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AIRCREW OXYGEN SYSTEM DEVELOPMENT

FLIGHT BREADBOARD SYSTEM
FLIGHT AND ENVIRONMENTAL TESTS

by R. J. KIRALY, A.D. BABINSKY AND J. D. POWELL

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PREPARED UNDER CONTRACT NO. NAS2-4444

by

TRW INC.
CLEVELAND, OHIO

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

April 1970

TRW
MECHANICAL PRODUCTS DIVISION

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FOREWORD

The Flight Breadboard System operation and testing reported here is part of an aircrew oxygen system development program being performed by the TRW Mechanical Products Division, Cleveland, Ohio, under Contract NAS2-4444. R. J. Kiraly had responsibility for system design and test of the Aircrew Oxygen Flight Breadboard System. R. K. Mitchiner led the fabrication and assembly effort for the FBS and FBS accessories. J. D. Powell and F. H. Schubert provided engineering support during assembly, checkout and test operations. Technician support was provided by R. H. Graham, C. A. Novotny, R. L. Englehaupt and K. J. Urbanek. The aircrew oxygen system development program is under the overall direction of A. D. Babinsky. The contract technical monitor is P. D. Quattrone, Biotechnology Division, NASA Ames Research Center, Moffett Field, California.

Excellent support during test operations was provided by personnel of the Point Mugu Naval Missile Test Center. LCDR. D. J. Horrigan, Jr. co-ordinated the test operations between TRW, NASA and Point Mugu Naval Missile Center.

Man-in-the-loop testing of the Flight Breadboard system is reported in a separate report.

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SUMMARY

TRW, under NASA Contract NAS2-4444, is developing an aircrew oxygen system using electrochemical oxygen generation and carbon dioxide removal. The program objective is the development of a safe, reliable, compact system which would replace the LOX system currently in use, thereby minimizing logistics, service and facilities required. The Flight Breadboard System (FBS) used in the flight testing is the first packaging of the laboratory type components into a complete oxygen system allowing operation outside of the laboratory. The Aircrew Oxygen System, Flight Breadboard System, consists of four primary subsystems. 1) Water Electrolysis, 2) Carbon Dioxide Concentrator, 3) Rebreather and 4) Electrical Control.

Hydrogen and oxygen gases are generated in the Water Electrolysis Subsystem at a selected pressure level. Oxygen gas is fed to the rebreather loop through the oxygen demand regulator. A blower in the rebreather loop circulates the oxygen gas through the carbon dioxide concentrator. The hydrogen gas from the electrolysis module is fed to the carbon dioxide concentrator where it reacts electrochemically with oxygen to remove carbon dioxide from the rebreather loop. The carbon dioxide is vented with excess hydrogen.

The pilot's exhalation enters the counter-lung which accommodates the pilot's tidal volume during breathing to maintain the loop at constant pressure during the breathing cycle. Inhalation oxygen is drawn from the circulating loop through a heat exchanger used as a dehumidifier.

The Electrical Control Subsystem provides power conditioning, oxygen generation rate control, carbon dioxide removal rate control, component temperature control, safety indicators and shutdown circuitry, system status readouts and fault isolation circuitry.

In addition to the FBS, four other packages were used in the testing. These were: 1) a breathing simulator to produce respiration flow rates and oxygen consumption and carbon dioxide addition at metabolic rates; 2) a resources adapter to provide coolant and compressed air services to the system which were unavailable on the C-131F aircraft; 3) an instrumentation package providing visual readouts of the system and component operating parameters; and 4) a tape recorder to record the important data.

The purpose of the Flight Test Program was to demonstrate operation of an integrated system away from a laboratory environment; provide first packaging experience; provide experience in working with potential user agency; identify

aircraft system interface problems; identify effects of flight environment upon system operation; provide preliminary flight reliability information and provide data regarding operation, maintenance and service of the system when installed in an aircraft.

The complete Flight Test Program, in addition to the flight testing aboard the aircraft, consisted of pre-flight ground tests with the FBS in the laboratory to check system baseline performance and post-flight ground tests in the laboratory to determine what changes in system operation may have occurred as a result of flight testing. Each test phase included four types of system operation: 1) baseline performance; 2) variation of breathing rates; 3) variation of breathing volumes and 4) off-design operation.

The flight testing of the breadboard version of the NASA Aircrew Oxygen System was conducted aboard a Navy C-131F aircraft at the Pacific Missile Range, Point Mugu, California during July 1969. As a result of shipping damage and some minor ground service problems, a number of system and accessory repairs were required. Spare parts and maintenance equipment provided to support the test program were adequate to effect the required servicing and repairs. A total of five flight tests accumulated 14.85 hours of flight operation. The significant problem identified was that of gas generation by electrolysis in the water feed plumbing due to electrical current leakage paths.

No significant change in performance of the system was observed over the course of the flight test program. Specifically, no change was observed due to operation in the aircraft. Detailed analyses of gas samples taken during all phases of the test program indicate that the system is capable of maintaining the rebreather loop gas composition within the ranges required for adequate closed loop breathing.

The TRW personnel received excellent cooperation from the personnel at the Naval Missile Center, Point Mugu, California. A genuine interest and enthusiasm was displayed which made the flight test program a successful effort.

The Flight Breadboard System unmanned testing phase was completed with successful completion of the post-flight ground tests, low temperature tests including startup from $-5^{\circ}F$, and altitude chamber testing up to 38,500 feet. All gas sample analyses were completed, indicating satisfactory gas composition of the oxygen and the rebreather loop gases. The electrolysis module gassing in the water cavities experienced during flight testing was eliminated by additional electrical insulation between the module and cell current collector and the metal endplate.

Major conclusions reached as a result of the Flight and Environmental Test Program are: 1) the objectives of the Flight Test Program were successfully met; 2) the aircraft flight environment does not adversely affect system operation; 3) system operation, service and maintenance can be accomplished without laboratory support equipment; 4) the flight test program has successfully demonstrated the operation of an electrochemical aircrew oxygen system; 5) no limitations or design flaws were found which would negate the concept of this system for further development; and 6) the system is not adversely affected by large variations in operating environment.

Based upon results and experience of the Flight Breadboard System test program, it is recommended that the development of an electrochemical aircrew oxygen system be continued.

