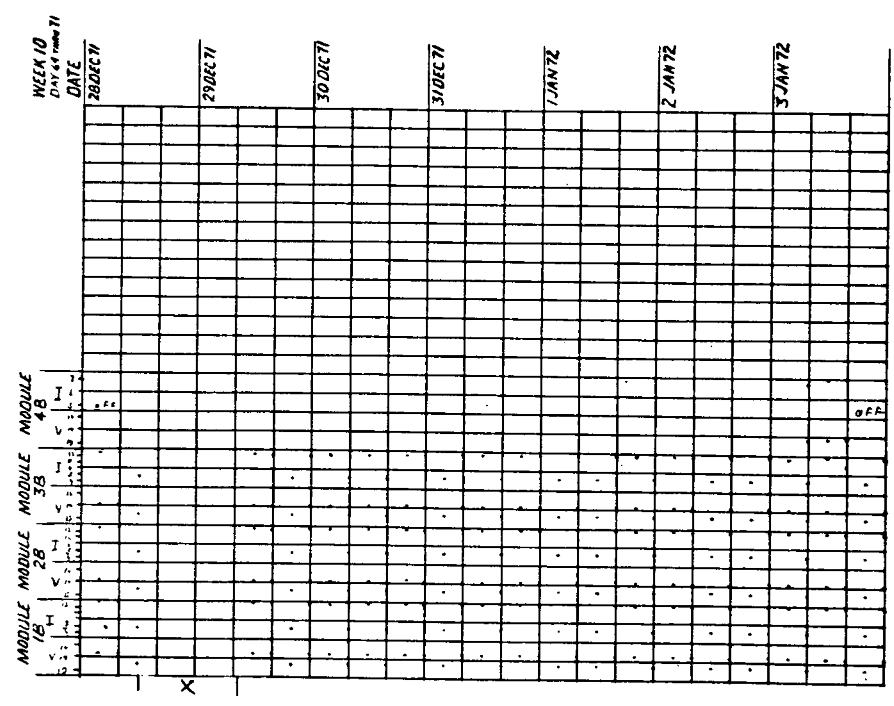


FIGURE A-20
CEU DAILY PERFORMANCE DATA

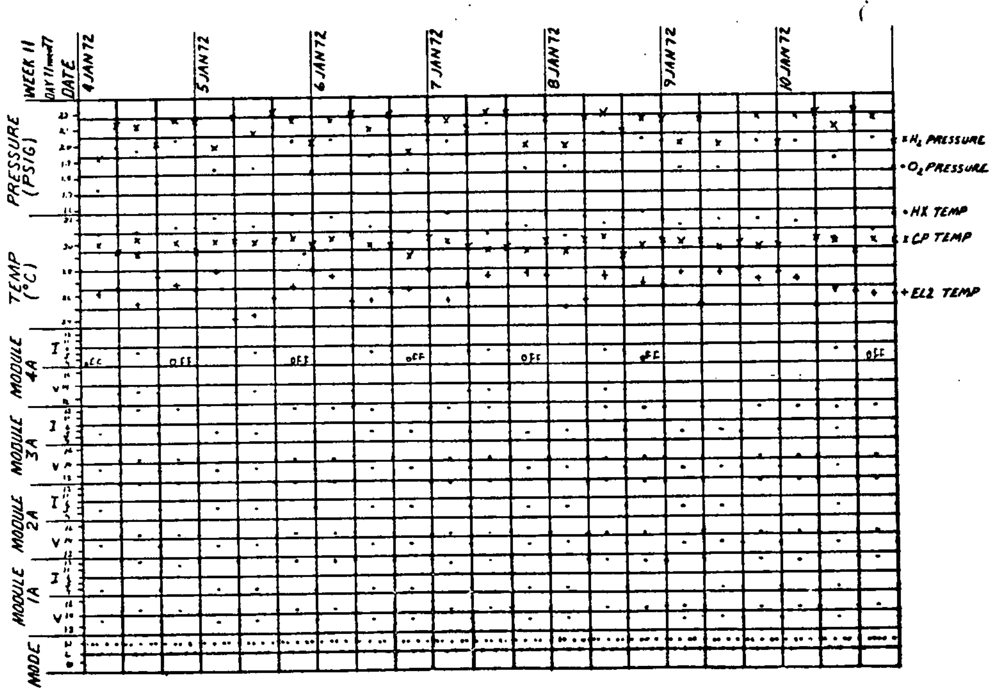


FIGURE A-21
CEU DAILY PERFORMANCE DATA

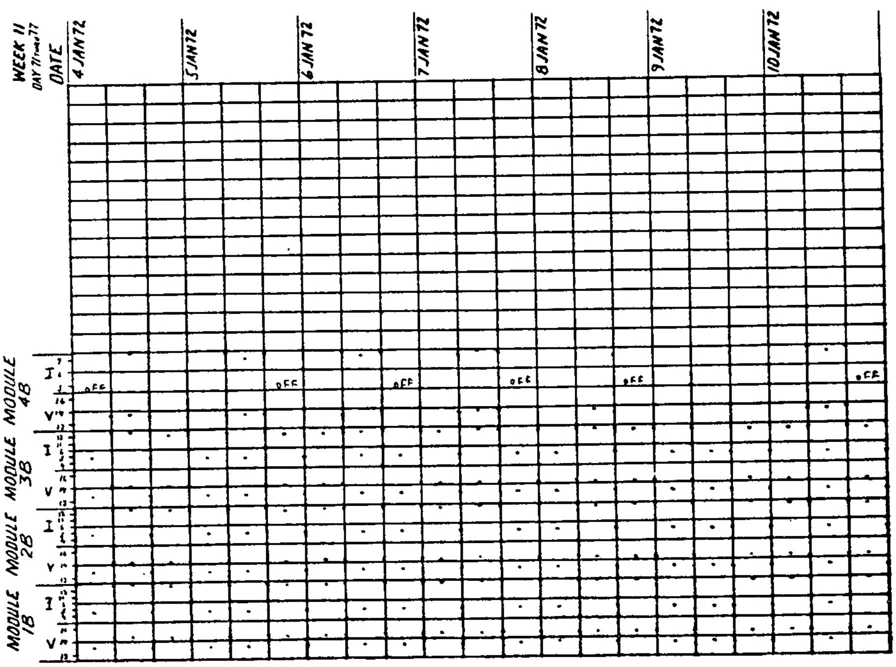


FIGURE A-22
CEU DAILY PERFORMANCE DATA

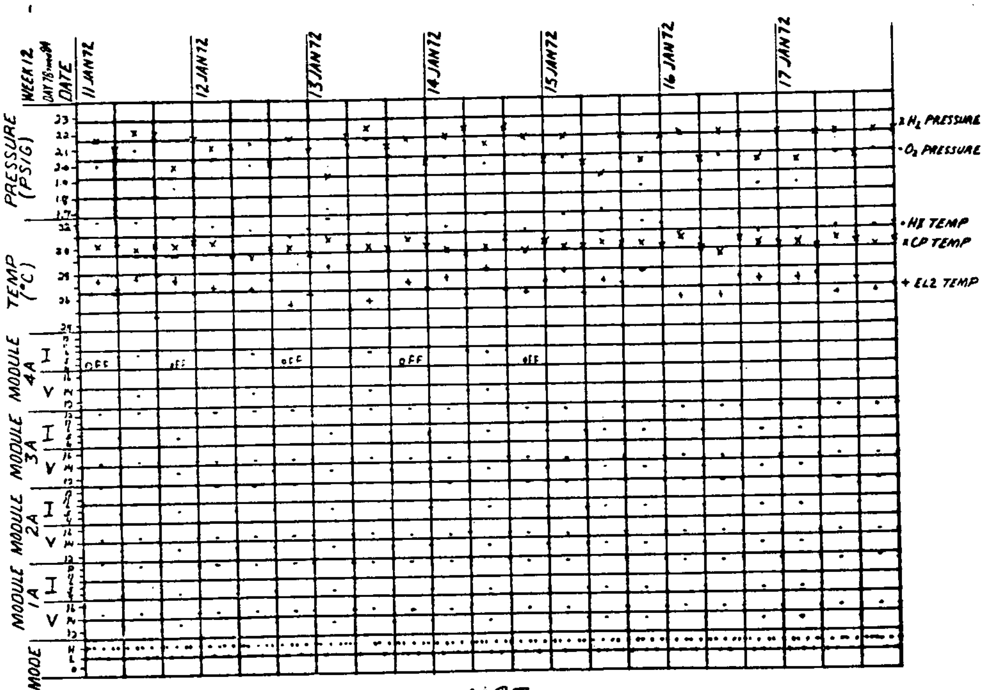


FIGURE A-23
CEU DAILY PERFORMANCE DATA

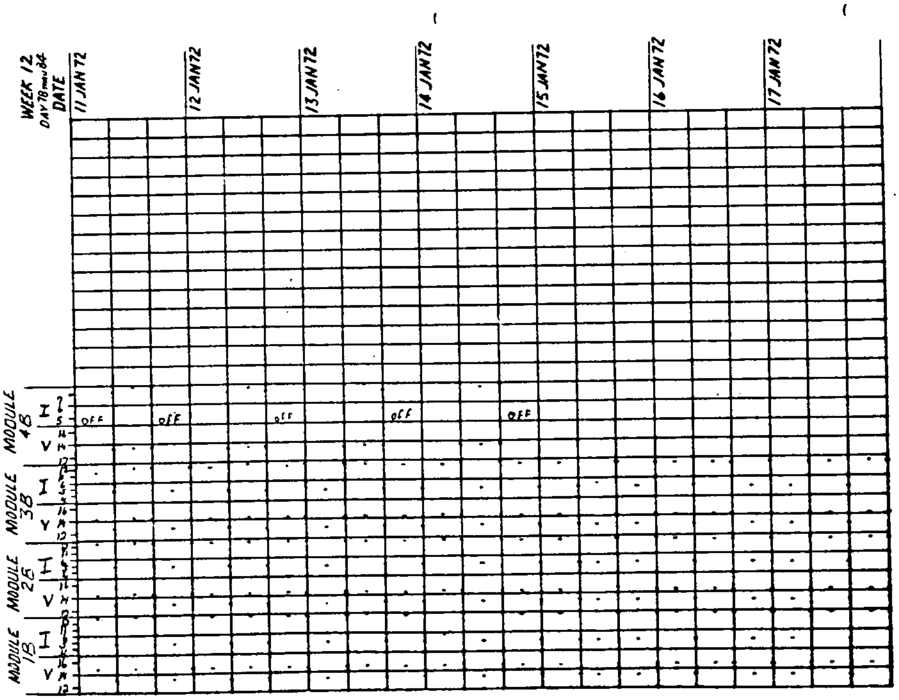


FIGURE A-24
CEU DAILY PERFORMANCE DATA

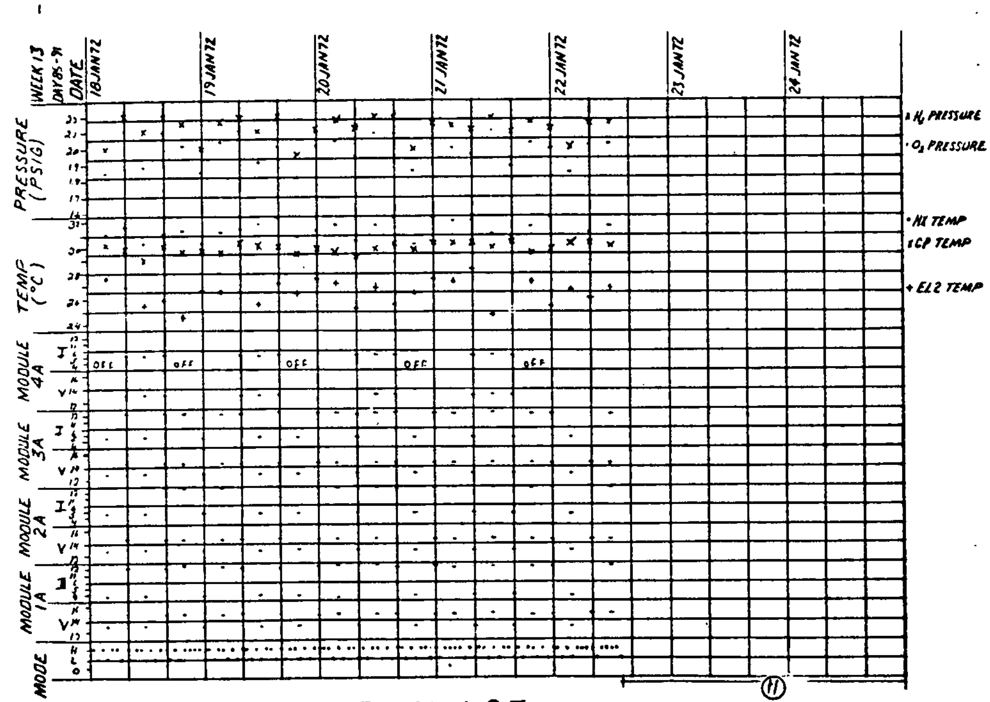


FIGURE A-25
CEU DAILY PERFORMANCE DATA

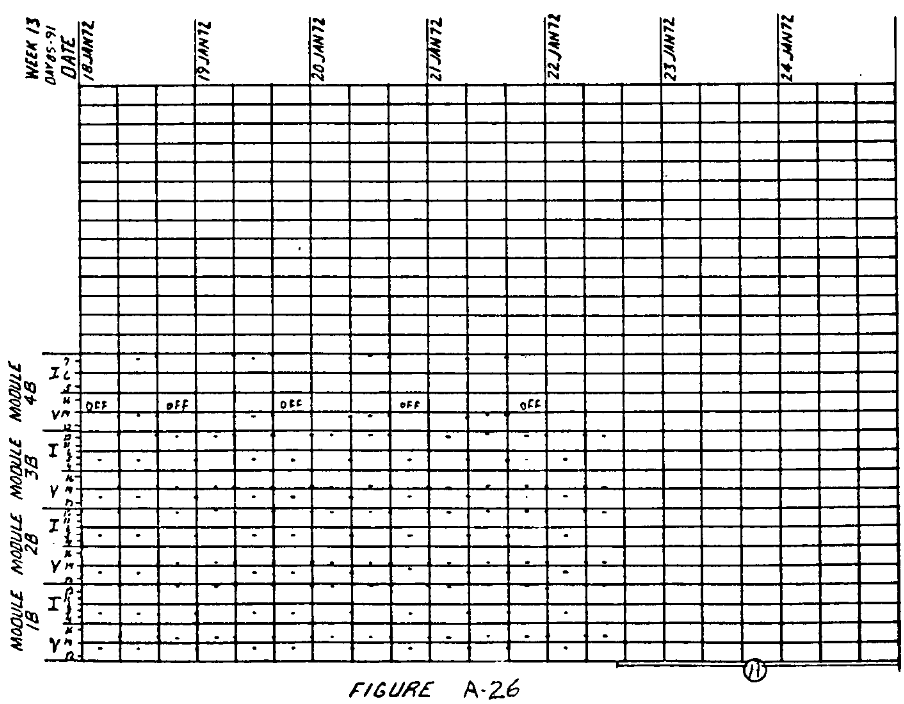


FIGURE A-26
CEU DAILY PERFORMANCE DATA

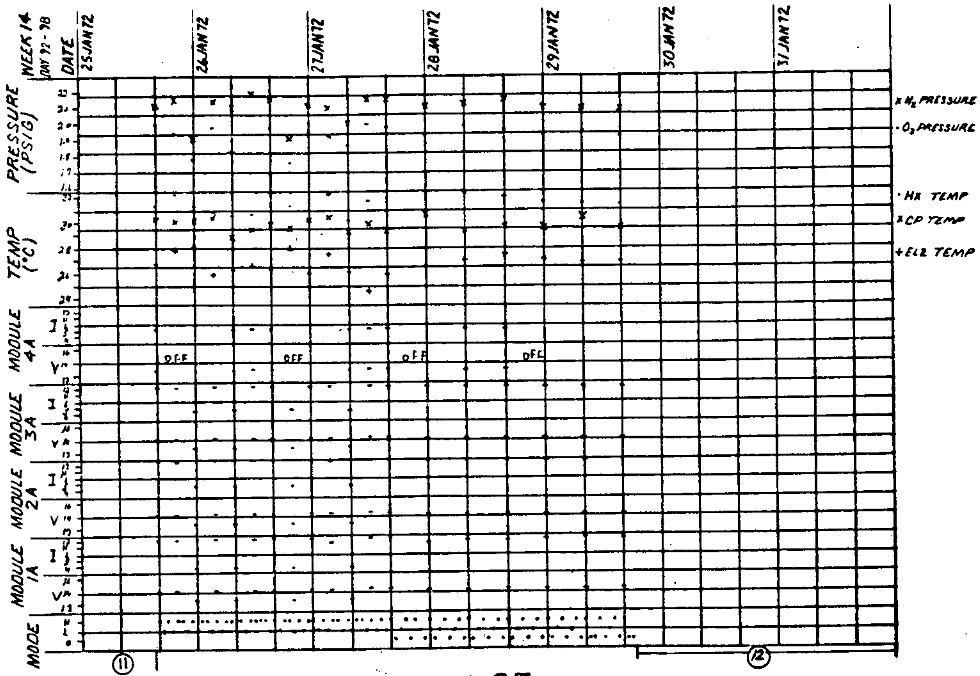


FIGURE A-27
CEU DAILY PERFORMANCE DATA

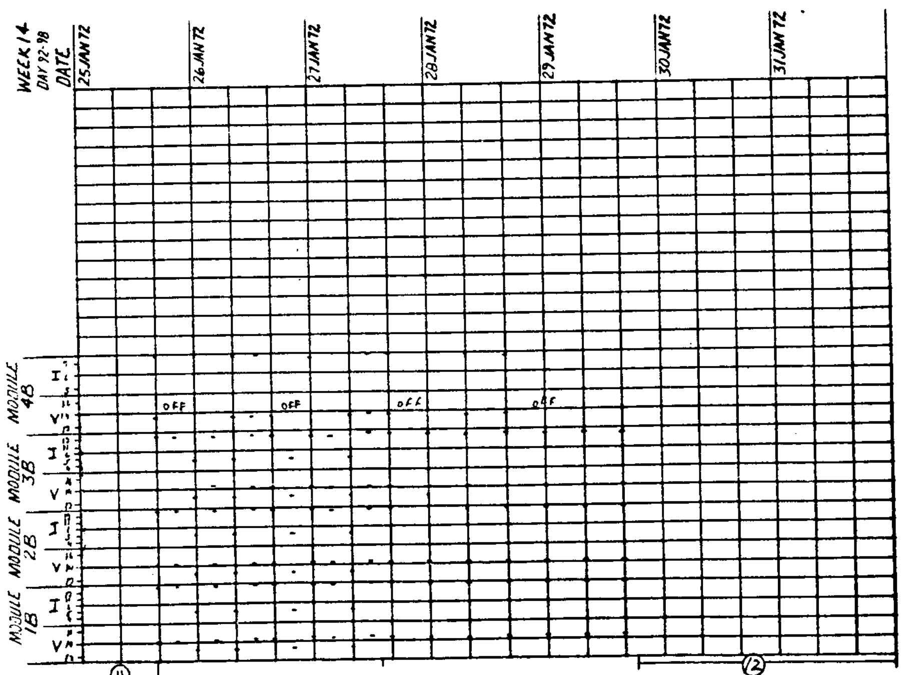


FIGURE A-28
CEU DAILY PERFORMANCE DATA