INTRODUCTION

TRW, under NASA Contract NAS2-4444, is developing an aircrew oxygen system using electrochemical oxygen generation and carbon dioxide removal. The objective of the program is to develop a safe, reliable, compact system which would replace the present LOX system.

Aircraft oxygen systems are currently limited to the use of stored supplies of oxygen in the form of liquid oxygen or high pressure gaseous oxygen. Use of oxygen from these sources limits the duration of a mission to the amount of stored gases and creates somewhat of a problem in logistics and service to provide the needed oxygen.

A means of avoiding these problems is the provision of a method of continuously generating oxygen on-board the aircraft as oxygen is required. This can be accomplished electrochemically by electrolysis of water or concentration of oxygen from the ambient air. The size and power requirements of these electrochemical oxygen generators would be large when coupled to an open loop aircraft oxygen system. If, however, a rebreather loop is provided such that the oxygen used corresponds to the pilot's metabolic consumption, the size of the oxygen generator and rebreather loop becomes competitive with a present-day LOX converter system.

The rebreather loop functions to recondition the exhaled gases such that it can be reused in the breathing cycle. The rebreather thus removes exhaled carbon dioxide, nitrogen, water vapor and heat.

Carbon dioxide can be removed by absorption in replaceable canisters by regenerative absorbers or by a continuous process electrochemical device. The regenerative absorbers are too big and complex for the intended application. Replaceable canisters re-introduce a minor logistics problem. The preferred mode of carbon dioxide removal is the continuous electrochemical process.

Generation of oxygen by water electrolysis was selected to make the system independent of air source (high altitude or space application). The water presently will be added by refill of a water tank between missions. Ultimately, one can envision the recovery of water from the pilot's breath and the reaction products of the carbon dioxide concentrator and thus "close the loop" such that water refill requirements would be reduced.

The major objectives of the development program are summarized as follows:

- Design the system based on current technology
- Design, fabricate and test a laboratory model oxygen generating electrolysis module with static water feed
- Design, fabricate and test both single cell and full-scale laboratory models of a carbon dioxide concentrator
- Design, fabricate and test laboratory models of the system's power conversion and conditioning equipment

- Design, fabricate or purchase and test breadboard models of the remaining system components

- Design, fabricate and test a breadboard of the complete aircrew oxygen system using laboratory models of the components

- Begin long-term operating tests on the laboratory electrolysis module, the CO_2 concentrator single cells, and CO_2 concentrator laboratory module

- Design, fabricate and test a flight breadboard of the aircrew oxygen system. (This has been designated as a Flight Breadboard System (FBS)).

The FBS was the first packaging of the complete oxygen system allowing operation outside of the laboratory. The purpose of the flight testing was not a test of an aircraft-integrated prototype subsystem but was a step in the early development of the system. Environmental testing was aimed at determining possible system sensitivity to widely varying environmental operating conditions. Additional tests utilizing man-in-the-loop were also conducted. Results of the manned tests are reported separately.

FLIGHT BREADBOARD SYSTEM DESCRIPTION

The Flight Breadboard System is essentially the same functional system as the Laboratory Breadboard System, Figure 1, reconfigured to meet the requirements of portability and size compatible with aircraft testing.

Flight Breadboard System Repackaging

In order to facilitate aircraft installation, the system was repackaged using components similar to those used in the Laboratory Breadboard where feasible. This permitted use of proven components which reduced the amount of checkout and troubleshooting required to get the repackaged system into operation. In most cases "off-the-shelf" items were used to reduce costs and delivery times. In cases where Laboratory Breadboard components were not compatible with aircraft resources, substitution was made to allow the unaltered use of aircraft power. Various views of the Flight Breadboard System are shown in Figures 2 through 9.

Repackaging reduced the size of the system from the Laboratory Breadboard (see Figure 1) to a package 25" high x 26" wide x 25" long. This size reduction was gained by using module endplates to support the required pressure regulators, valves, traps and other hardware. Further size reduction was gained by using module bolts where possible to support system components. This eliminated the need for complex bracket assemblies to secure the subsystem components to the frame. This arrangement also permits all components to be readily accessible and eliminates the need for extensive disassembly and/or special tools to remove and replace a faulty component.

It should be noted that a further reduction in the size and weight of the unit could be made by the use of custom components such as regulators and aerosol traps. This could be done using the existing electrochemical modules. Modifications to the electrochemical modules were kept to a minimum to avoid variations in their performance. Adaption of the water electrolysis module (see Figure 10) required only the shortening of the gas outlet tubes to permit close coupling of the pressure control assemblies. Brackets to secure the aerosol traps, regulators, water tank and solenoid valve were mounted using the endplate bolts.

The Z bars used to mount the entire Water Electrolysis Subsystem to the frame were also fastened to the endplate via the module bolts. The cooling shroud was modified slightly to accept a small high-speed blower to provide cooling air. Cavity vent and water fill connectors (quick disconnects) were mounted on the bottom of the water tank and are easily accessible from outside the package.

Modifications required to adapt the Carbon Dioxide Concentrator Module (see Figure 6) for flight breadboard use were the addition of gas inlet tubes to correlate with gas exit tubes from the Water Electrolysis Subsystem, construction of a new cooling shroud to permit use of two small high-speed blowers to control cell temperature, and the modification of one endplate to accept the oxygen recirculating blower. This blower is fastened directly to the endplate

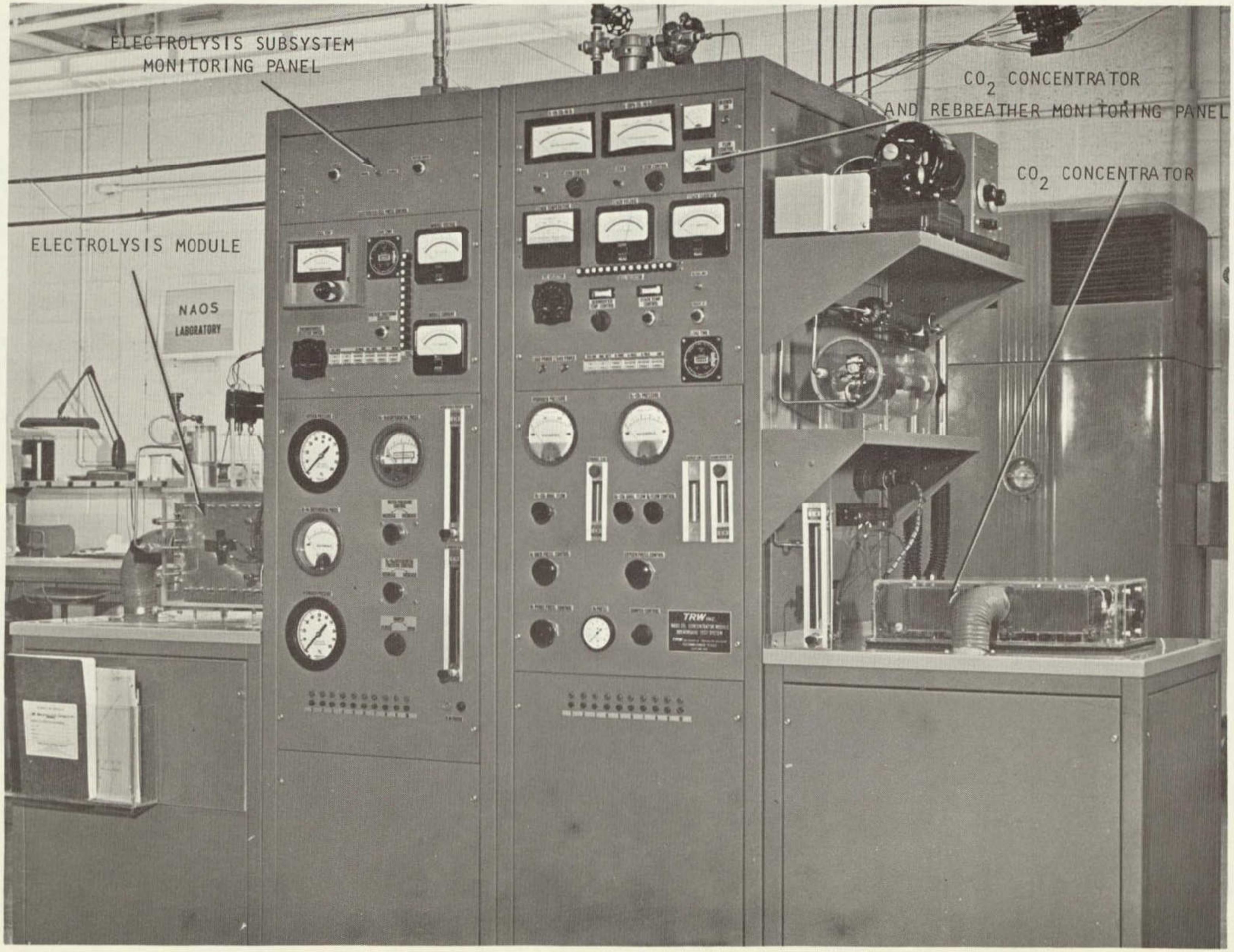

FIGURE 1 NAOS LABORATORY BREADBOARD SYSTEM

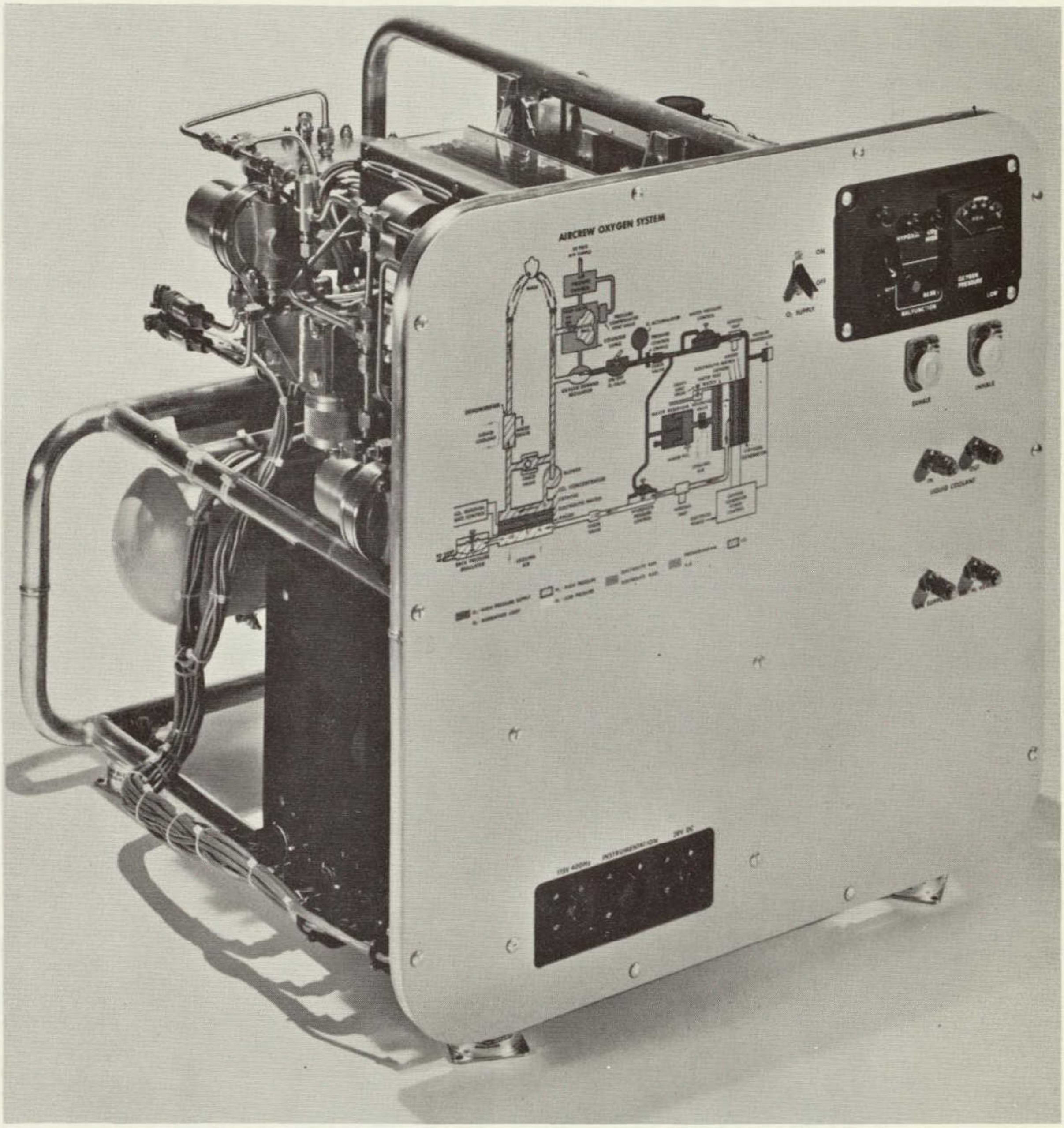