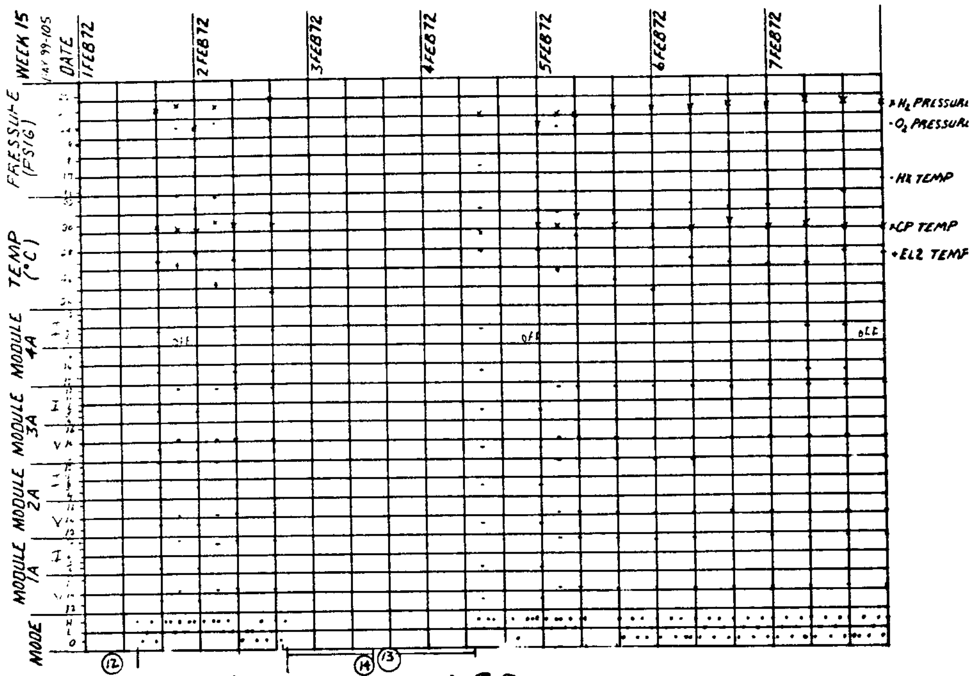


FIGURE A-29
CEU DAILY PERFORMANCE DATA

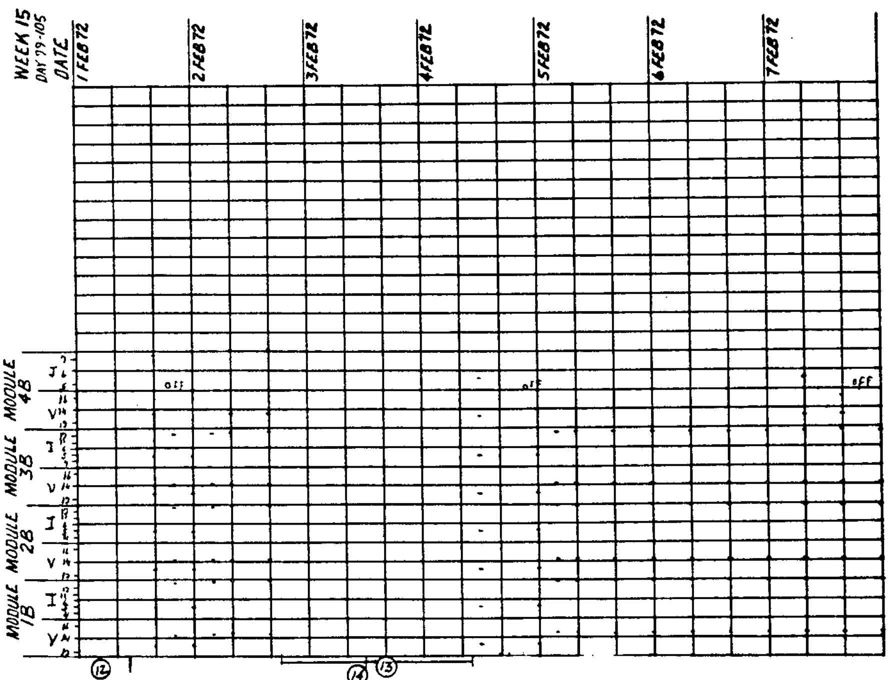


FIGURE A-30
CEU DAILY PERFORMANCE DATA

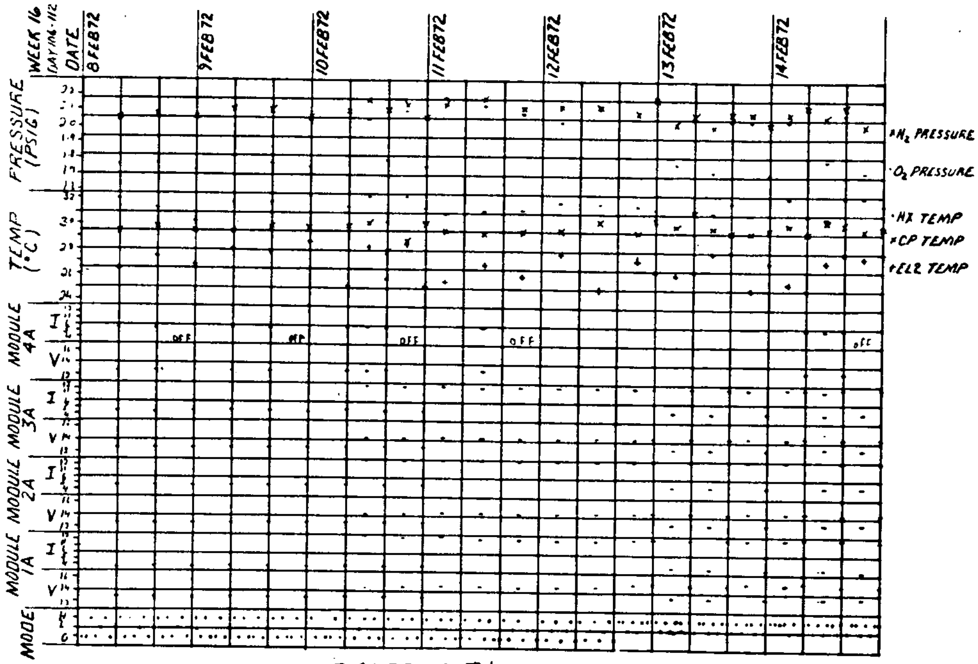


FIGURE A-31
CEU DAILY PERFORMANCE DATA

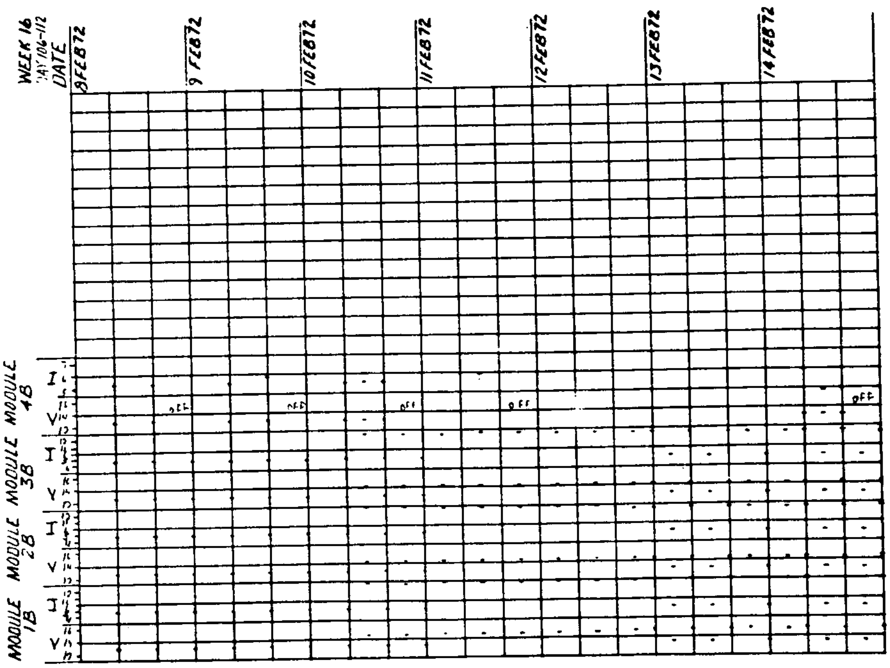


FIGURE A-32
CEU DAILY PERFORMANCE DATA

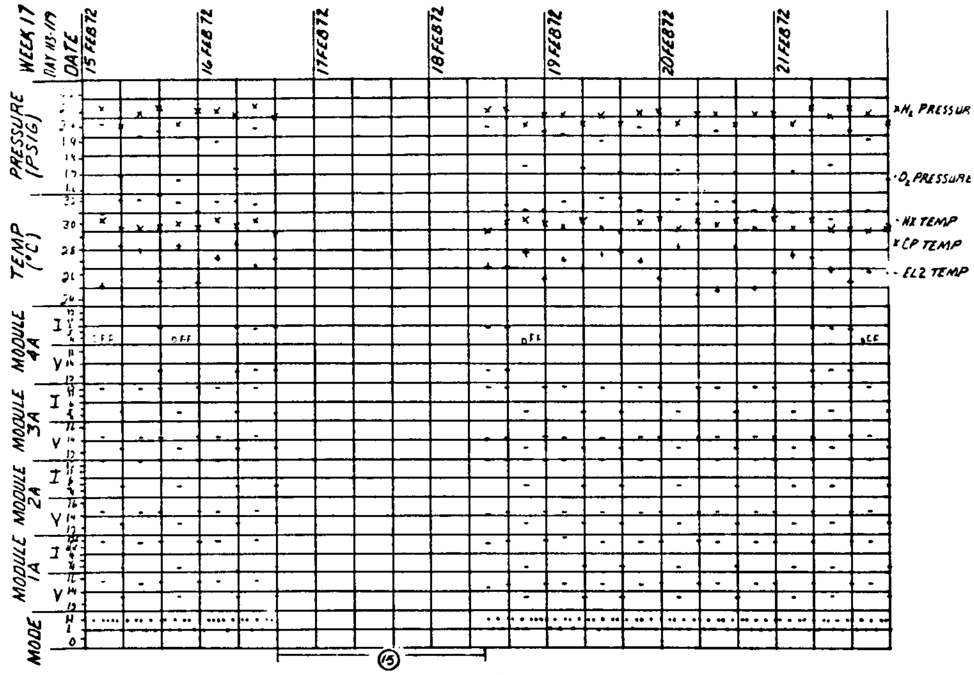


FIGURE A-33
CEU DAILY PERFORMANCE DATA

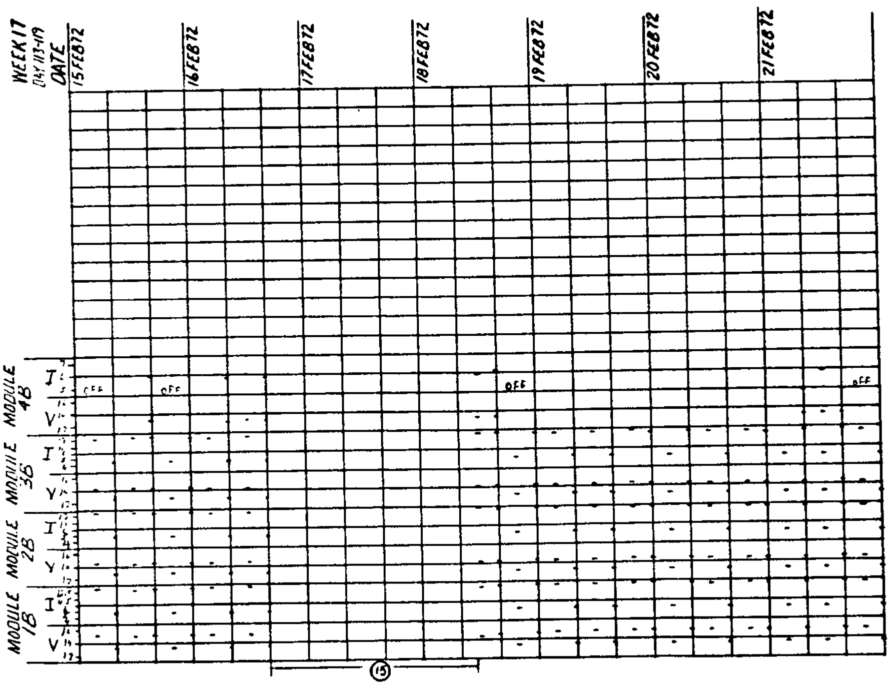


FIGURE A-34
CEU DAILY PERFORMANCE DATA

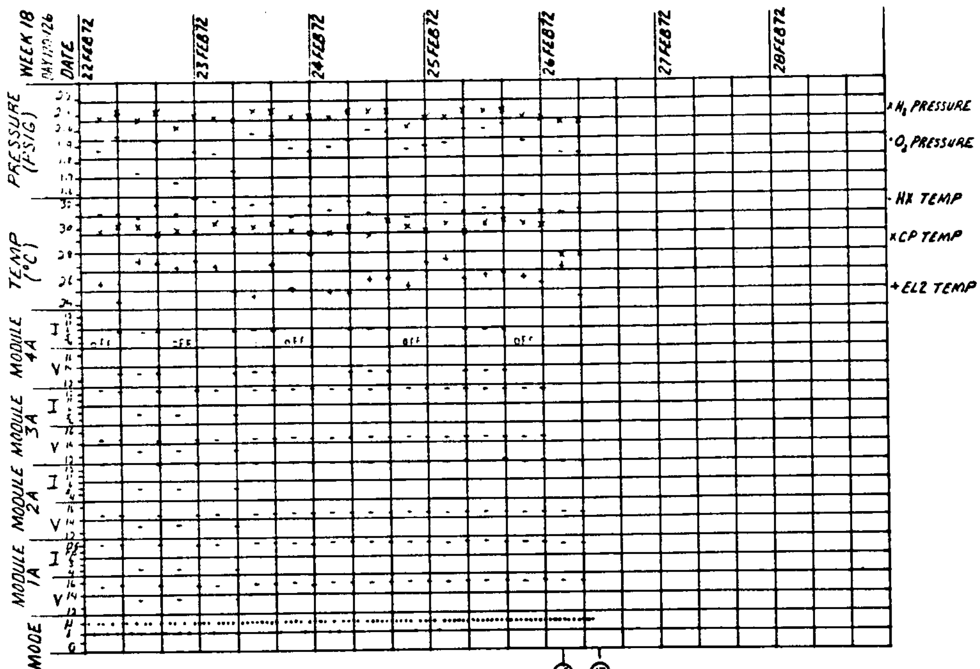


FIGURE A-35
CEU DAILY PERFORMANCE DATA

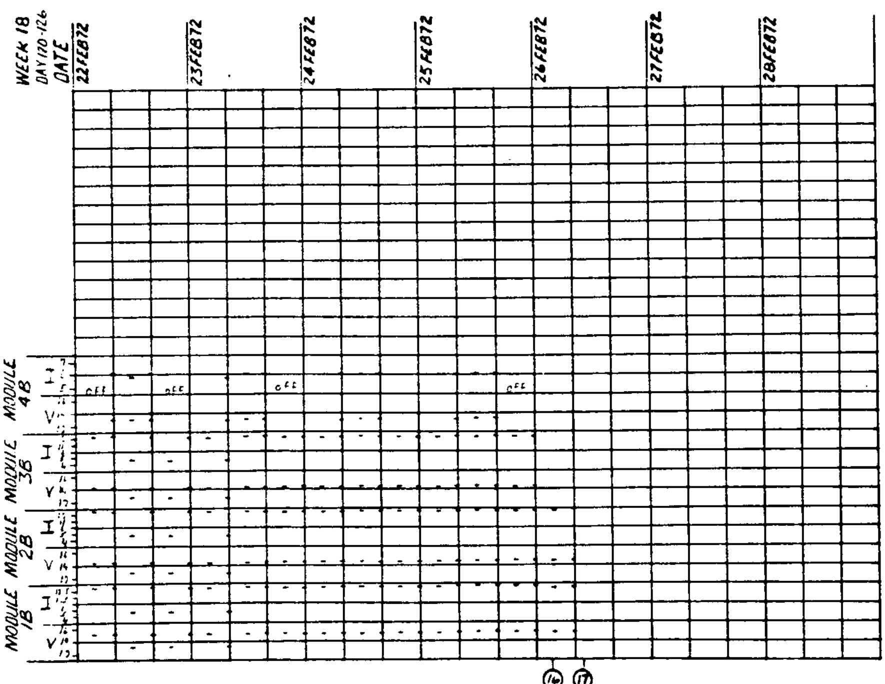


FIGURE A-36
CEU DAILY PERFORMANCE DATA

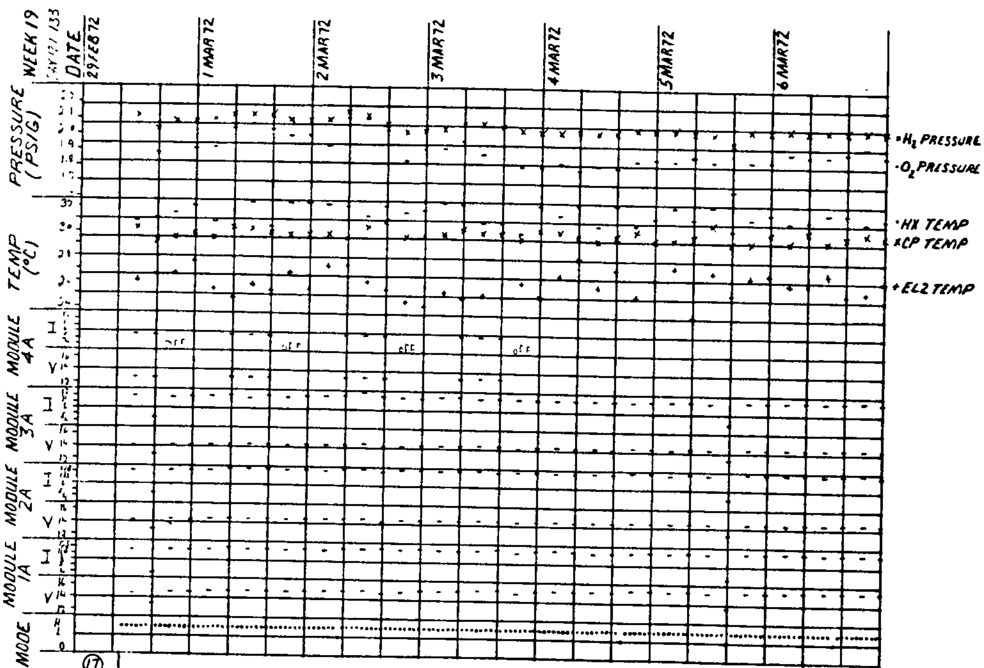


FIGURE A-37
CEU DAILY PERFORMANCE DATA

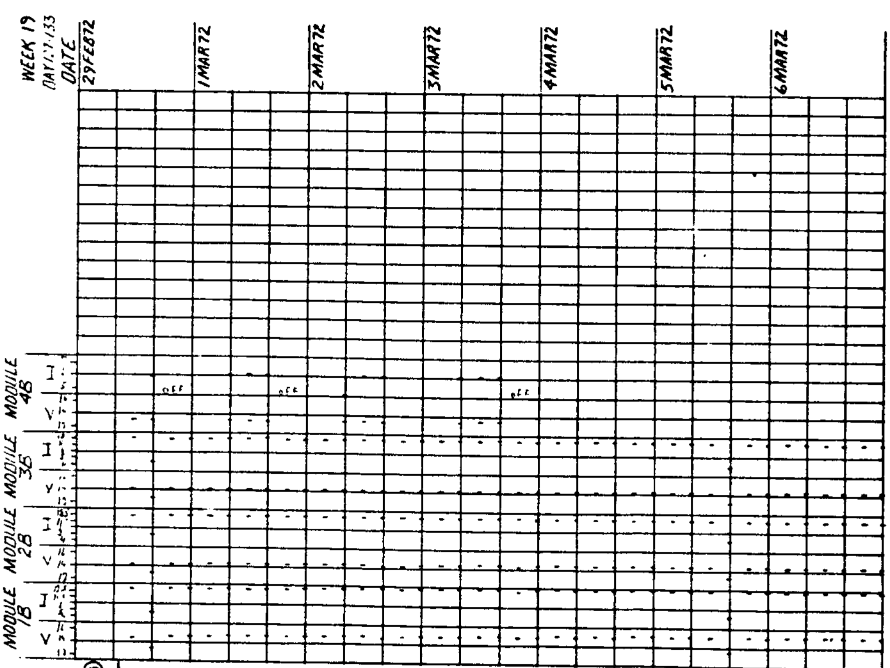