FIGURE 2   FLIGHT BREADBOARD SYSTEM

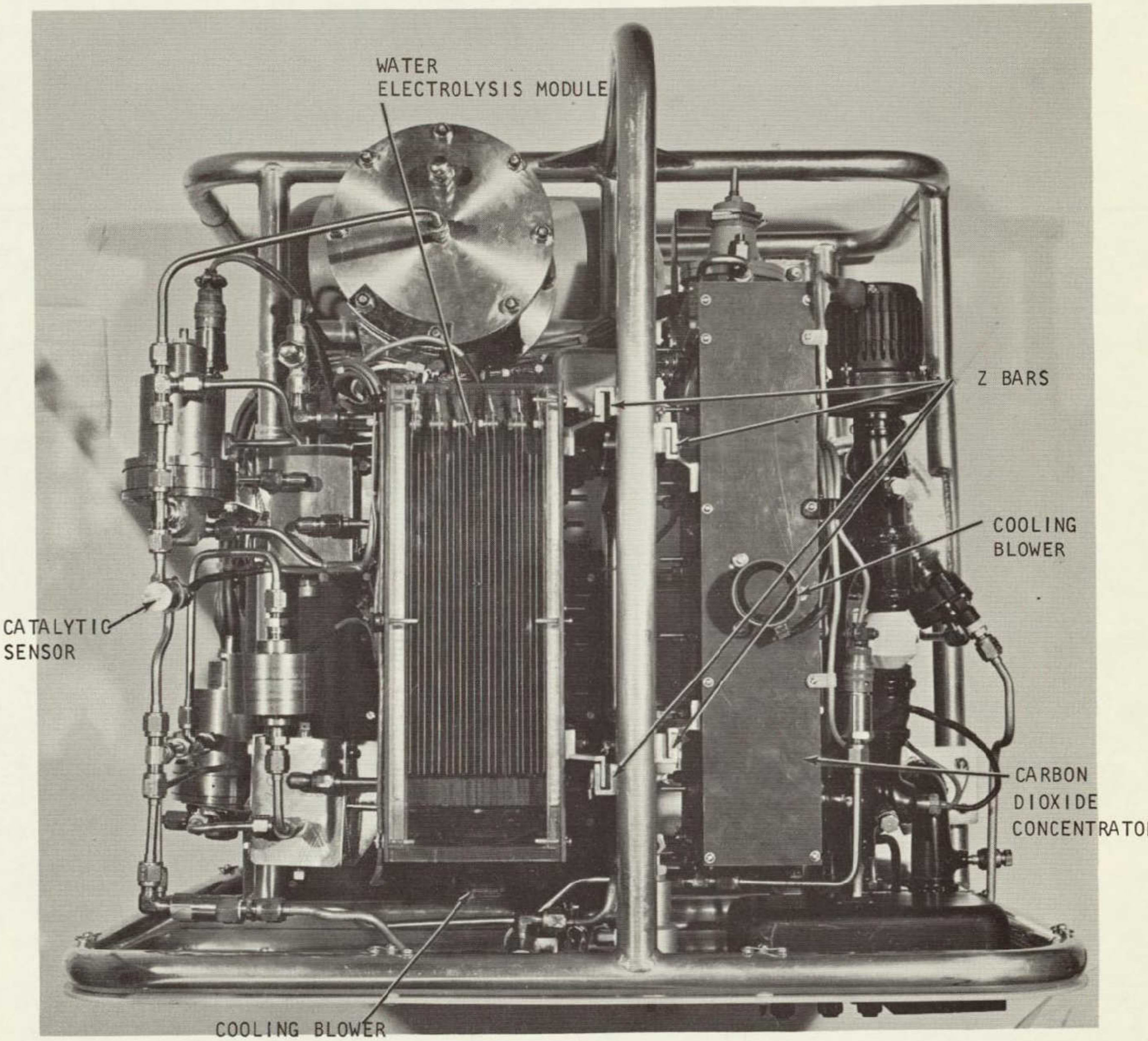

FIGURE 3 FLIGHT BREADBOARD SYSTEM
(TOP VIEW)