FIGURE A-38
CEU DAILY PERFORMANCE DATA

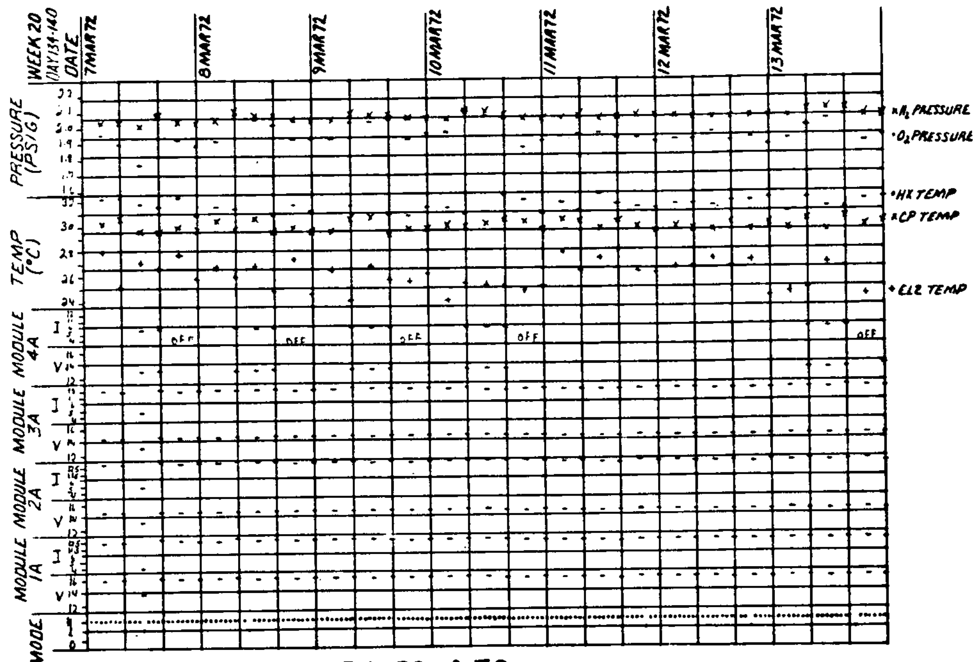


FIGURE A-39
CEU DAILY PERFORMANCE DATA

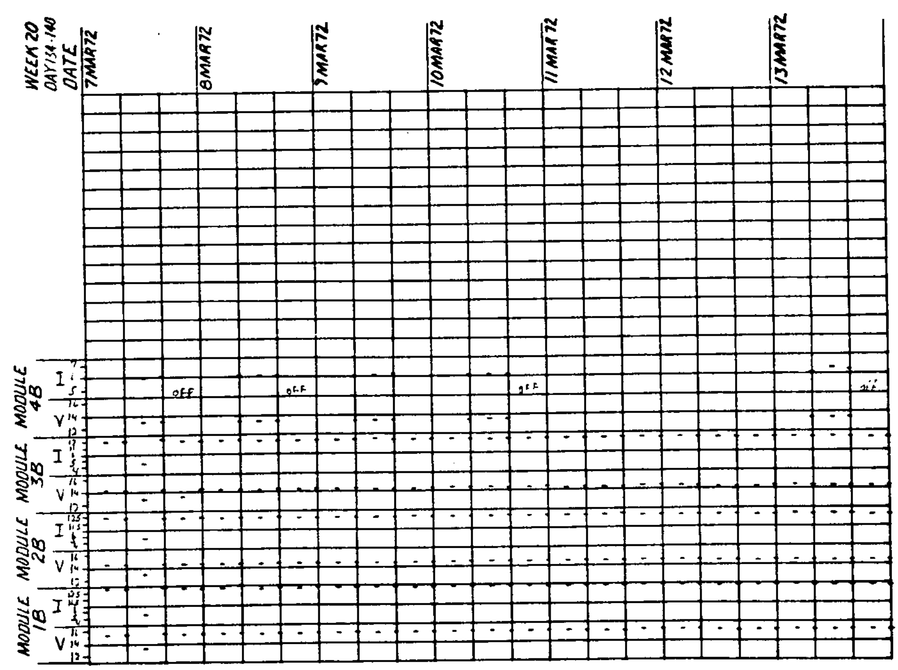


FIGURE A-40
CEU DAILY PERFORMANCE DATA

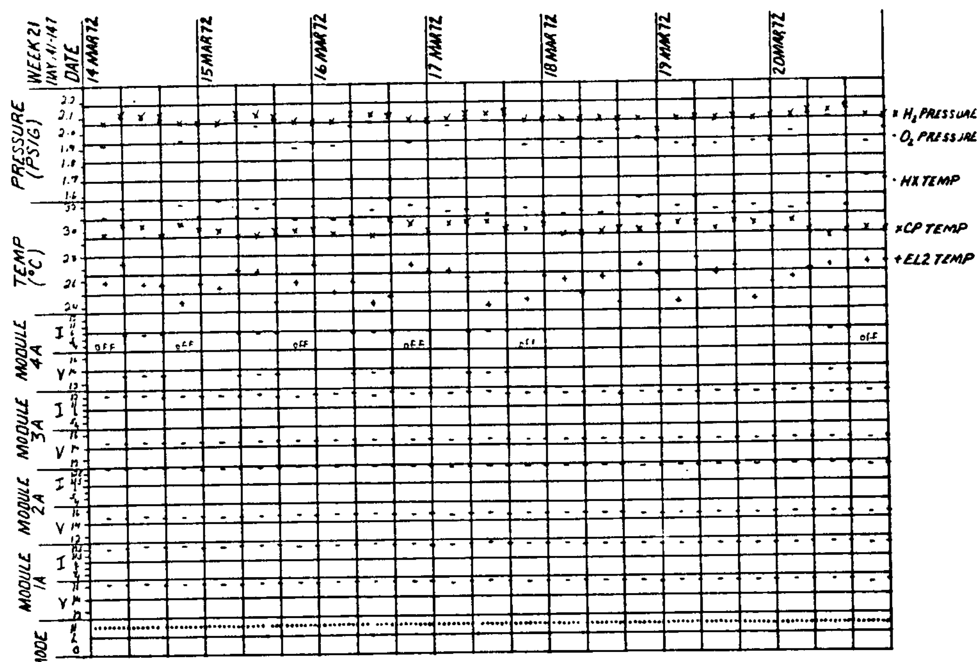


FIGURE A-41
CEU DAILY PERFORMANCE DATA

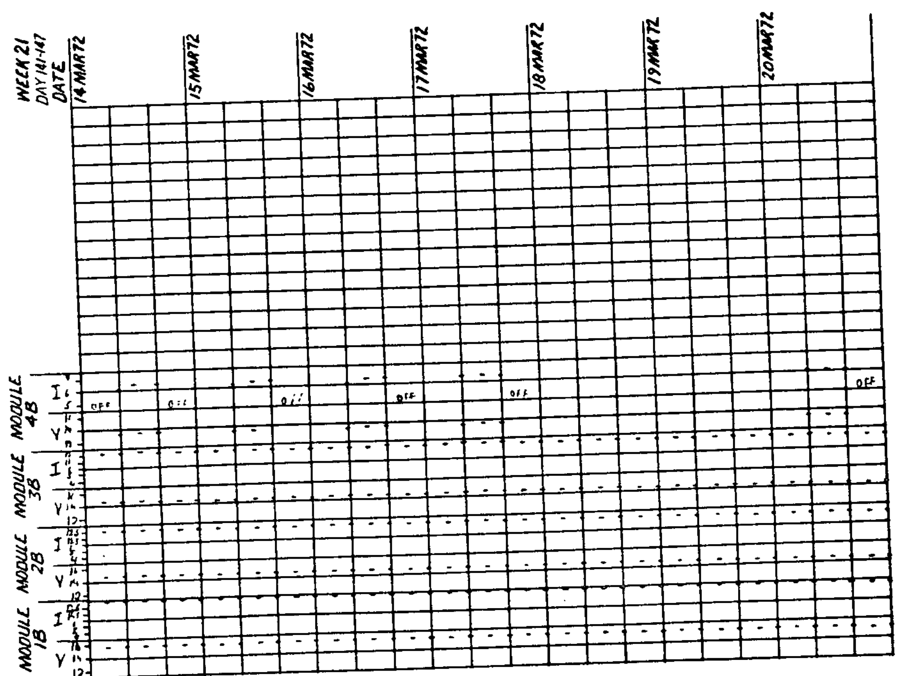


FIGURE A-42
CEU DAILY PERFORMANCE DATA

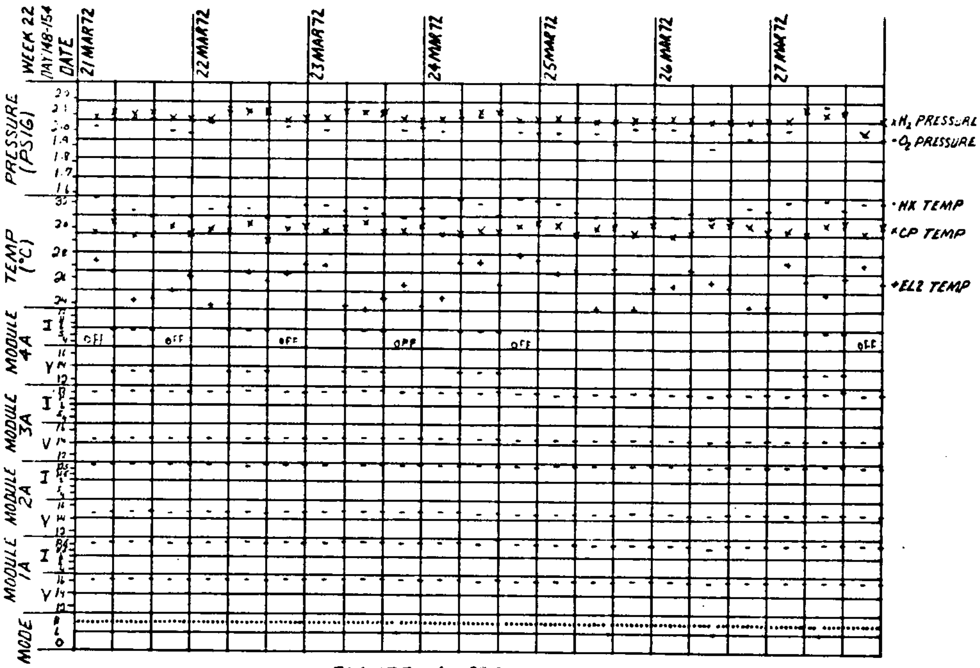


FIGURE A-43
CEU DAILY PERFORMANCE DATA

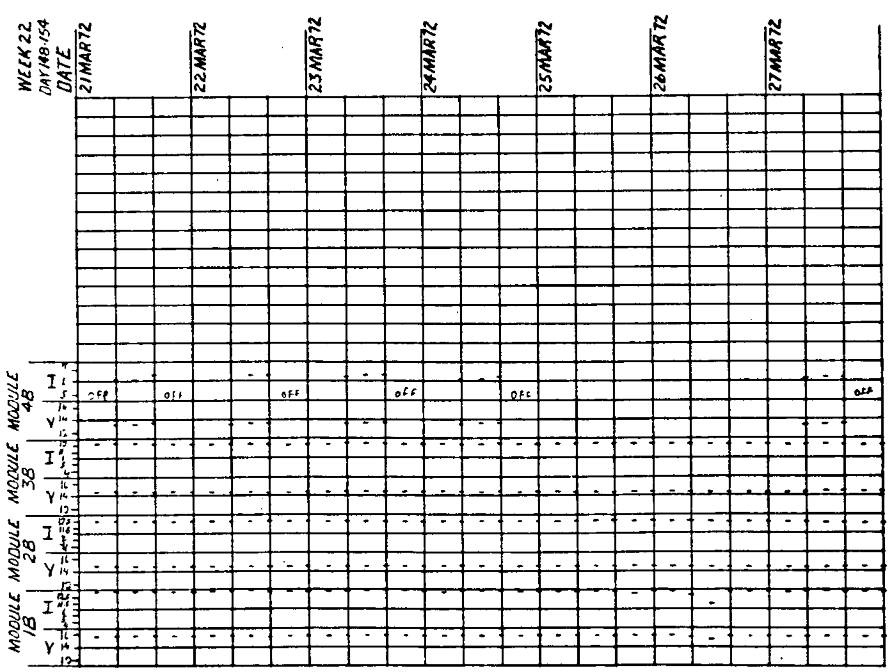


FIGURE A-44
CEU DAILY PERFORMANCE DATA

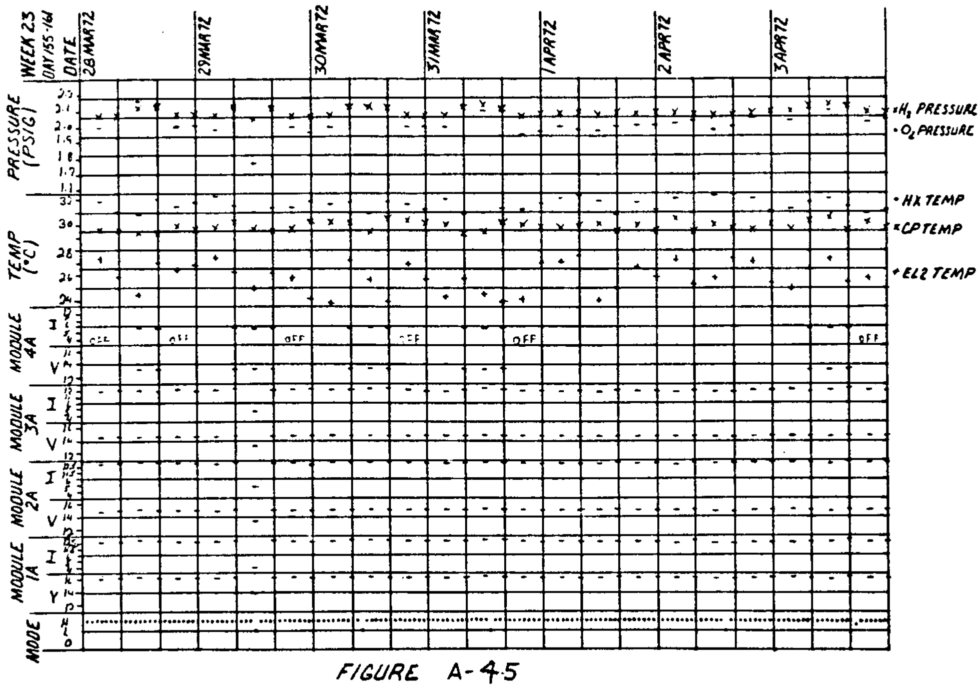


FIGURE A-4.5

CEU DAILY PERFORMANCE DATA

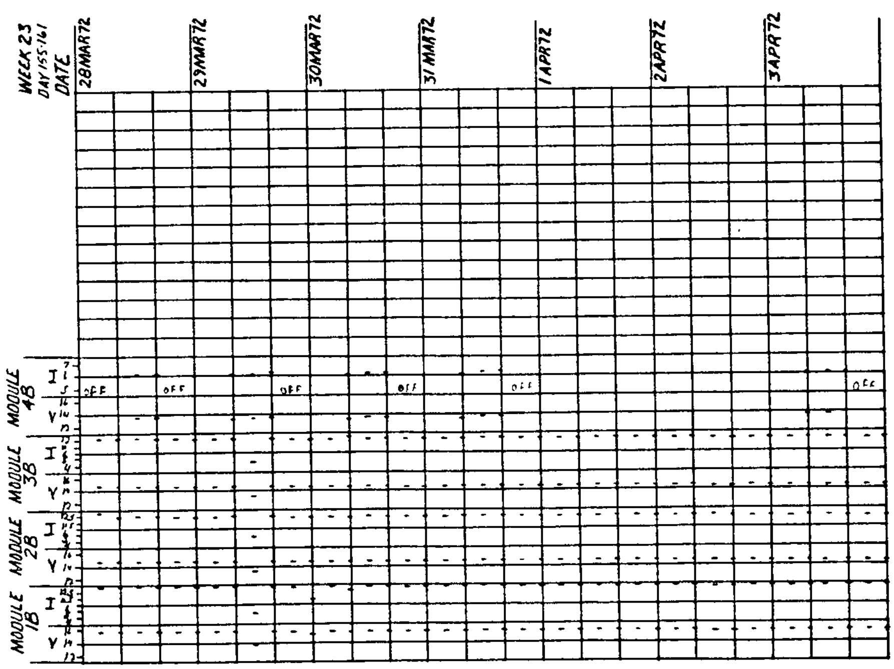


FIGURE A-4.6

CEU DAILY PERFORMANCE DATA

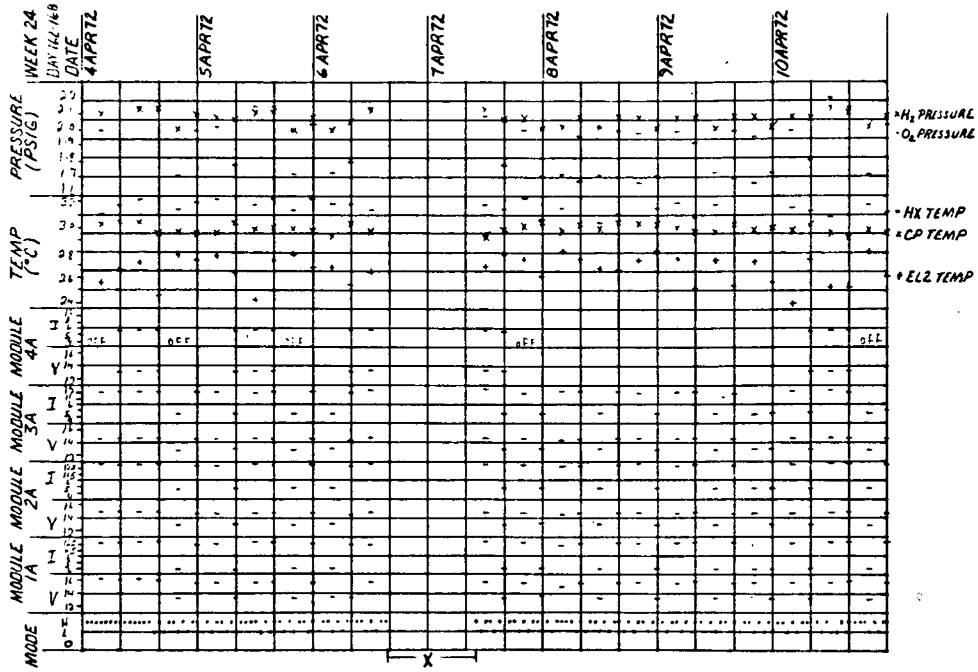