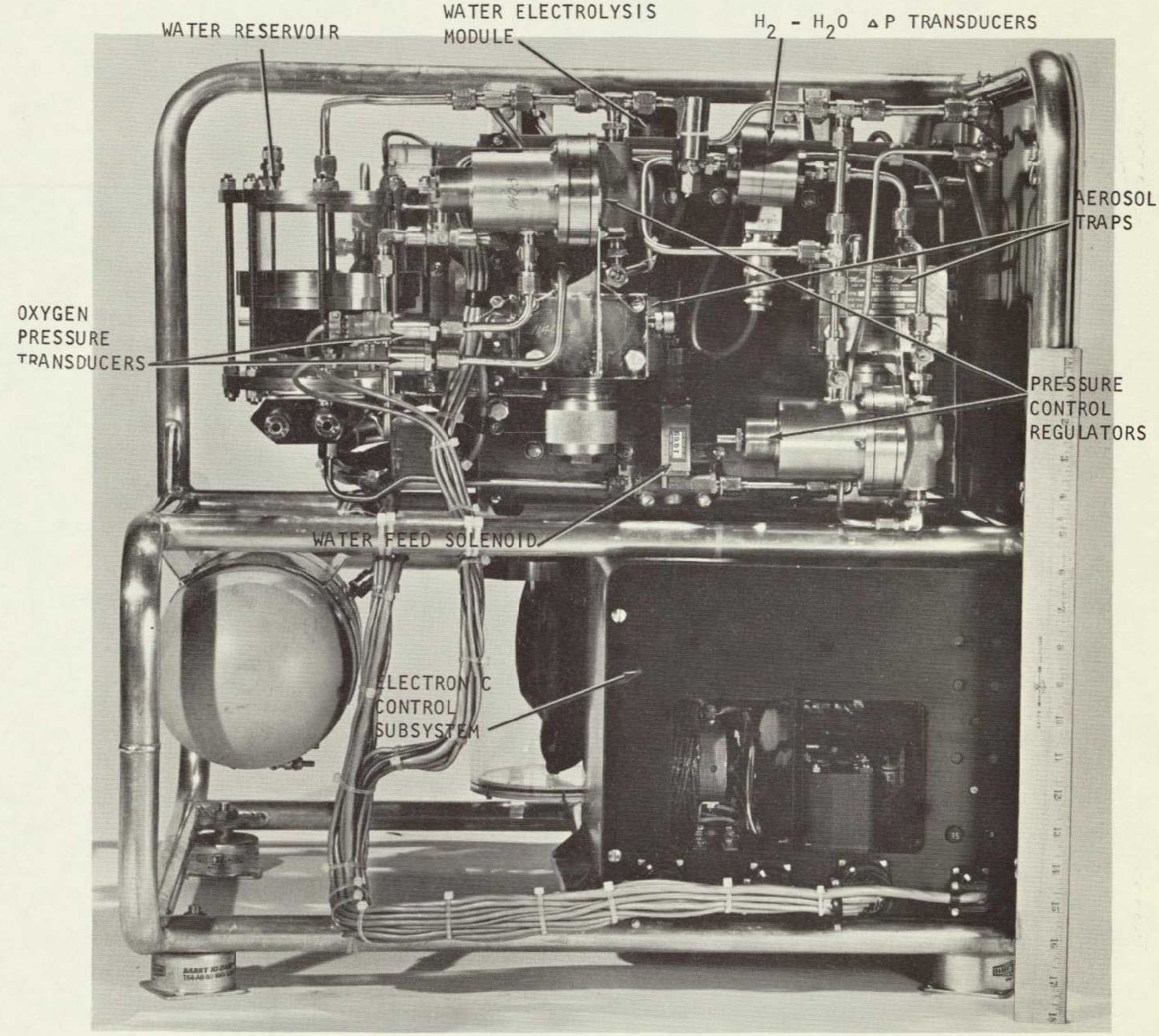

FIGURE 4 FLIGHT BREADBOARD SYSTEM (LEFT SIDE VIEW)

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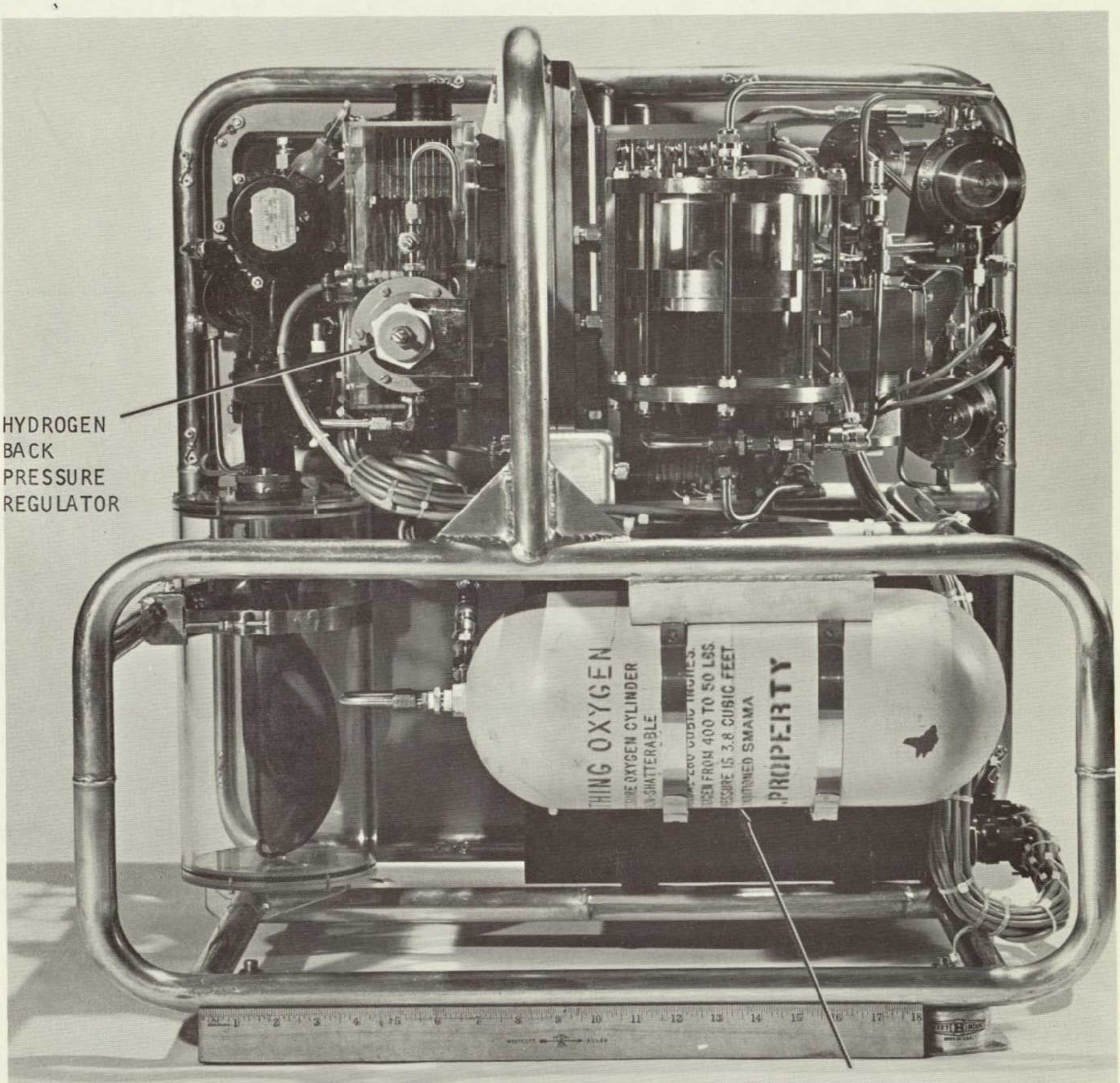