FIGURE A-47
CEU DAILY PERFORMANCE DATA

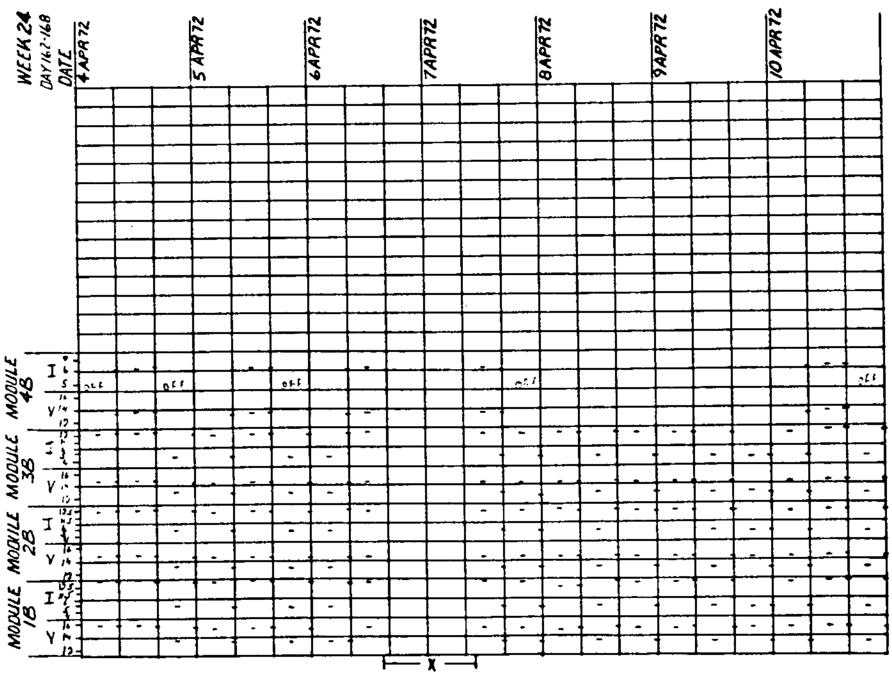


FIGURE A-48
CEU DAILY PERFORMANCE DATA

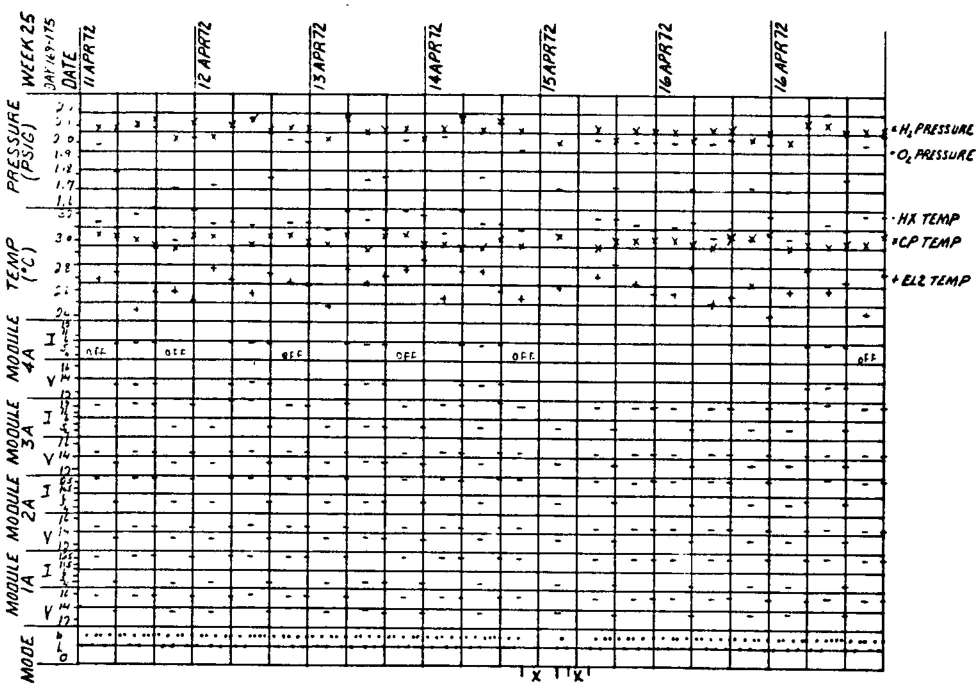


FIGURE A-49
CEU DAILY PERFORMANCE DATA

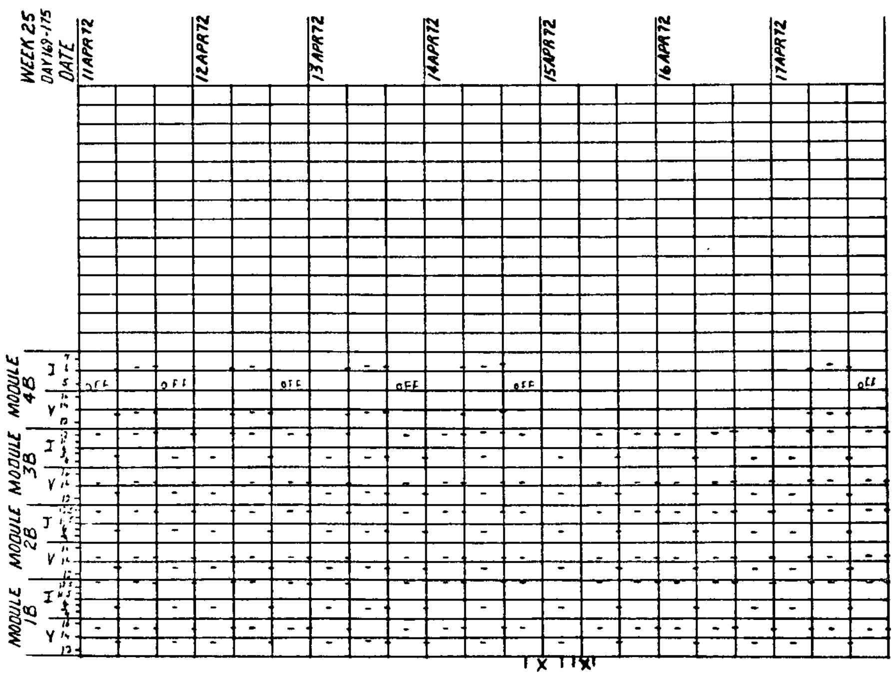


FIGURE A-50
CEU DAILY PERFORMANCE DATA

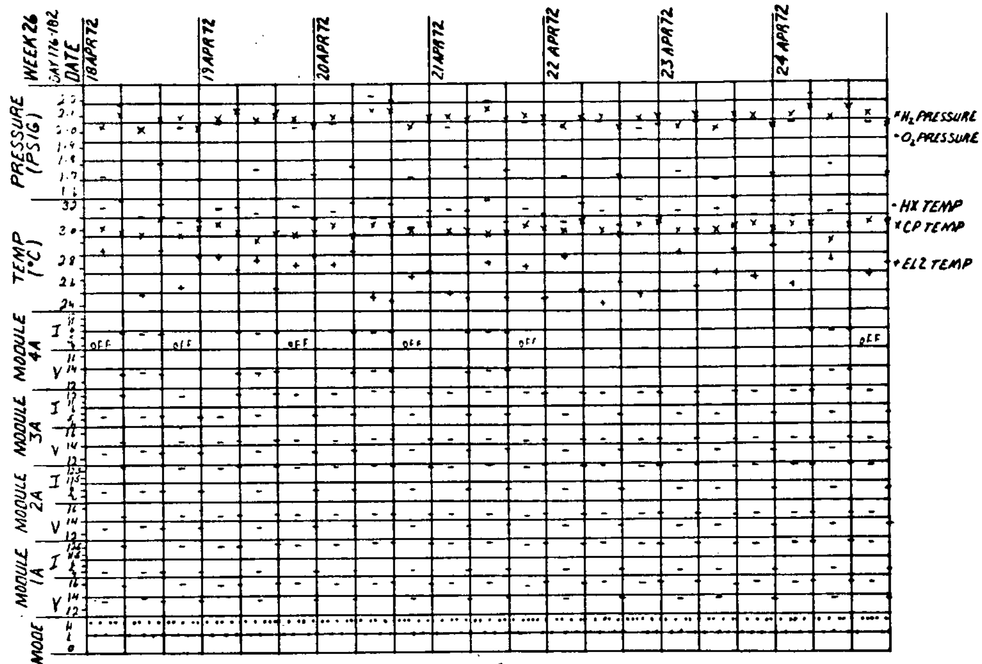


FIGURE A-51
CEU DAILY PERFORMANCE DATA

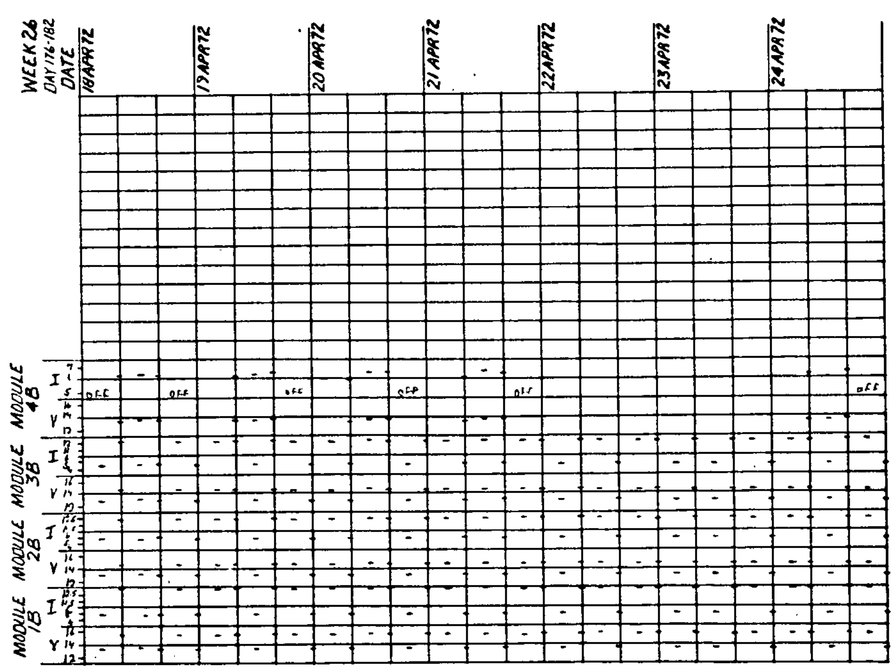


FIGURE A-52
CEU DAILY PERFORMANCE DATA

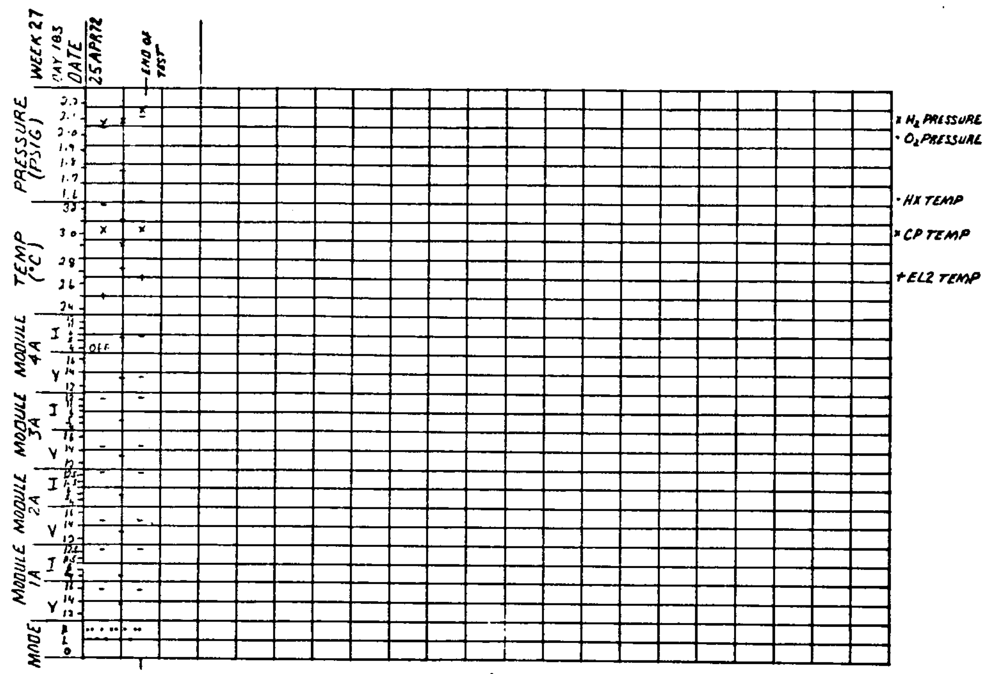


FIGURE A-53
CEU DAILY PERFORMANCE DATA

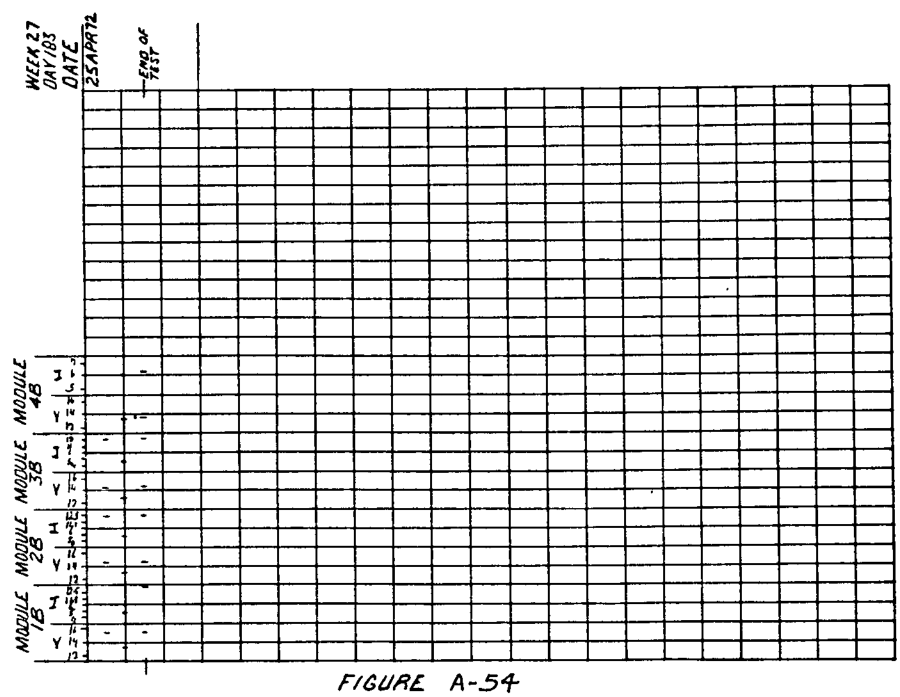


FIGURE A-54
CEU DAILY PERFORMANCE DATA

FIGURE A-55
MODULE 1 SUMMARY PERFORMANCE DATA

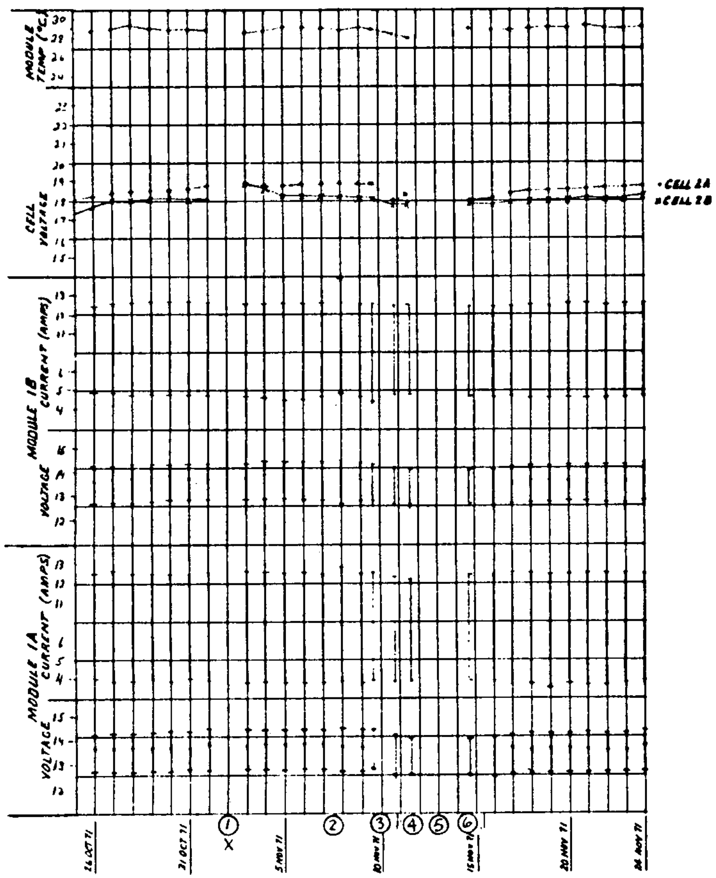
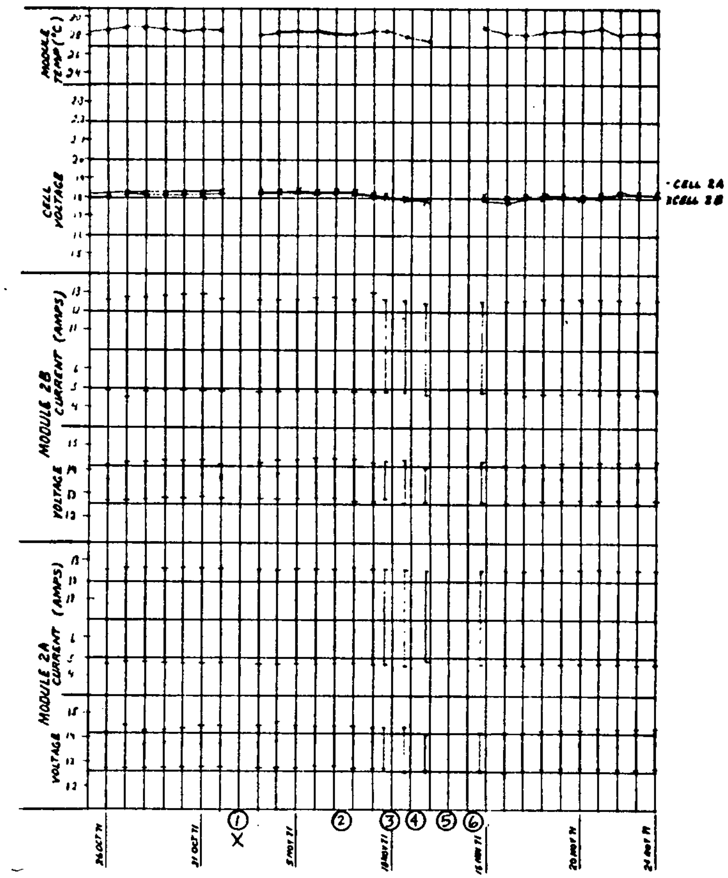


FIGURE A-56
MODULE 2 SUMMARY PERFORMANCE DATA



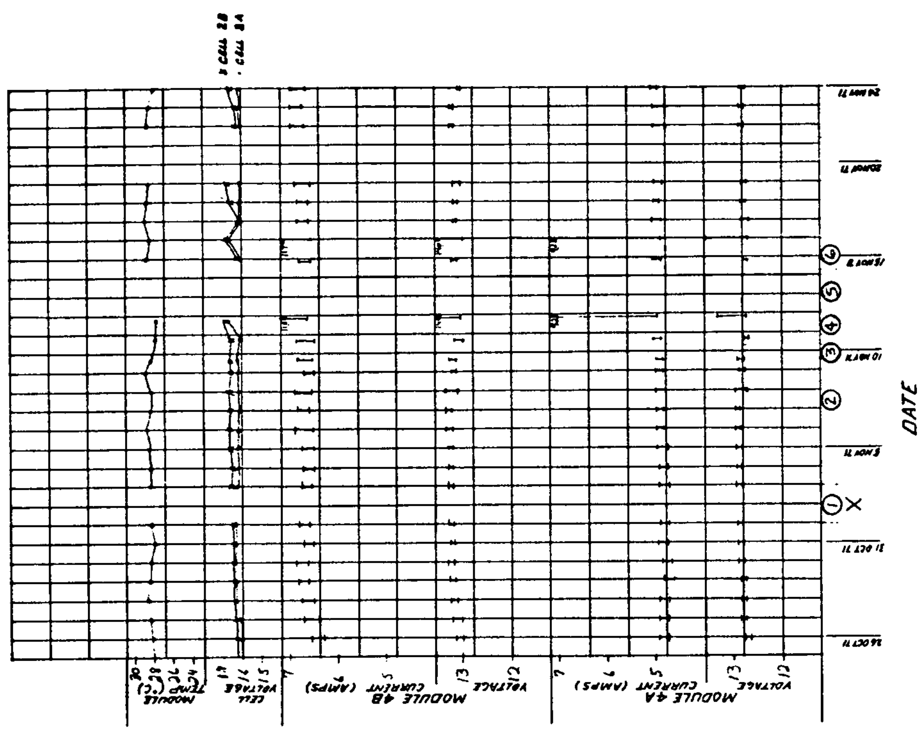


FIGURE A-58
MODULE 4 SUMMARY PERFORMANCE DATA

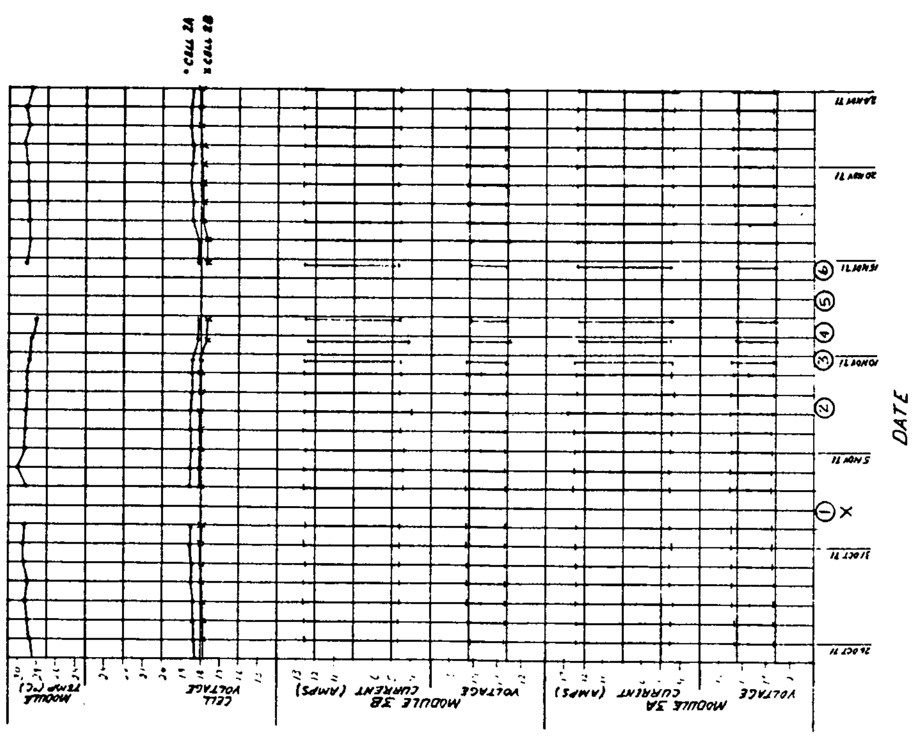


FIGURE A-57
MODULE 3 SUMMARY PERFORMANCE DATA

FIGURE A-59

MODULE 1 SUMMARY PERFORMANCE DATA

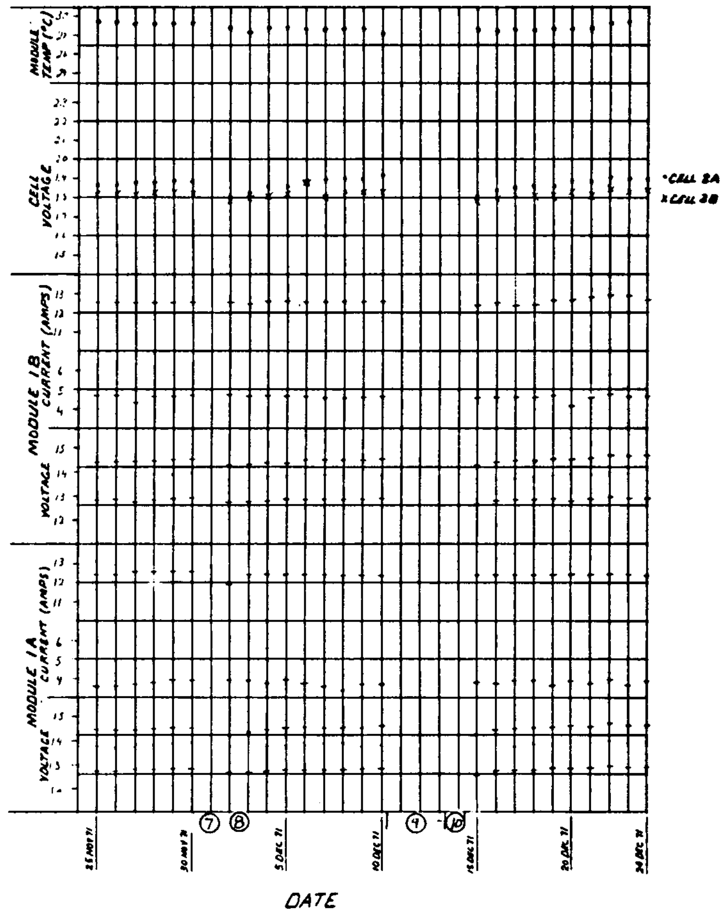


FIGURE A-60

MODULE 2 SUMMARY PERFORMANCE DATA

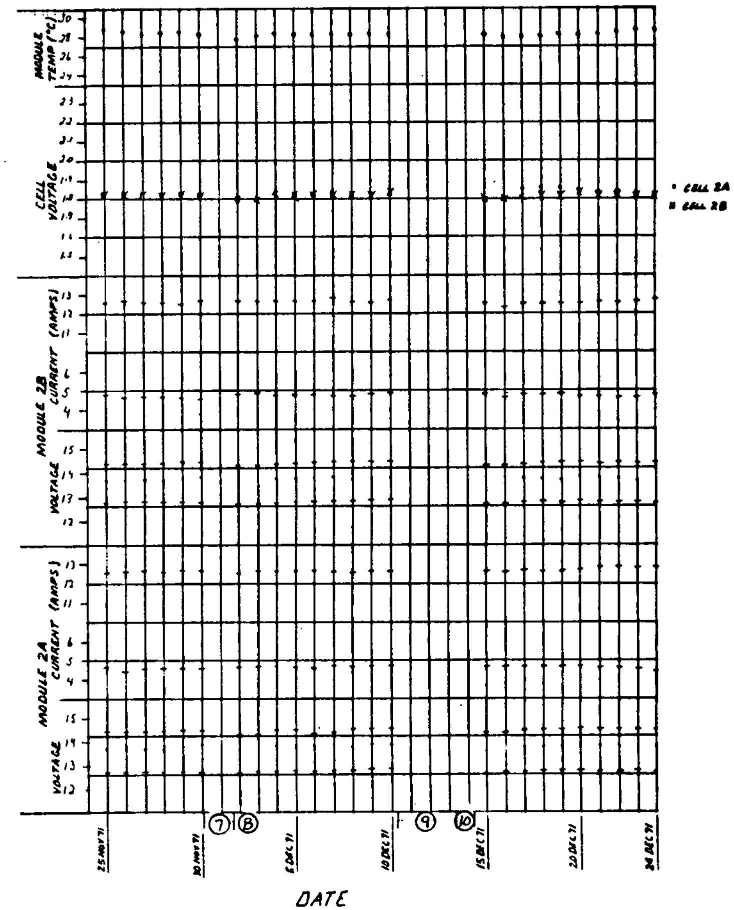


FIGURE A-62
MODULE 4 SUMMARY PERFORMANCE DATA

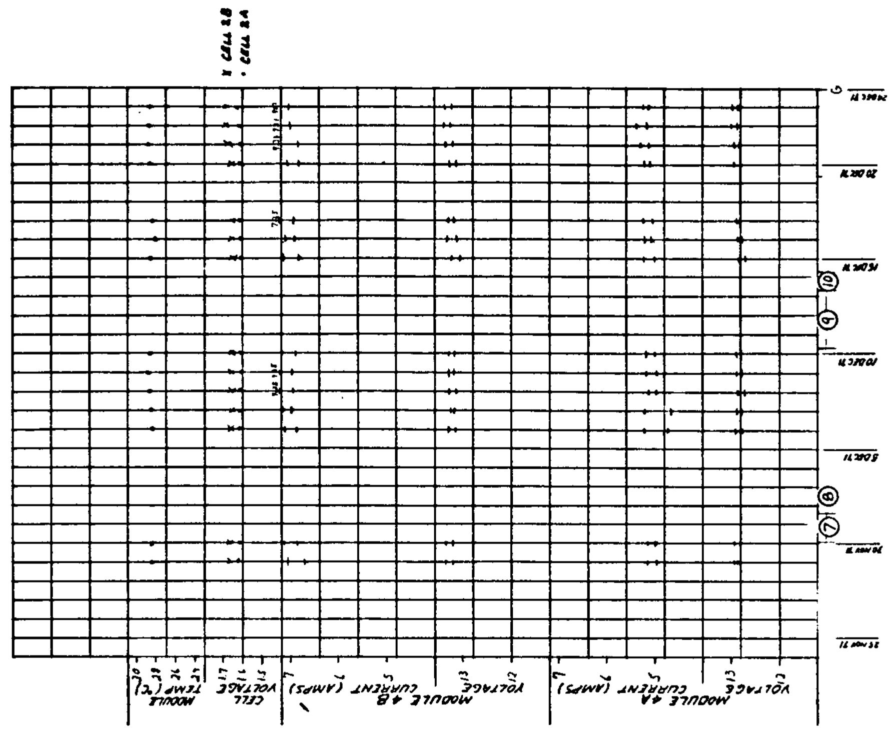


FIGURE A-61
MODULE 3 SUMMARY PERFORMANCE DATA

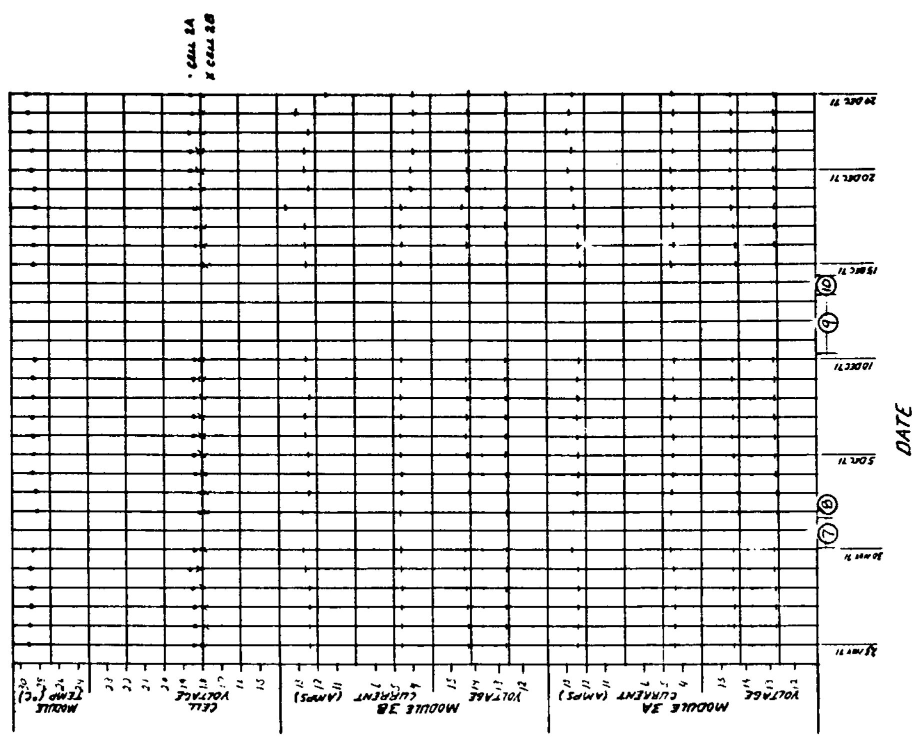


FIGURE A-64
MODULE 2 SUMMARY PERFORMANCE DATA

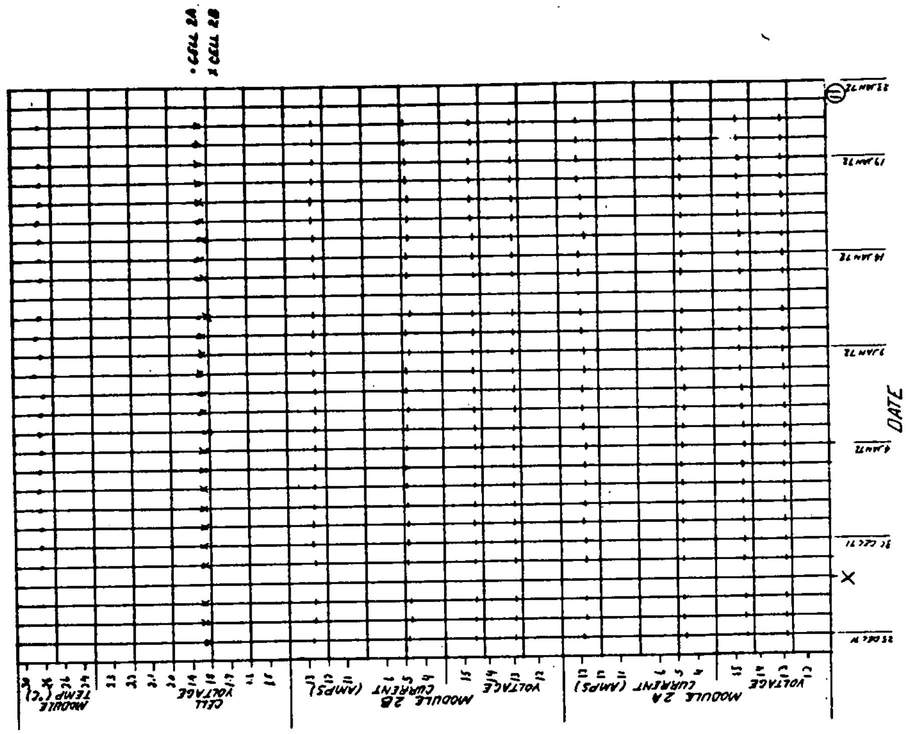
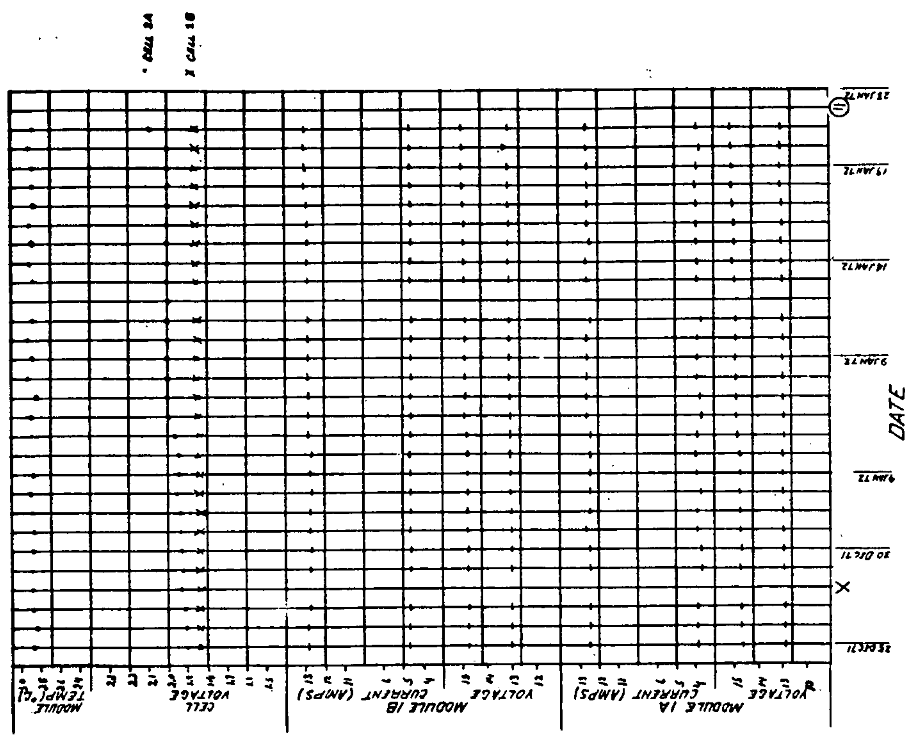


FIGURE A-63
MODULE 1 SUMMARY PERFORMANCE DATA



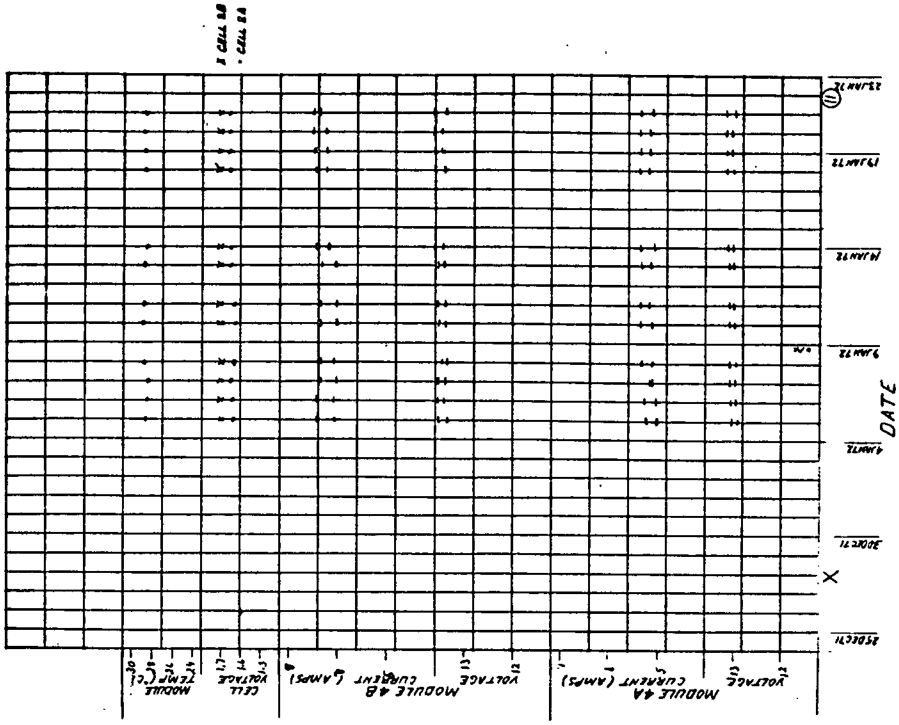


FIGURE A-66
MODULE 4 SUMMARY PERFORMANCE DATA

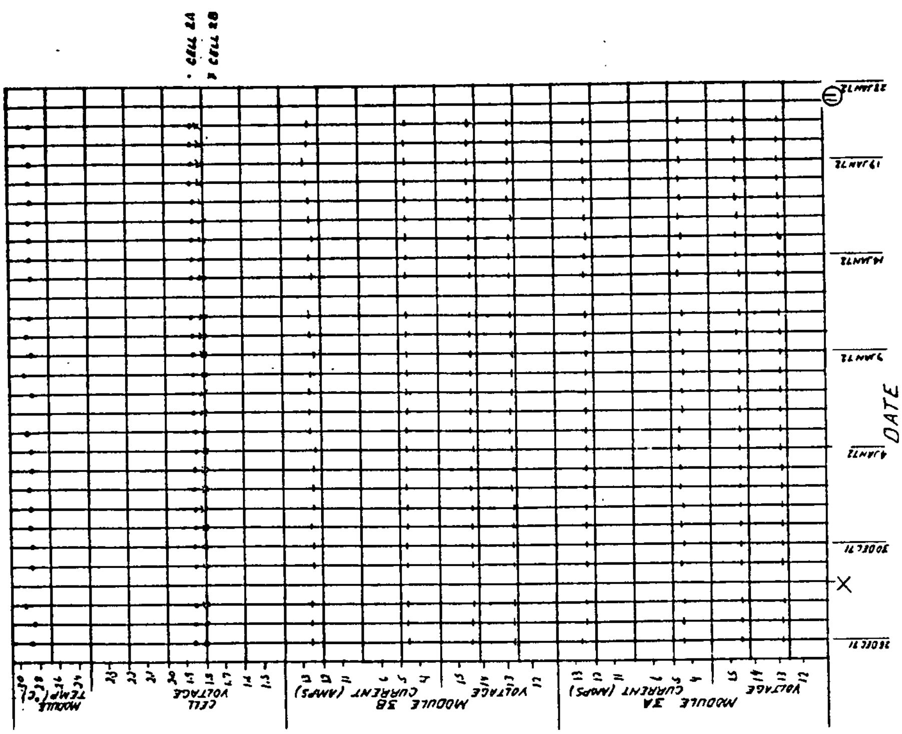


FIGURE A-65
MODULE 3 SUMMARY PERFORMANCE DATA

FIGURE A-67
MODULE 1 SUMMARY PERFORMANCE DATA

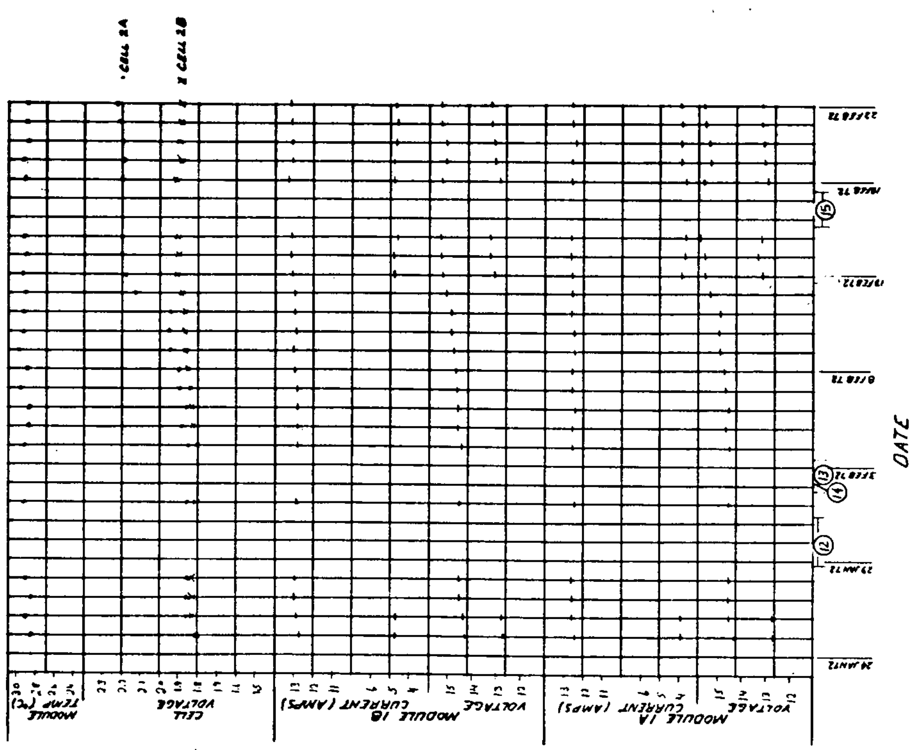
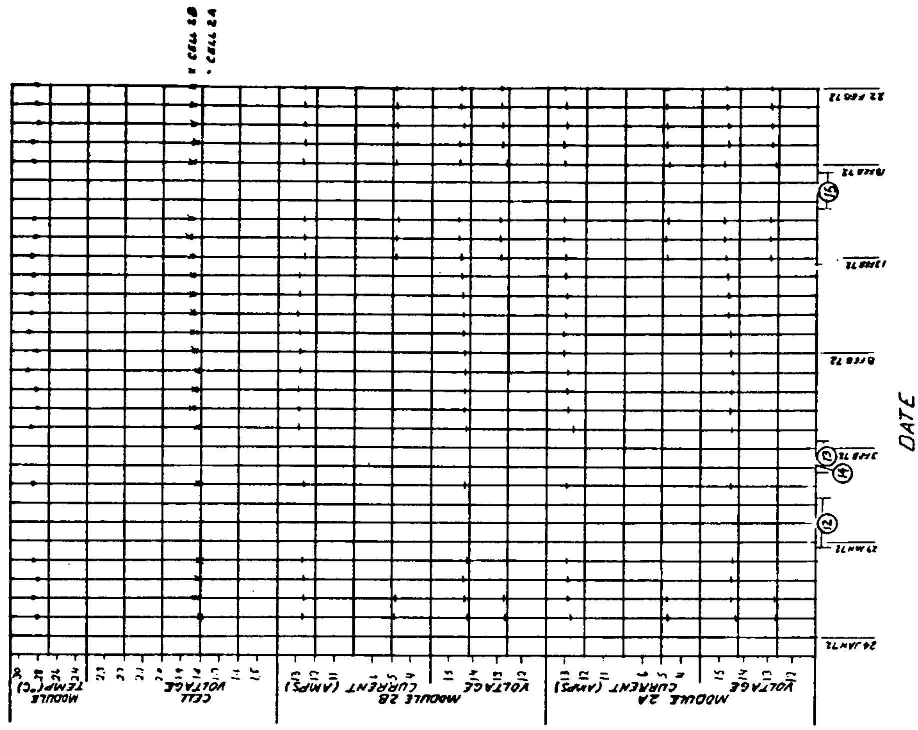