FIGURE 5 FLIGHT BREADBOARD SYSTEM
(REAR VIEW)

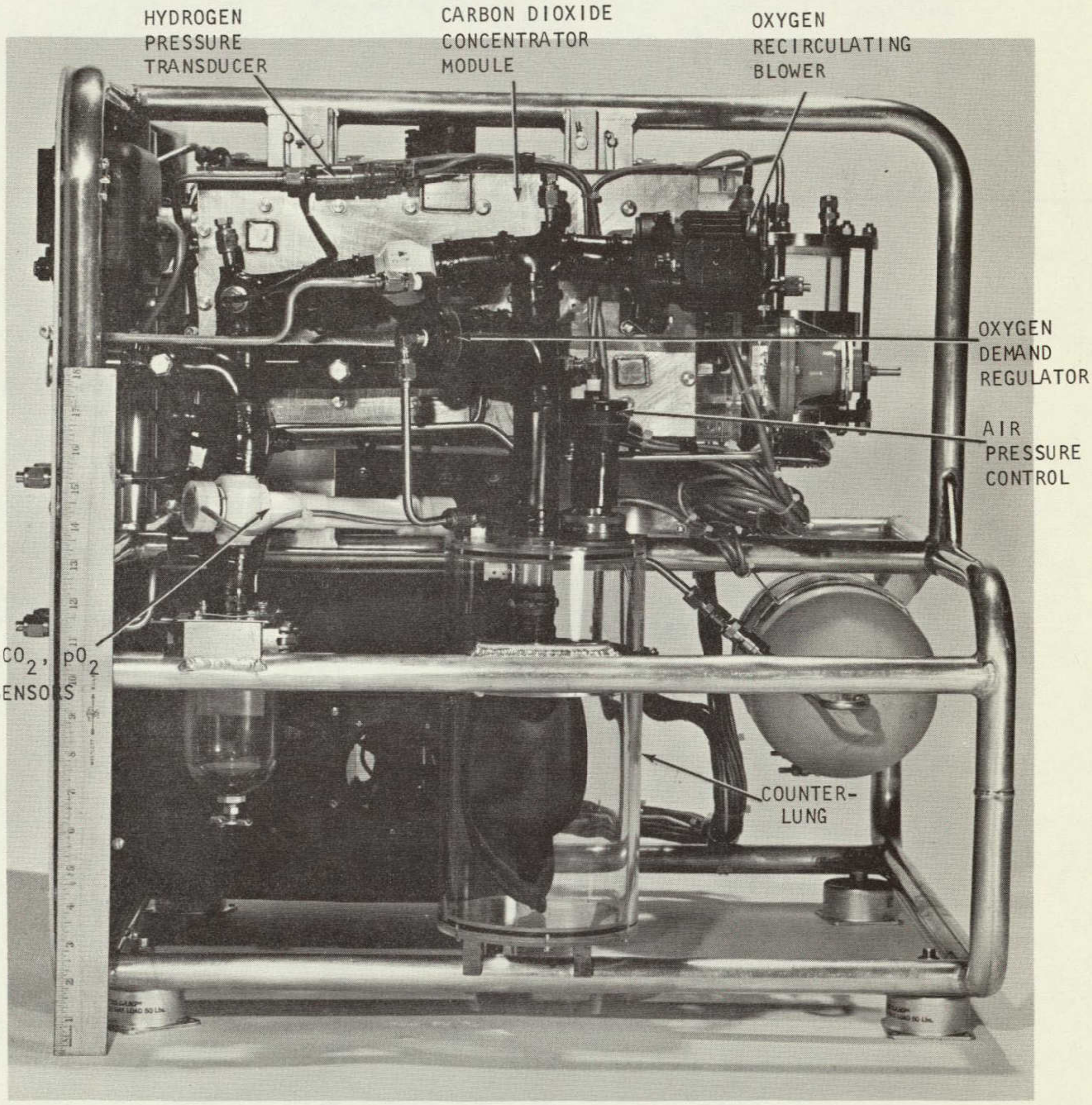

FIGURE 6 FLIGHT BREADBOARD SYSTEM (RIGHT SIDE VIEW)

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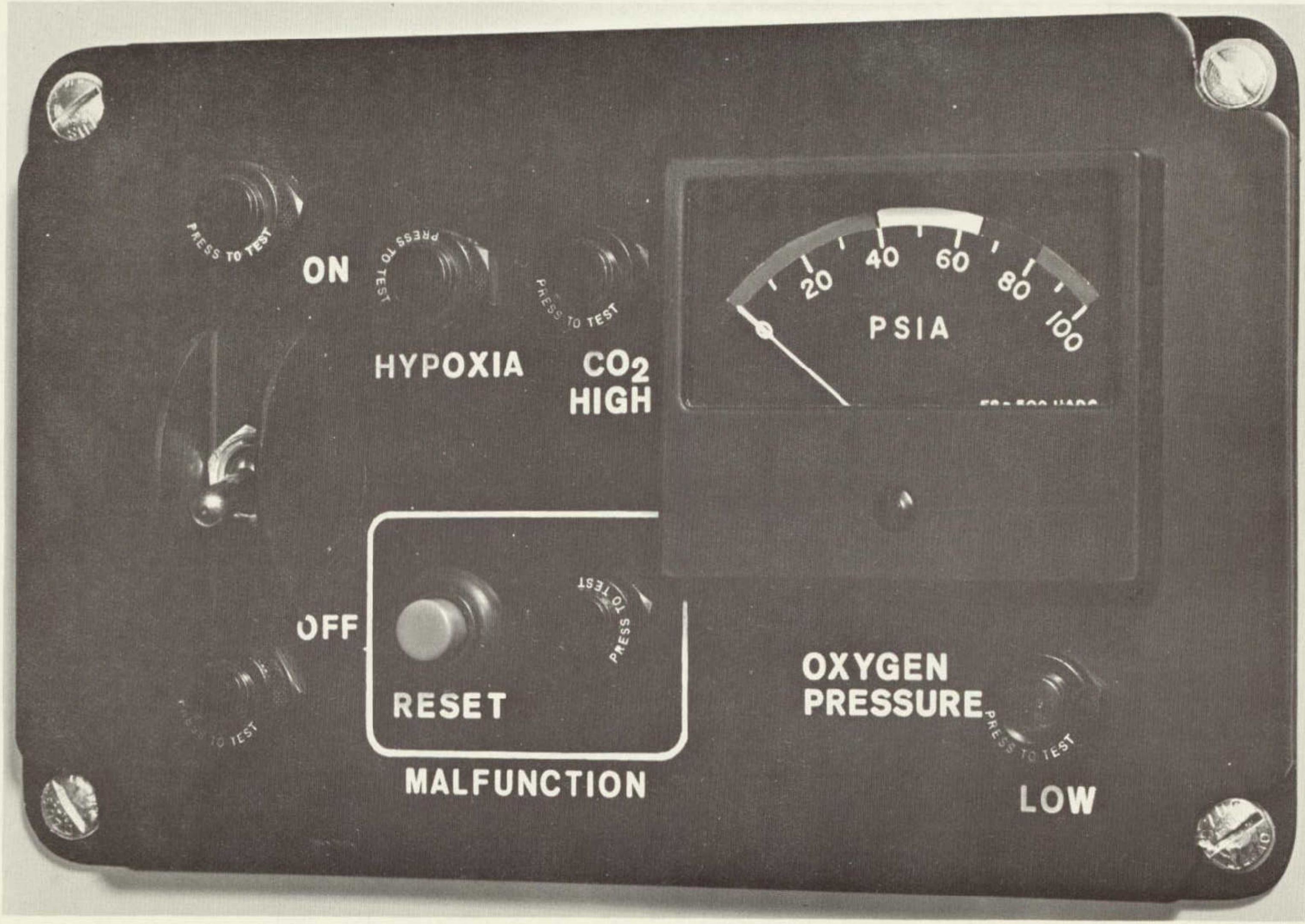