FIGURE A-68
MODULE 2 SUMMARY PERFORMANCE DATA



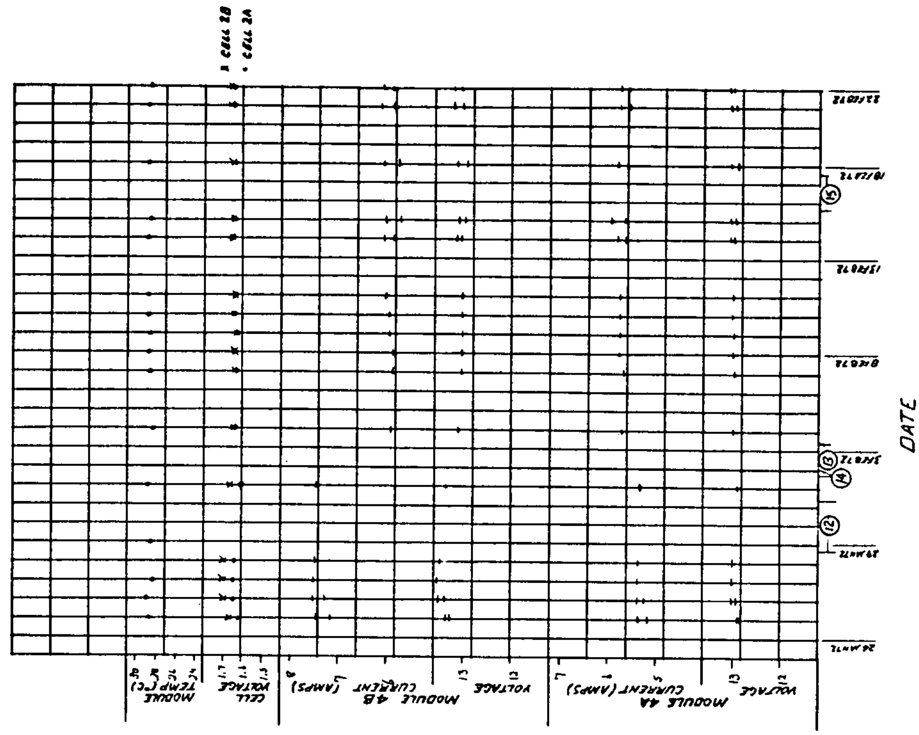


FIGURE A-70
MODULE 4 SUMMARY PERFORMANCE DATA

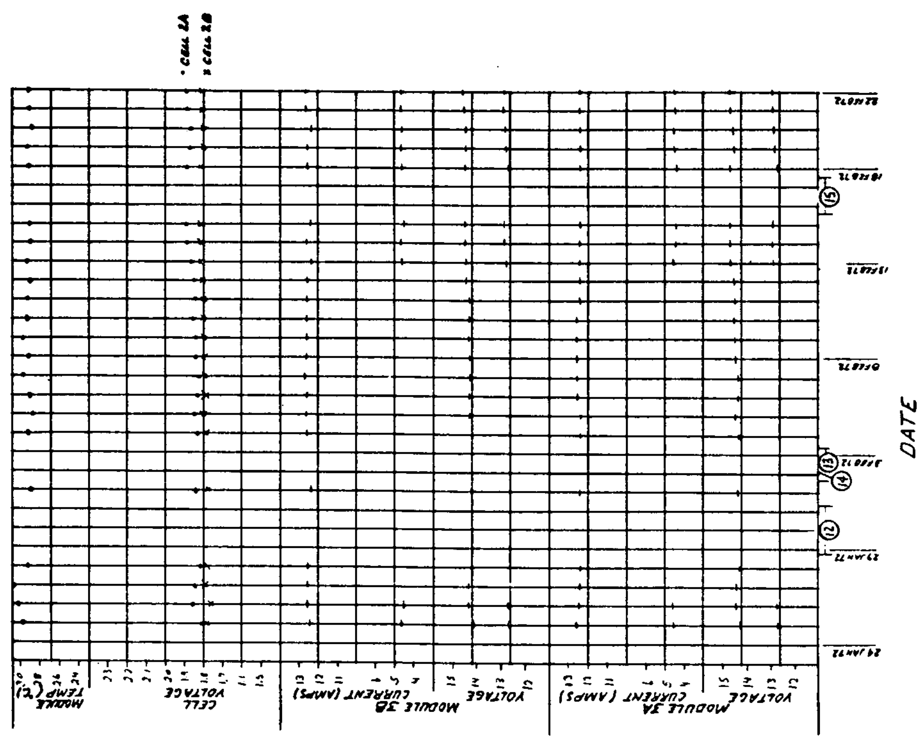


FIGURE A-69
MODULE 3 SUMMARY PERFORMANCE DATA

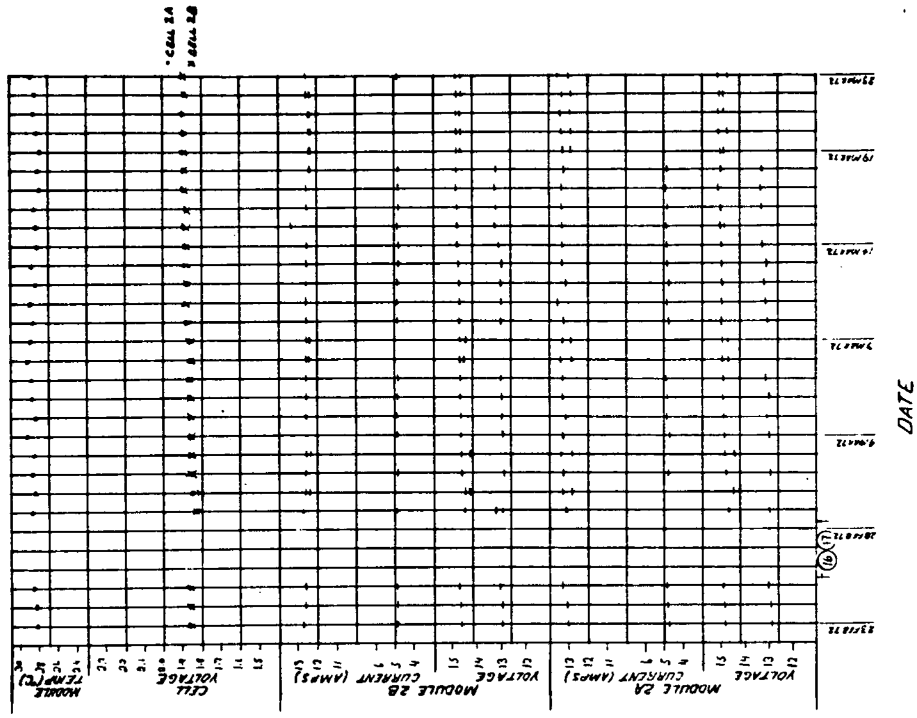


FIGURE A-72
MODULE 2 SUMMARY PERFORMANCE DATA

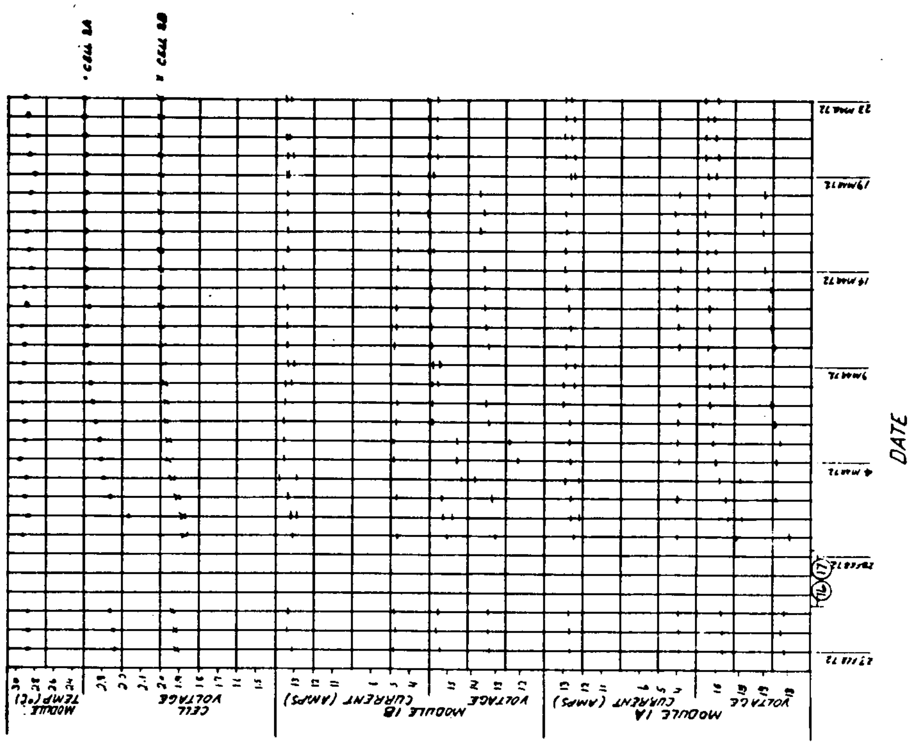


FIGURE A-71
MODULE 1 SUMMARY PERFORMANCE DATA

FIGURE A-73
MODULE 3 SUMMARY PERFORMANCE DATA

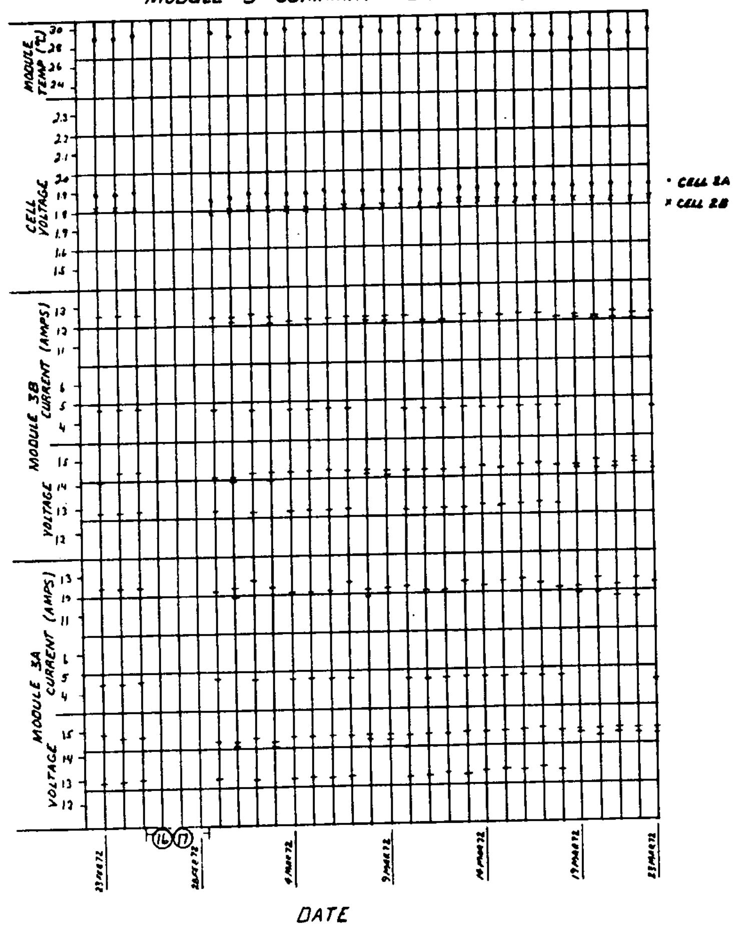


FIGURE A-74
MODULE 4 SUMMARY PERFORMANCE DATA

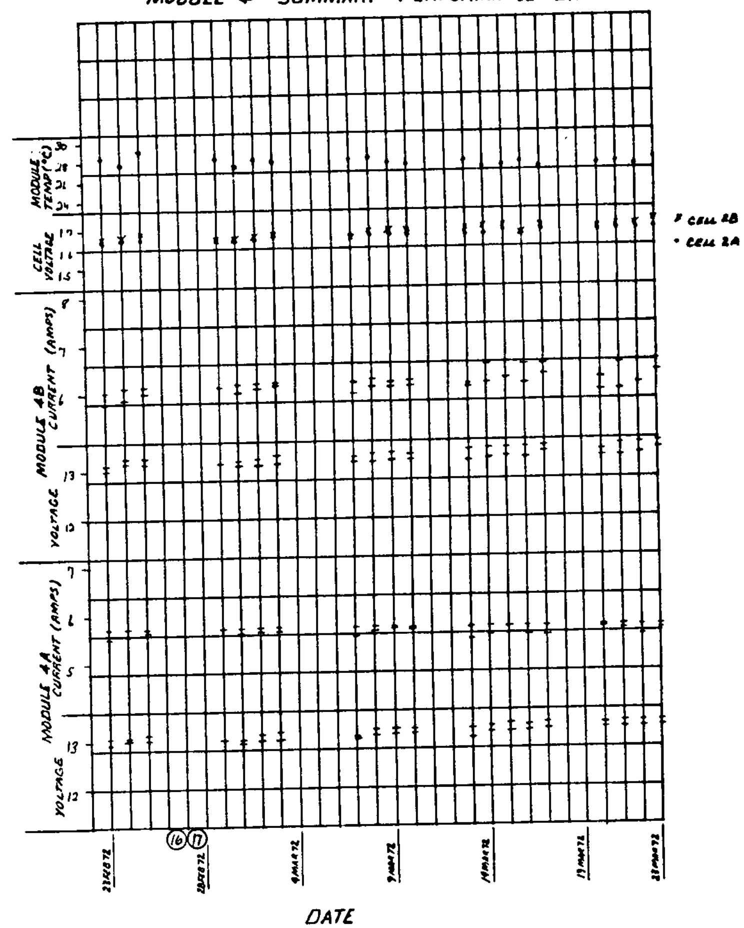


FIGURE A-76
MODULE 2 SUMMARY PERFORMANCE DATA

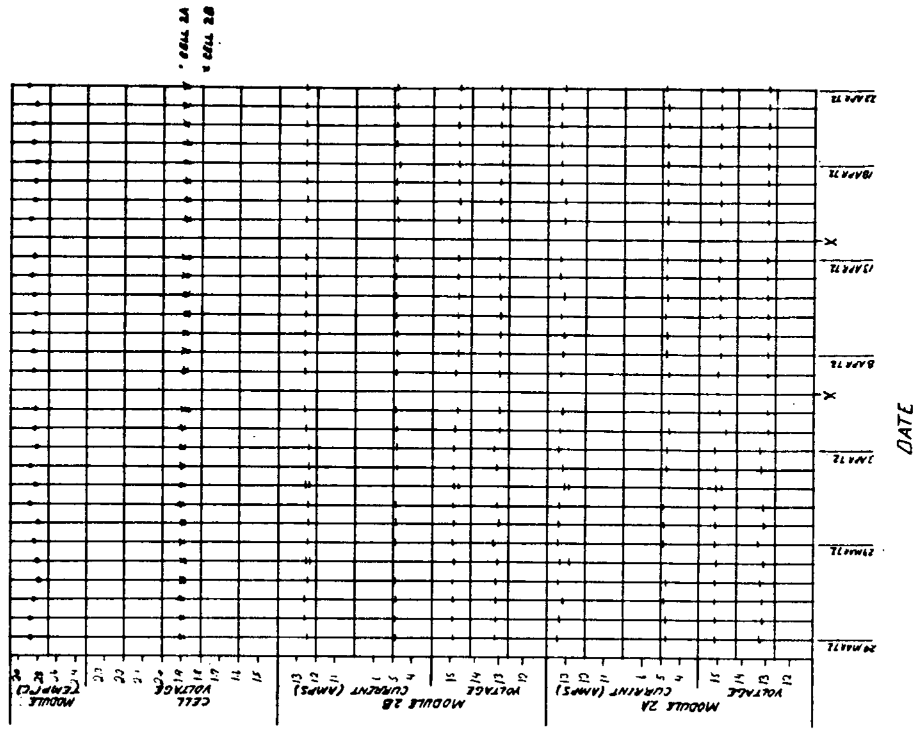


FIGURE A-75
MODULE 1 SUMMARY PERFORMANCE DATA

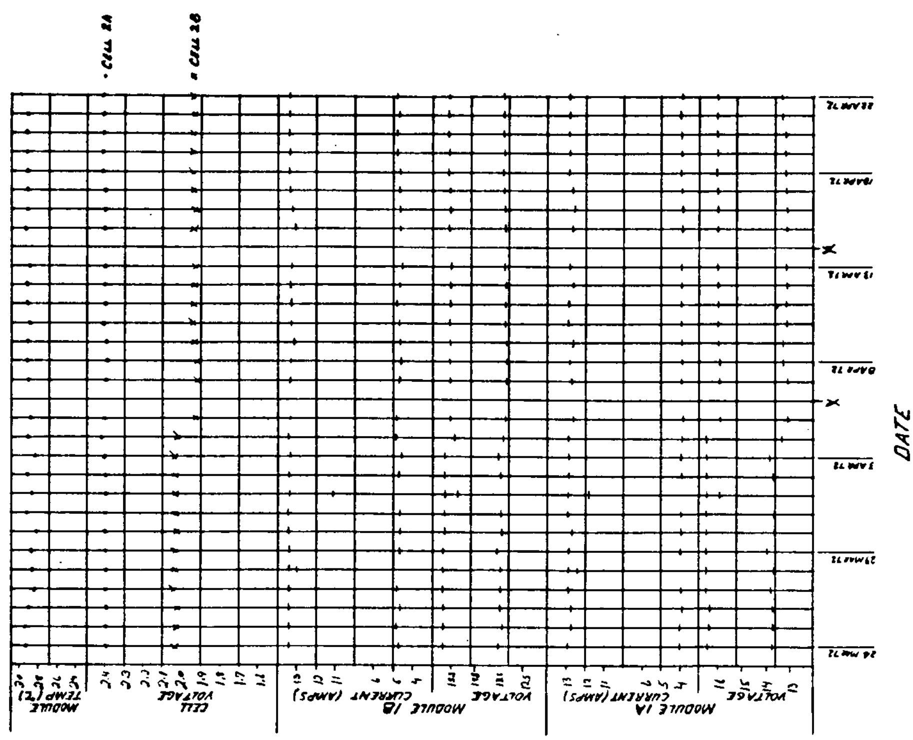


FIGURE A-78
MODULE 4 SUMMARY PERFORMANCE DATA

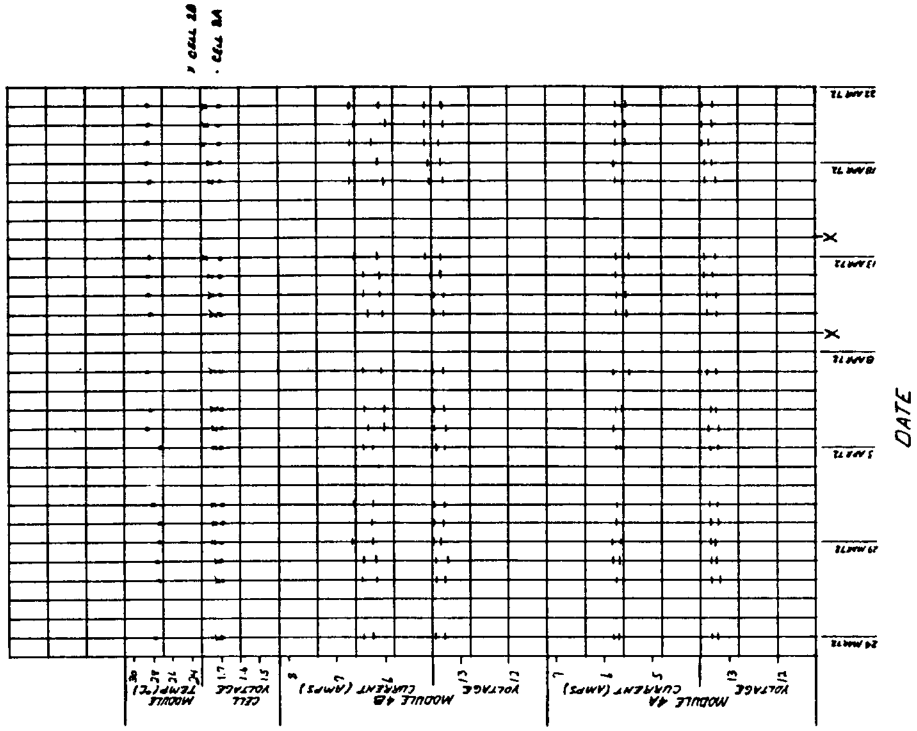


FIGURE A-77
MODULE 3 SUMMARY PERFORMANCE DATA

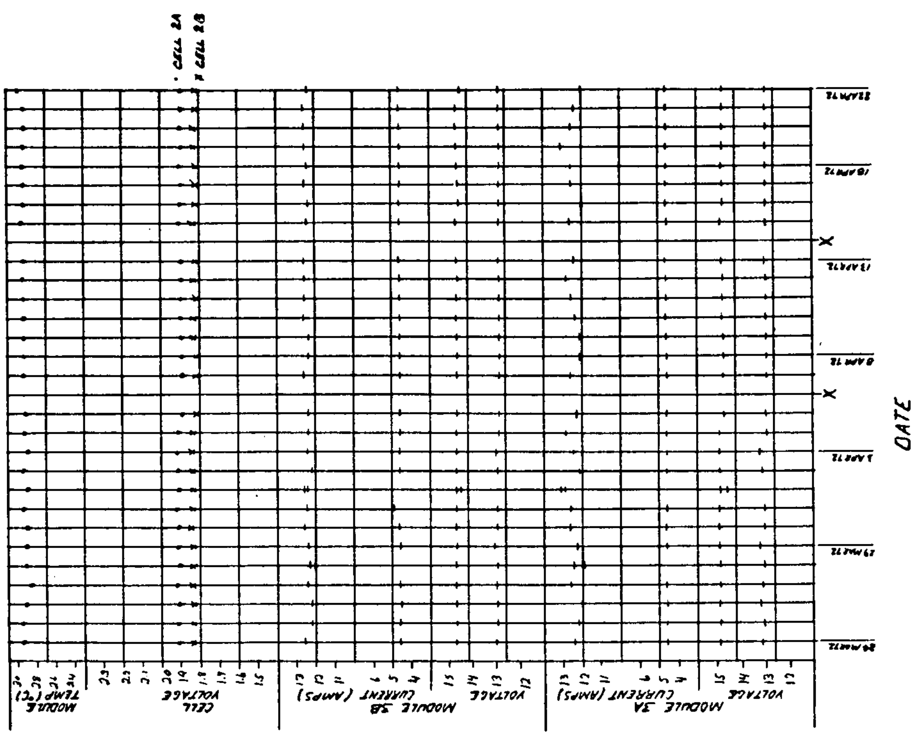


FIGURE A-79
MODULE 1 SUMMARY PERFORMANCE DATA

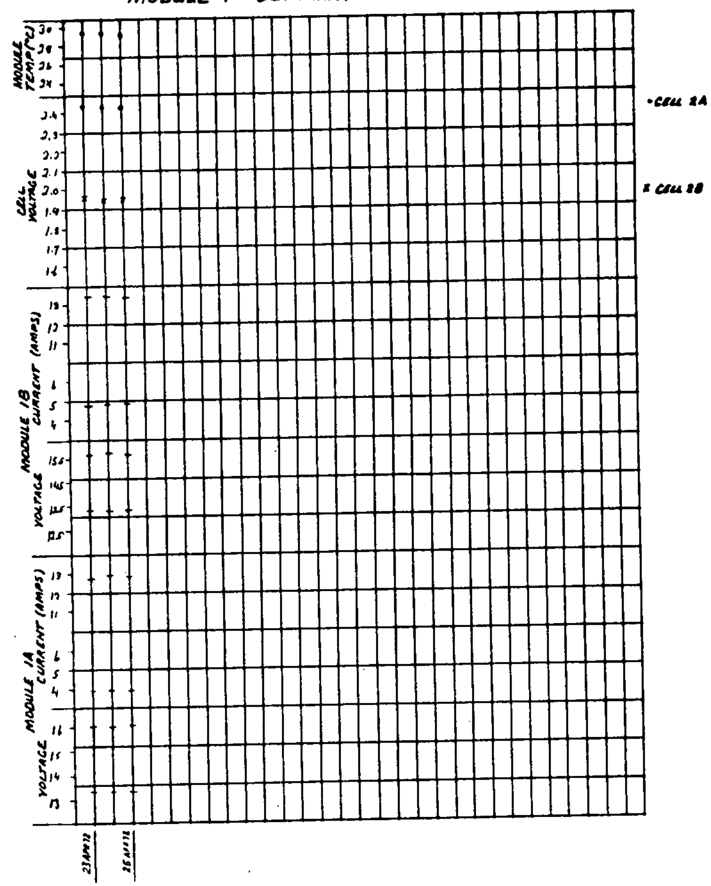


FIGURE A-80
MODULE 2 SUMMARY PERFORMANCE DATA

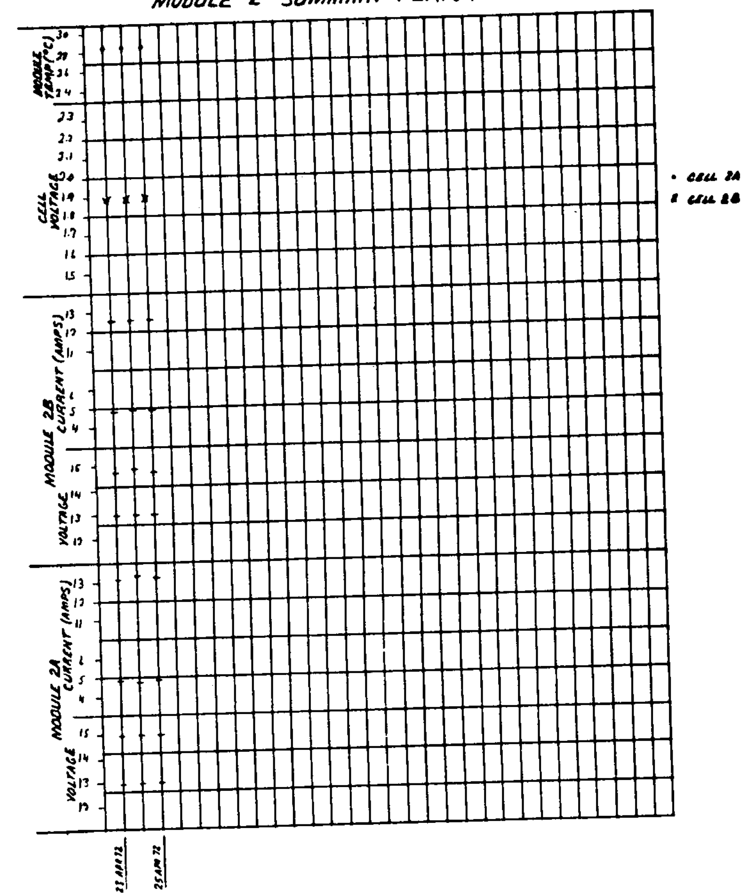


FIGURE A-81
MODULE 3 SUMMARY PERFORMANCE DATA

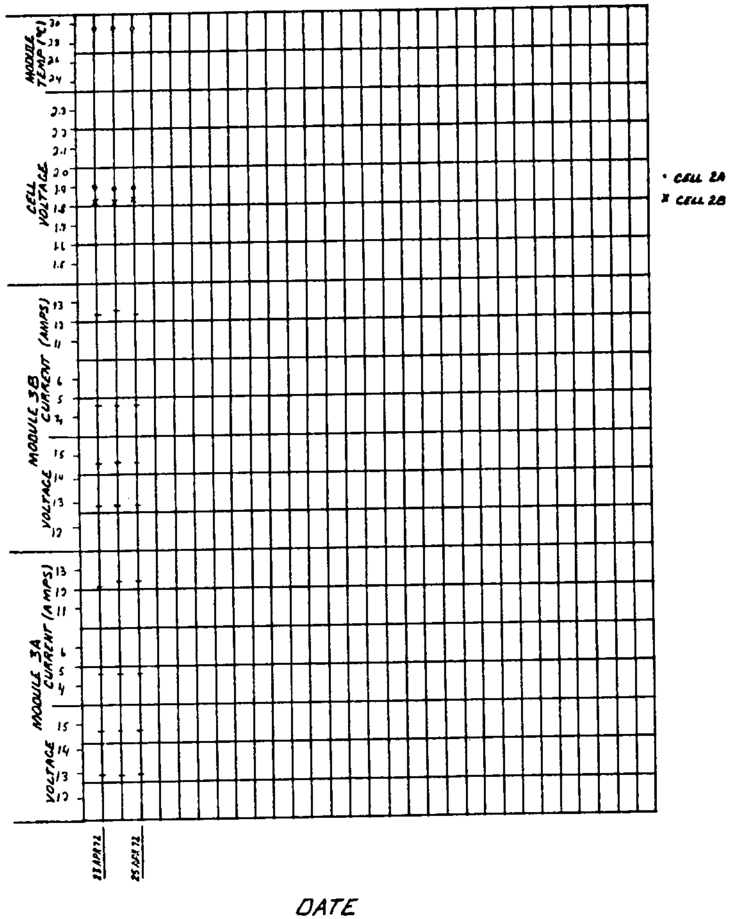


FIGURE A-82
MODULE 4 SUMMARY PERFORMANCE DATA

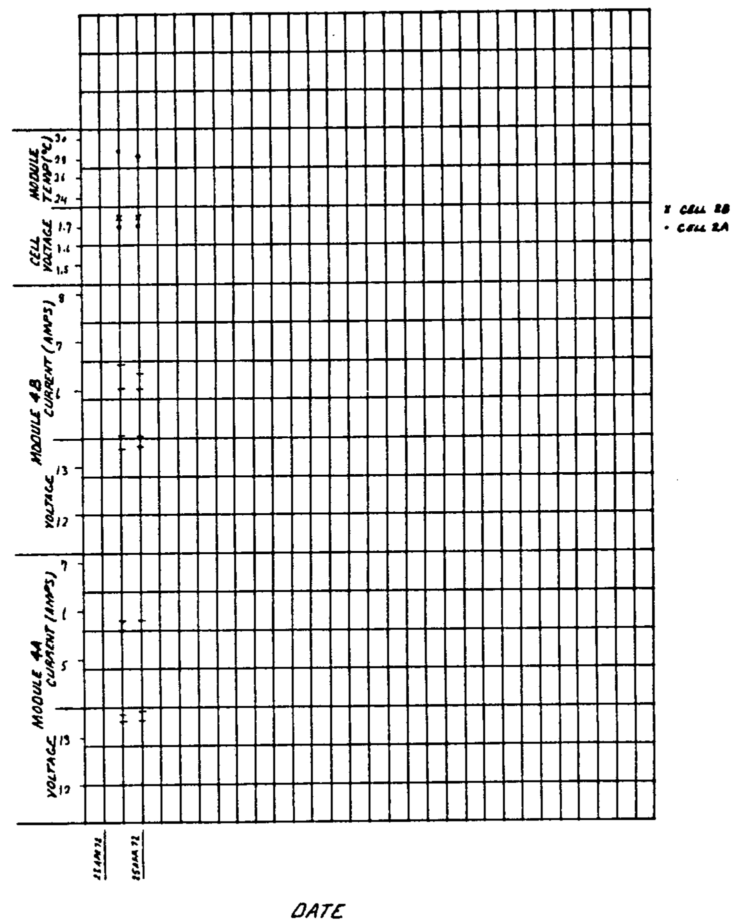


FIGURE A-84
MODULE 2 TEMPERATURE HISTORY

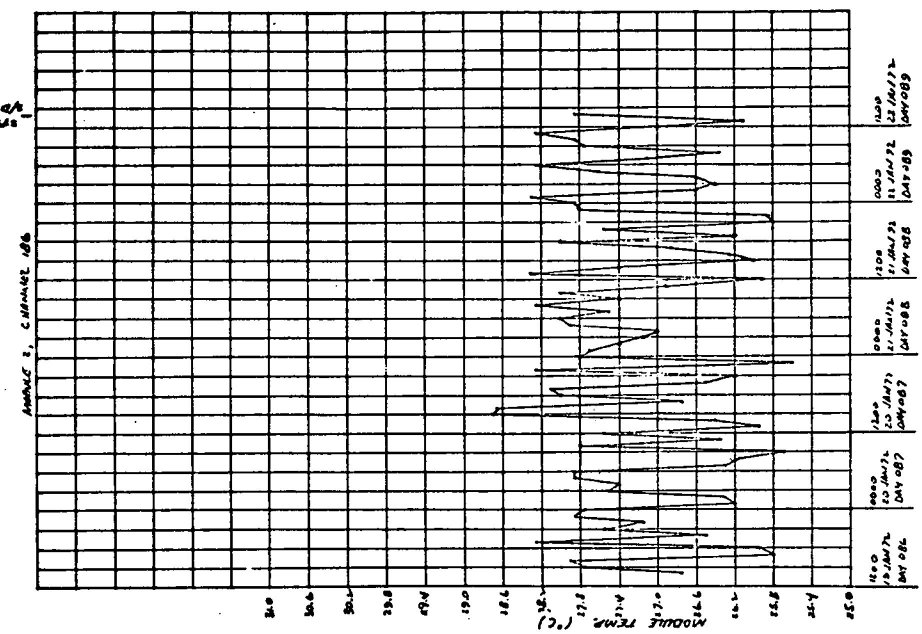
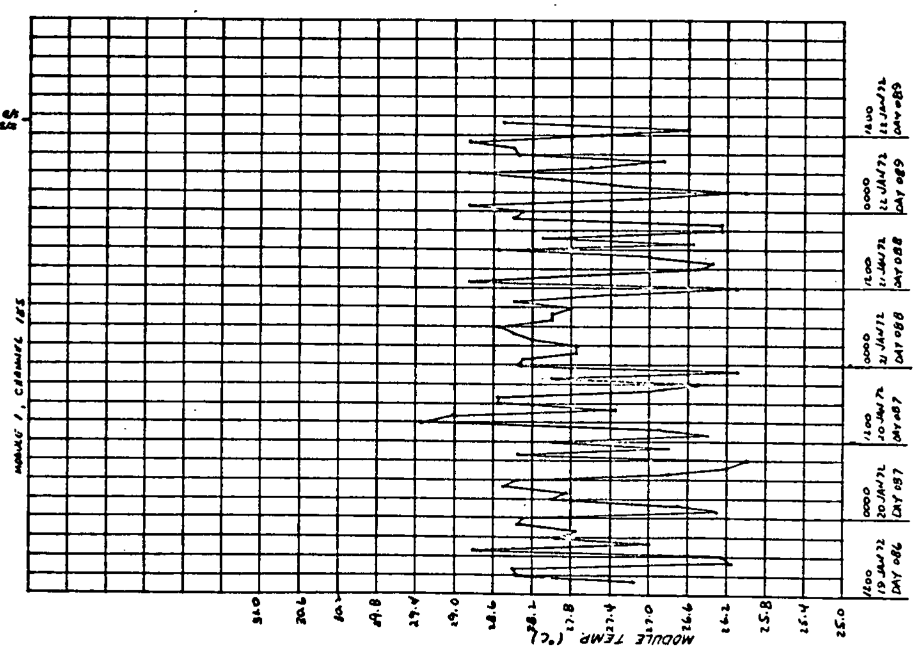


FIGURE A-83
MODULE 1 TEMPERATURE HISTORY



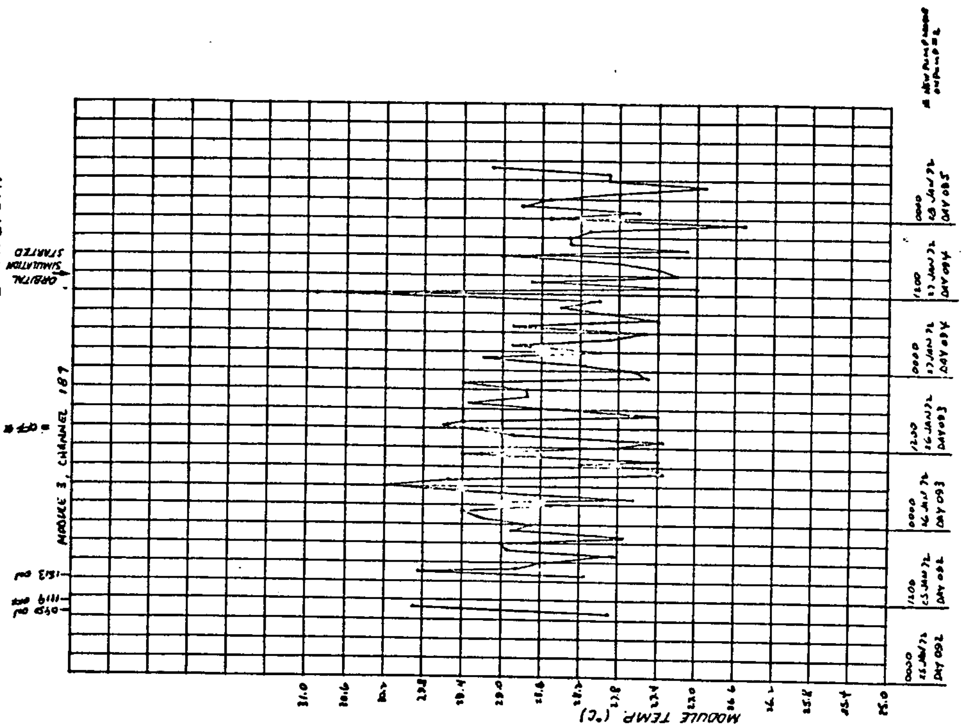


FIGURE A-86
MODULE 3 TEMPERATURE HISTORY

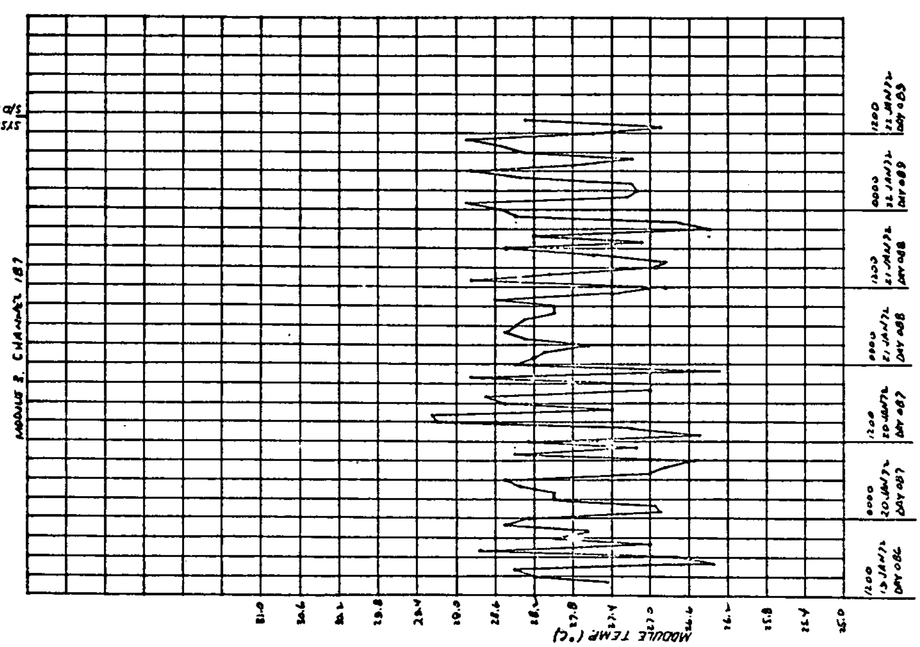


FIGURE A-85
MODULE 3 TEMPERATURE HISTORY

FIGURE A-87
MODULE 1 ORBITAL SIMULATION DATA

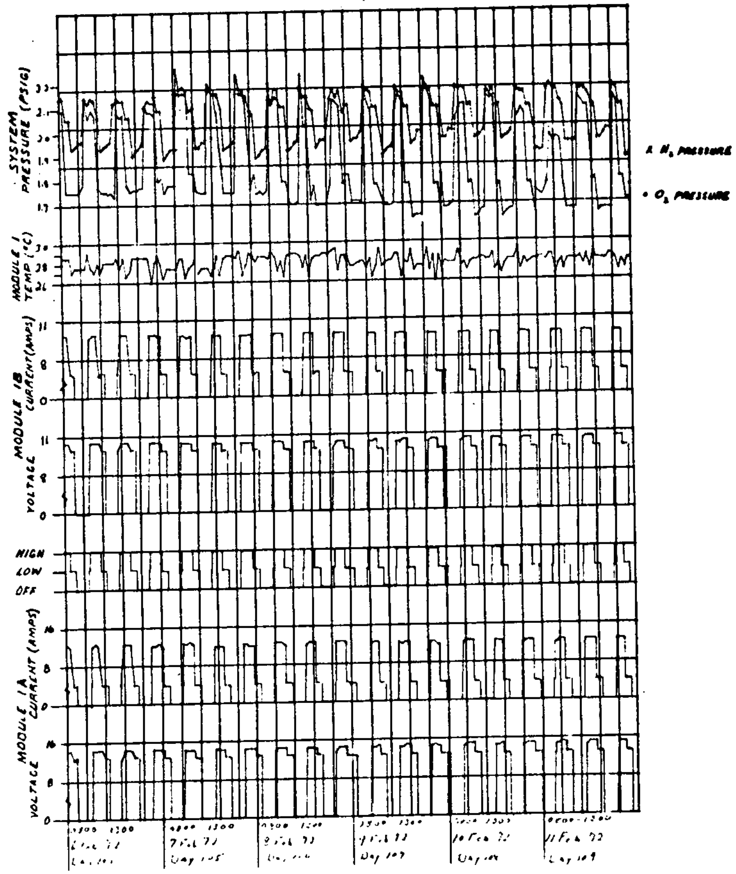
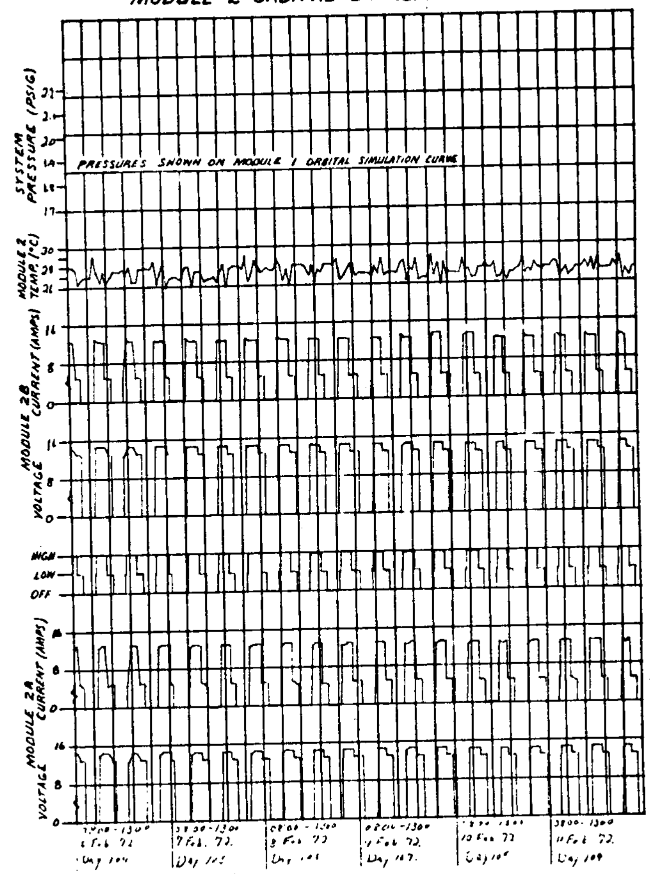