FIGURE 7 PILOT CONTROL PANEL

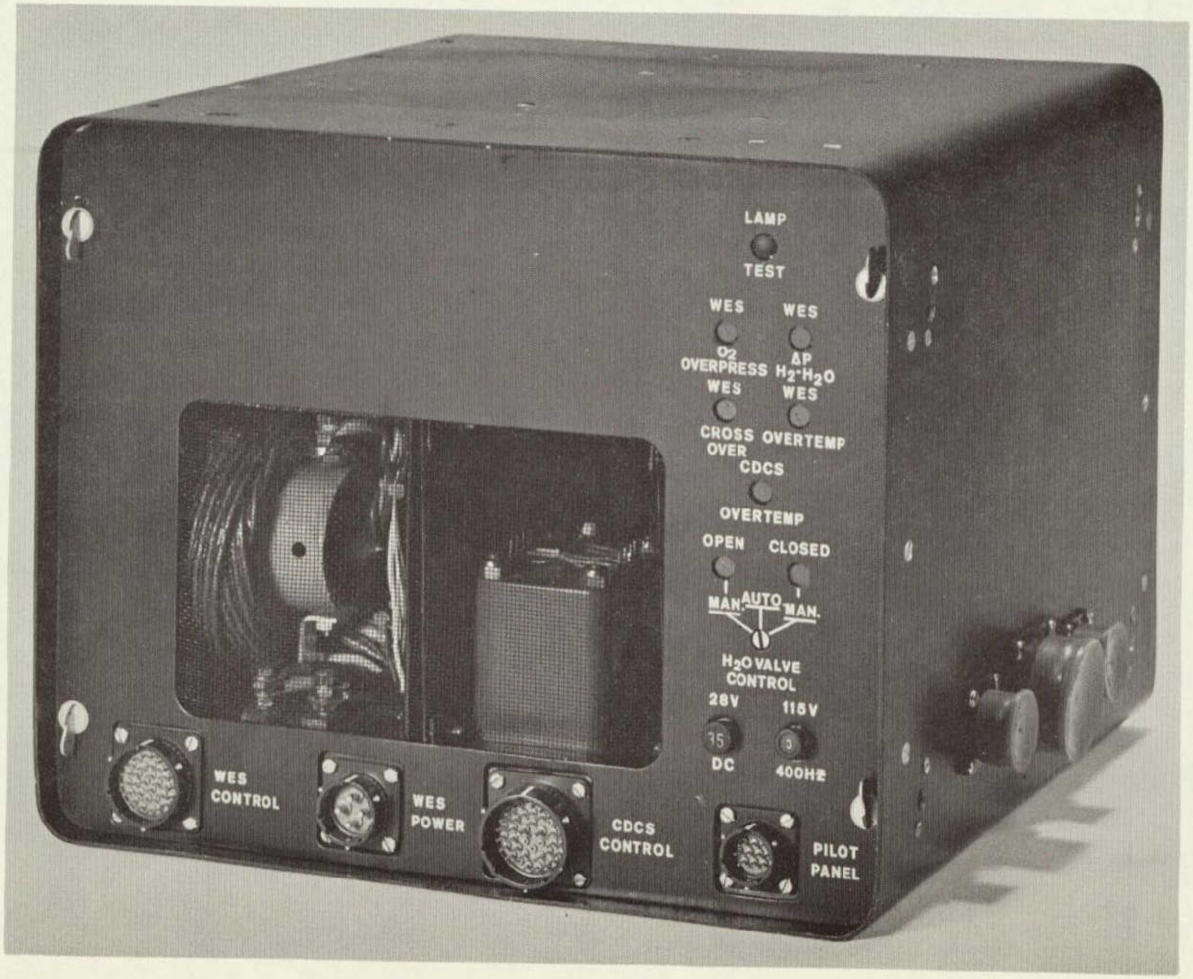


FIGURE 8 ELECTRICAL CONTROL SUBSYSTEM PACKAGE

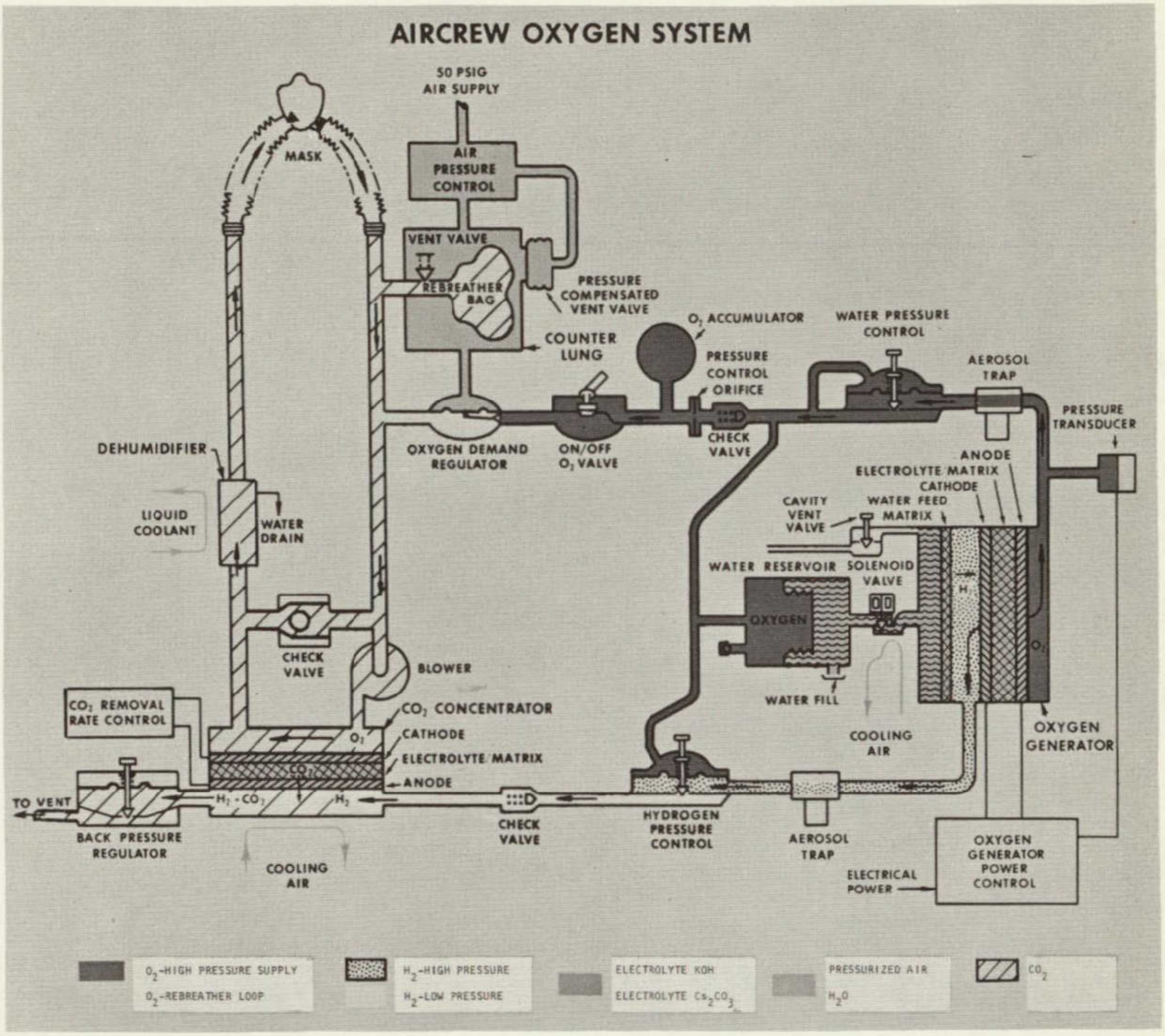


FIGURE 9 AIRCREW OXYGEN FLIGHT BREADBOARD SYSTEM SCHEMATIC

and the blower inlet is connected to the recirculating loop. This loop, together with the module with its check valve and connections to the rebreather subsystem, make up the carbon dioxide concentrating subsystem. This entire subsystem may be removed from the frame by loosening two clamps and the removal of two locating pins. Insulation of the recirculating loop and associated breathing gas tubes was accomplished by coating the tubing with 1/4" thickness of polyvinyl chloride tubing. In this way, tubing which was susceptible to water vapor condensation was uniformly insulated combining both adequate insulation with a neat exterior appearance.

Except for minor changes in tubing configuration, the rebreather subsystem (see Figure 6) remains unchanged from the laboratory breadboard. One notable modification was the addition of partial pressure sensors for CO_2 and O_2. This unit was placed in the inhalation line and provides continuous monitoring of the amount of CO_2 and O_2 in the breathing gases. In addition, all tubes which carry or contain breathing gases were insulated in the same manner as the tubes in the Carbon Dioxide Concentrating Subsystem.

The Electronic Control Subsystem (ECS) is housed in one 12½" wide x 9-3/4" high x 12" deep package which weighs 26 pounds (see Figure 8). The only electronic equipment external to this package is the pilot control panel (see Figure 7) and a small (2¼ x 2¼ x 2½) pCO_2 sensor pre-amp. The sensors, transducers, thermistors and blowers are located in the system where required to measure or