FIGURE A-88
MODULE 2 ORBITAL SIMULATION DATA



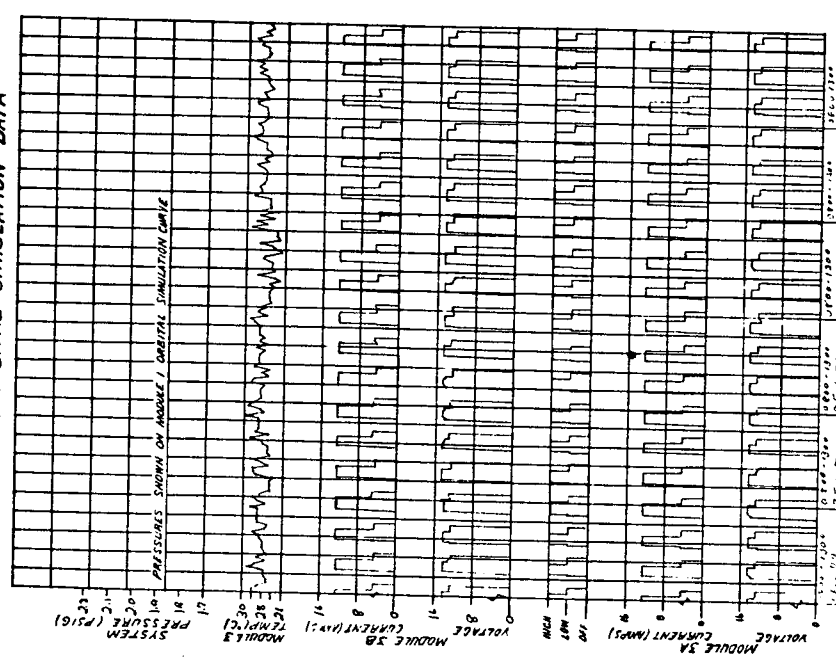


FIGURE A-89
MODULE 3 ORBITAL SIMULATION DATA

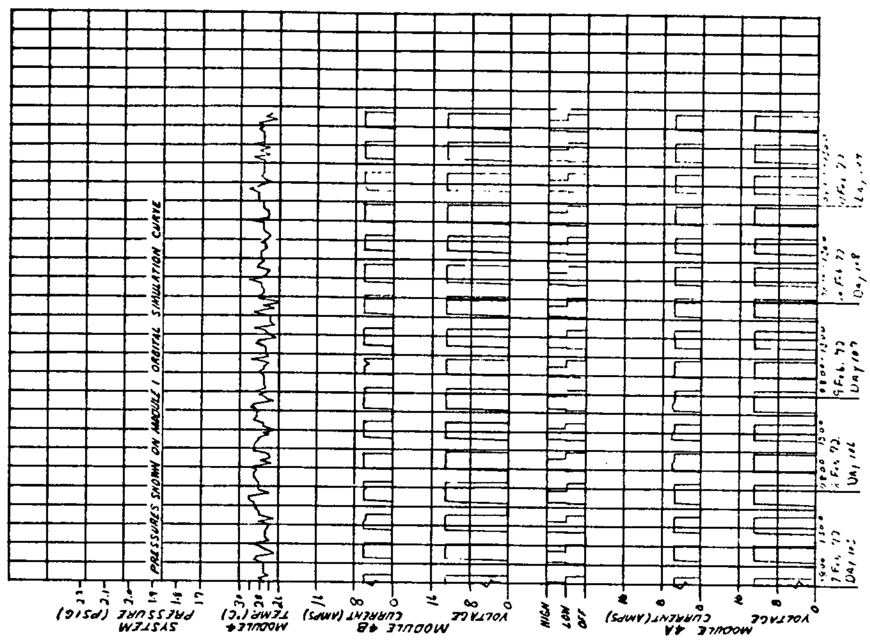


FIGURE A-90
MODULE 4 ORBITAL SIMULATION DATA

FIGURE A-92
MODULE 1 ONE MINUTE ORBITAL SIMULATION DATA

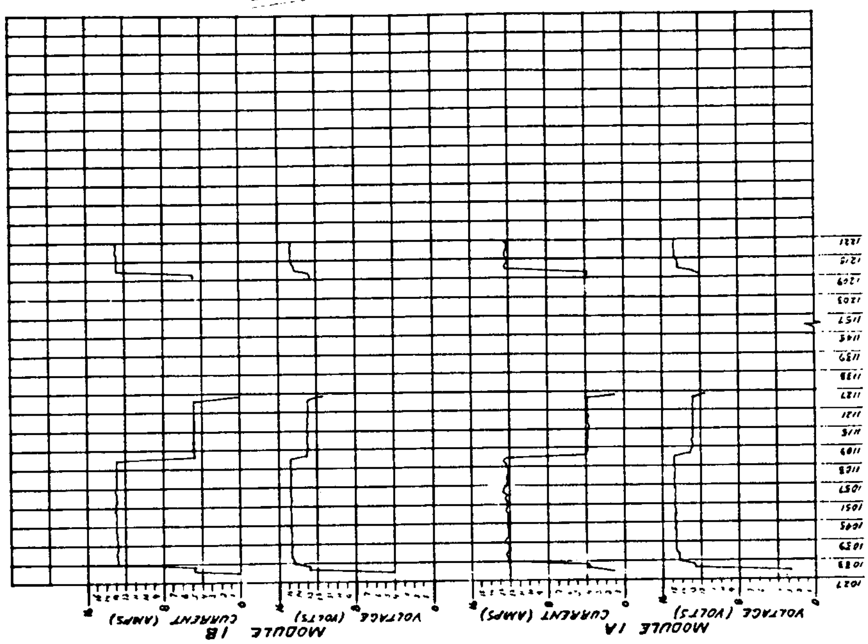
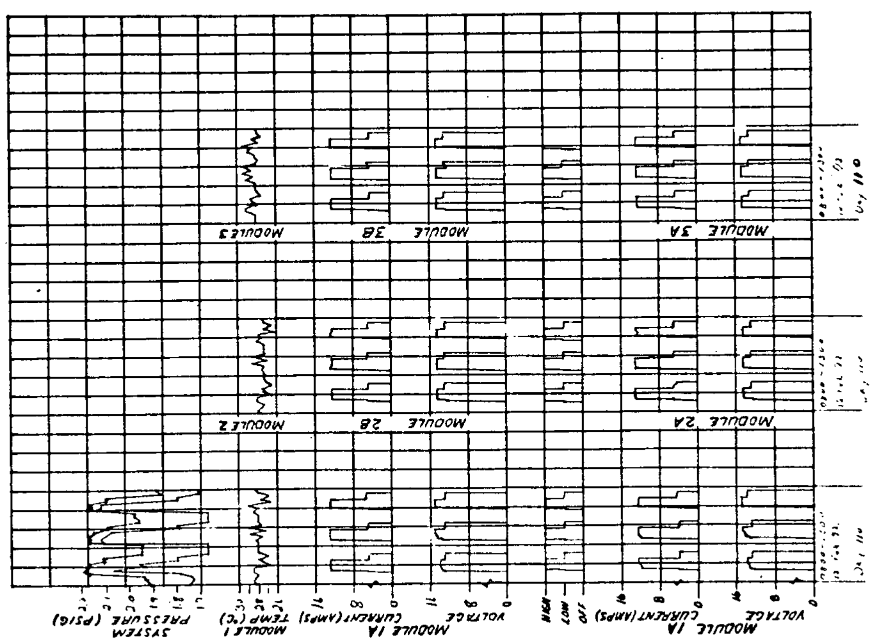


FIGURE A-91
MODULE 1,2, AND 3 ORBITAL SIMULATION DATA



Appendix B

CONDENSED TEST LOG

Pertinent information extracted from the official LMSC test log for the 182-Day Test is contained in this section. This condensed log documents the significant events and actions of the test in chronological order in a format intended to define and explain problems which occurred. Reference numbers shown in the last column of the log appear also on Figure B-1 which illustrates the system status on a day-to-day basis. Notations for shutdowns are as follows:

X System shutdown for diagnosis, troubleshooting or repair; or due to a secondary failure.

XX System shutdown due to a primary failure. Shutdowns so noted are discussed in detail in the Failure Analysis, Section 5.4 of the text.

Test Day	Time	Logbook Entry/Event	Diagnosis/Comment	Shutdown Auto	Shutdown Manual	Reference Number
1	1200	Started 182-Day Test.	Test procedure.			
	1718	Problem noted in external timer. Found bad component and replaced.	No effect on system operation.			
2	1610	Made further adjustment of external timer to get close to desired 100-minute interval.	No effect on system operation.			
3	0845	Further adjustment of external timer.	No effect on system operation.			
8	--	No data printout.	MDAC printer malfunction.			1
9	1114	Oxygen gas sample taken.	Test procedure.			
14	0745	System shutdown, cause unknown at this time.	Cause was traced later in the test to a missing capacitor in the master shutdown circuit which allowed intermittent noise spikes to trigger the shutdown I.C. Refer to Day 127.	XX		2
	1159	Unsuccessful auto restart.	Electrolyte pump did not reach full speed in the required 10 seconds.			
	1201	Unsuccessful auto restart.	Same as above.			
	1204	Unsuccessful auto restart.	Same as above.			
	1207	Auto restart with pump #2	For diagnosis.			
	1213	Manual shutdown and switch to Pump #1.	For diagnosis.		X	
	1214	Auto restart.	System on line-no repairs.			
	1455	Turned override on and swithced to Pump #2 then back to Pump #1. A few gas bubbles were observed leaving the pump. Override turned off.	For diagnosis.			
15	0850	Drained 25 cc from hydrogen and oxygen bubblers for pH measurement.	Test procedure.			
16	1030	Oxygen and hydrogen gas samples taken.	Test procedure.			
	1443	System shutdown with high oxygen pressure light on. Checked discharge gas line with gauge and nitrogen flow - no obstruction apparent. System put in manual standby with pump running overnight.	Cause was later attributed to intermittent electronic noise. See reference 2.	XX		3
17	0800	System shutdown from standby with low oxygen pressure light on.	Electronic noise. See Reference 2.	XX		4
	1100	Installed pressure gage in O_2 line.	For diagnosis.			
	1112	System restarted in manual mode - switching manually high to low current mode every 5 minutes for one hour.	For diagnosis.			
	1216	Switched to automatic mode.	System on line.			
	1500	Oxygen and hydrogen samples taken.	Test procedure.			
	1638	Shut system down to install a pressure transducer in O_2 line and connect to strip chart recorder.	For diagnosis.		X	
	1644	Plastic fitting on Module #1 electrolyte outlet from flowmeter broke. In removing fitting, broke a wire on current indicating light. Resoldered wire. Left system in manual standby overnight awaiting parts from LMSC.	Mechanical failure.			5
18	1500	Replaced broken fitting and installed new solenoid valves.	See Reference 5.			
	1540	Auto restart.	System on line.			
	1605	Shutdown to check if new solenoid valves work properly.	Test procedure		X	
	1606	Auto restart	System on line			
	2153	System shutdown with low oxygen pressure light on.	Electronic malfunction. See Reference 2.	XX		6
19	0915	Put system in manual standby. Review of data from shutdown indicated Module 4 had received several false "on" commands after shutdown at 2153 on Day 18.	System was left in standby mode over week-end until false on-commands to Module 4 could be investigated.			
21	0900	Removed 20 cc from each bubbler for pH analysis.	Test procedure.			
	1003	Actuated auto restart.	System on line.			
	1730	Manual shutdown per Test Committee instructions.	Unattended operation was deemed advisable until Module 4 problem could be resolved.		X	

Test Day	Time	Logbook Entry/Event	Diagnosis/Comment	Shutdown Auto	Shutdown Manual	Reference Number
22	0803	Actuated auto start.	System on line.			
	1021	Shut system down to replace I.C. chips Z1 and Z2 on Card W3 and Z5 on Card W2 and to check wiring to Module #4 current regulator card.	For diagnosis. There was no direct evidence of failure of these chips. They were replaced and put on accelerated life test at LMSC where no indication of malfunction was observed.		X	
	1053	Actuated auto restart.	System on line.			
	1703	Module #4 circuit breaker and switch turned off.	Test Committee decision to turn Module #4 off nights and weekends when no one in attendance for remainder of test. No further attempt to correct Module #4 false "on"-command problem.			
28	0840	Removed 30 cc from each bubbler for pH analysis.	Test procedure.			
30	1110	Gas samples taken. Noted organic contaminant.	Contaminant later traced to mineral oil in solenoid valves installed on Day 18.			
37	0206	System shutdown with low oxygen pressure light on. System put in manual standby overnight.	See Reference 2.	XX		7
38	1000	Re-installed I.C. chips removed on Day 22.	For diagnosis.			
	1005	System startup in manual mode for fault diagnosis.	For diagnosis.			
	1125	Increased low O_2 pressure limit from 1.3 to 1.5 psig. Ran tests injecting gas into electrolyte pump to determine if pump cavitation could cause low pressure shutdowns.	For diagnosis. It was later determined that electronic noise was causing shutdown (Ref. 2). Pump tests indicated that pump was not causing the shutdowns.			
	1643	Actuated auto restart.	System on line.			
39	0752	System shut down. Low pressure light on.	Electronic noise. See Reference 2.	XX		8
		Installed 4 test points to monitor electronics. Strip chart recorder on Test Point #1.	For diagnosis.			
		Modified shutdown logic so that low pressure light comes on only if it receives the primary shutdown signal. Mode operational check ok.	Diagnostic aid.			
	1645	Actuated auto restart.	System on line.			
43	1630	Module 1A current drifted from 12.4 down to 10.5 then back to 12.35.	No effect on system operation.			
44	0753	Module 1A current drift again noted.	No effect on system operation.			
	1000	Hydrogen and oxygen gas samples taken.	Test procedure.			
	1500	8-channel strip chart recorder received from LMSC. All 4 test points were connected.	For diagnosis.			
47	0858	System shutdown. High oxygen pressure light on. Put system in manual standby over the weekend.	Electronic noise. See Reference 2.	XX		9
49	1402	Oxygen pressure transducer signal picked up at circuit card and connected to 8-channel recorder.	For diagnosis.			
	1521	Actuated auto restart.	System on line.			
50	0755	System shut down manually because no flow was observed in gas bubblers.	Interface power supply malfunction.		XX	10
	1020	System started in manual mode and operated only while attended for remainder of the day.	For diagnosis.			
	1401	Added monitor of 30V, 24V and 5V power supply voltage to 8-channel recorder.	For diagnosis. At this time, the recorder was monitoring 4 electronic test points, the O_2 pressure transducer and the three power supplies.			
	1509	System put in manual standby overnight.				
51	0839	Actuated auto restart.	System on line. MTAC installed an additional vent to prevent a safety hazard if the malfunction (Ref. 10) re-occurs.			

Test Day	Time	Logbook Entry/Event	Diagnosis/Comment	Shutdown Auto	Shutdown Manual	Reference Number
56	0755	Module 3B current readings erratic.	No effect on system operation.			
	1419	Module 3B current readings erratic.	No effect on system operation.			
58	0756	Module 3B current readings erratic.	No effect on system operation.			
59	1008	Gas samples taken.	Test procedure.			
	1418	Removed 27 cc from oxygen bubbler and 25 cc from hydrogen bubbler for pH analysis.	Test procedure.			
85	1355	Removed 25 cc from each bubbler for pH analysis.	Test procedure.			
86	1400	Gas samples taken.	Test procedure.			
89	1404	System shutdown. Low system pressure light on. Electrolyte discharge fitting on Module 4 discharge broke.	Mechanical failure. Slow leak of KOH dripped on pump motor and shorted the hot lead to chassis ground. Failure occurred on Saturday with no one in attendance. System remained shut down until Monday.	XX		11
91	1430	Replaced broken fittings and cleaned up KOH spillage. System put in manual standby overnight.				
92	0952	Actuated auto restart.	System on line.			
	1004	Module 3 warning temperature light on intermittently throughout the day.	No effect on system operation.			
	1119	System shut down manually because pump motor was running hot. Exchanged motors with installed spare.	Secondary failure resulting from fitting failure (Reference 1). KOH had leaked into motor armature.		X	
	1513	Actuated auto restart.	System on line.			
93	0747	Intermittent warning light on Module #3 still noted.	No effect on system operation.			
	1408	Received new pump motor from LMSC. Manual shutdown to replace failed motor.			X	
	1427	Actuated auto restart.	System on line.			
94	1402	System put in cyclic operating mode.	Test procedure. Scheduled test condition change.			
96	1837	System shutdown. Low system pressure System put in manual standby for remainder of weekend.	Failure due to low pressure on cycle from off to on in orbital mode.	XX		12
98	1400	Module 3 overtemperature light on. System left in manual standby overnight.	Failure of temperature sensor.			
99	0845	Put insulating tape on tip of Module #3 temperature sensor.	Interim repair until replacement sensor available.			
	1021	Actuated auto restart.	System on line for trouble-shooting.			
100	1100	Gas samples taken.	Test procedure.			
	1300	Module 3 temperature warning light even though sensor has been taped.				
	1811	System shutdown. No indicator lights. Test Point #3 on 8-channel recorder very noisy.		XX		13
101	1416	Actuated auto restart to continue trouble-shooting. No current to Module 4B.	System on line for trouble-shooting.			14
	1502	Manual shutdown to investigate Module 4B problem.	Trouble-shooting.		X	
102	0941	Replaced I.C. Chip Z1 on W2.	Z1 was suspected of causing shutdown (Reference 13). This has not been verified. Refer to Day 127.			
		Found loose cable on Module 4 electronics. Retightened. System restarted to check Mod 4 current - ok.	Loose cable was cause of no current to Module 4B (Reference 14).			
	1542	Modified card SC6 to provide 15 sec overlap of nitrogen purge and module current on startup. System restarted for checkout-found wiring error.	To correct orbital operation problem (Reference 12).			
	2036	System put in continuous operation overnight until wiring error on SC6 is corrected.	System on line.			

Test Day	Time	Logbook Entry/Event	Diagnosis/Comment	Shutdown Auto	Shutdown Manual	Reference Number
103	0916	Manual shutdown to correct wiring error on SC 6.	Trouble-shooting.		X	
	0955	Actuated restart-manual, continuous mode.	Trouble-shooting, system on line.			
	1545	Switched to auto mode. Initiated cyclic operating mode.	System on line in orbital mode.			
110	1613	Switched from cyclic mode to continuous mode.	Test procedure. Scheduled orbital operation completed.			
113	0830	Removed 25 cc samples from bubblers for pH analysis.	Test procedure.			
	1547	Observed small KOH leak at #3 outlet on the flow meter.	System remained on line.			
114	1600	System shut down manually in preparation for replacement of nylon fittings with stainless steel.	The leak at 1547 was caused by a fitting failure. This was the third such occurrence of the test.		XX	15
116	0800	Replaced nylon fittings with Teflon-coated stainless steel.	Only fittings used with O-ring seals were replaced.			
	1139	Actuated auto restart.	System on line.			
120	1201	Changed high mode duty from 62 to 70 minutes.	Test procedure. Scheduled start of ramp to maximum output.			
121	1207	Changed high mode duty from 70 to 79 minutes.	Test procedure.			
122	1201	Changed high mode duty from 79 to 88 minutes.	Test procedure.			
123	0941	Changed high mode duty from 88 to 98 minutes.	Test procedure.			
124	0300	Module 3 circuit breaker tripped off.	Current regulator card failed to high current.			16
	1100	System shutdown with no indicator lights on.	Electronic noise. Reference 2.	XX		17
127	0940	Module 3 current regulator card replaced with spare.				
	0947	System restarted for checkout and adjustment of new regulator card.				
	1325	System shut down manually to continue diagnosis of electronic noise problem. Test points were added between Pins 1 and 8, Chip Z1, Card W2. Added capacitor to Chip Z1.	Circuit design included a requirement for this filtering capacitor of Z1, W2. It was inadvertently omitted during system assembly at LMSC. Lack of this filter allowed random noise to actuate system shutdown. Shutdowns referenced as follows are attributed to this problem: Day 14 Ref. 2 16 3 17 4 18 6 37 7 39 8 47 9 100 13		X	
	1545	Actuated auto restart.	System on line.			
130	0852	Deliberately induced known noise on Z1 to verify electronic noise as cause of previous shutdown.	Diagnosis of electronic problem was verified.			
	1302	System shutdown manually to increase amount of filtering on Z1.			X	
	1311	Actuated auto restart.	System on line at maximum output rate.			
133	0755	Module 4 failed to start when actuated.	Module 4 electronics problem.			
134	1032	Module 4 on okey. Started and stopped it several times; problem of Day 133 did not reoccur.				
140	1045	Removed 25 cc bubbler samples for pH analysis.	Test procedure.			
142	1500	Gas samples taken.	Test procedure.			
154	1632	Module 4 switch not working. Module 4 turned off with breaker.				
158	1630	Module 4 switch not working again.	Intermittent problem with switch.			
162		Changed high mode duty from 98 to 62 minutes.	Test procedure. Scheduled five weeks at maximum output completed.			

Test Day	Time	Logbook Entry/Event	Diagnosis/Comment	Shutdown Auto	Shutdown Manual	Reference Number
164	1530	No data printout.	MDAC data logging system failure.			
170	0754	Module 4 switch had to be actuated several times before it worked properly.				
	1040	Bubbler samples taken for pH analysis.	Test procedure.			
	1445	Gas samples taken.	Test procedure.			
	1630	Module 4 switch stuck again. Used breaker to turn module off.				
171	0757	Module 4 switch still not working. properly. Used breaker to turn module on.	Switch on Module 4 continues not to work. Will use breaker for the remainder of the test.			
183	1100	Gas samples taken	Test procedure.			
	1203	Actuated system stop switch.	END OF TEST.			

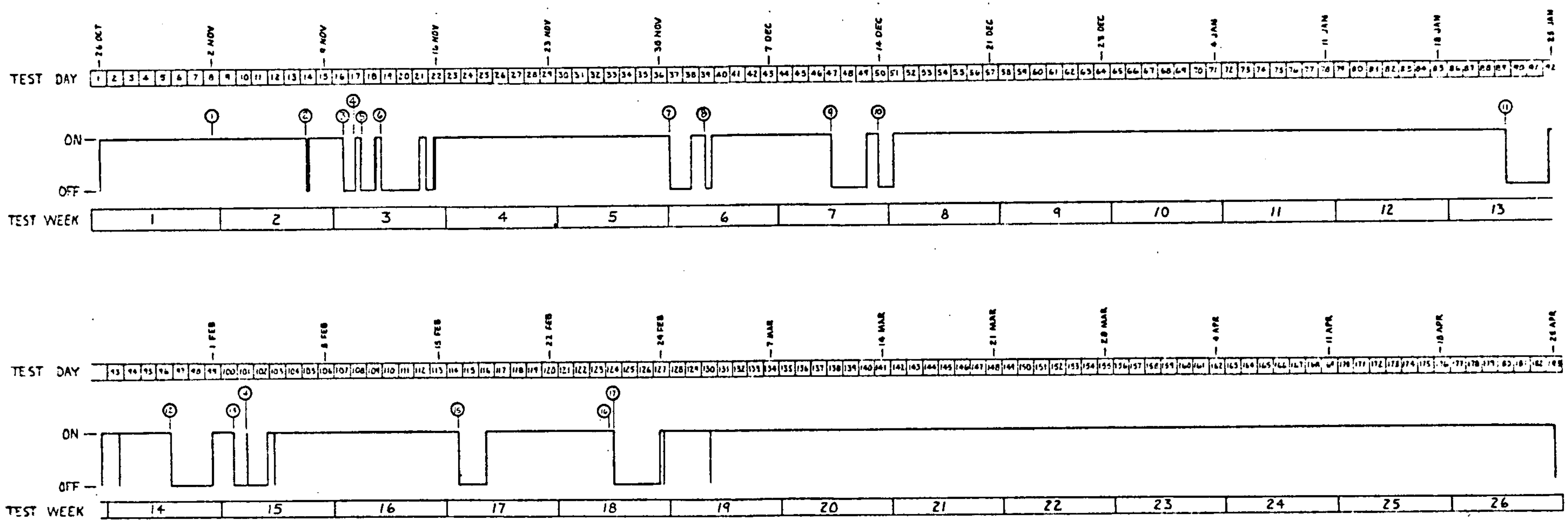


Figure B-1 SYSTEM STATUS