control. The ECS package consists of three basic pieces: 1) the WES power conditioning, control and instrumentation chassis, 2) the CDCS power, control and instrumentation chassis, and 3) the package frame which houses 1) and 2) as well as cooling blowers, system instrumentation, and some readout indicators. The two chassis are plug-in units and can easily be removed for repair or modification. Both chassis are electrically independent units and can be operated by themselves external to the ECS package with a minimum of additional circuitry.

To facilitate maintenance and to make modifications easier all low level electronic circuits are constructed on eight plug-in circuit boards. Five are in the WES chassis and three in the CDCS chassis. Two of the eight boards are identical (thermal control circuits). One of these is used on each chassis.

The panels on the sides of the ECS package are held in place with four quick release fasteners. The left side panel, besides being a cover panel, also holds the internal chassis in place. When this panel is removed any circuit board can be removed as can either chassis. All ECS adjustment controls are contained on the plug-in circuit boards. These controls are located such that when all boards are plugged in and the chassis are in the package they are all available for adjustment on the left side of the ECS package when the side panel has been removed.

Signals and power to and from the ECS package are all routed through high quality crimp type connectors with rear insertion and removal contacts.

Flight Breadboard System Operation

The Aircrew Oxygen System as shown in Figure 9 (Flight Breadboard System Schematic) consists of four primary subsystems: 1) Water Electrolysis, 2) Carbon Dioxide Concentrator, 3) Rebreather and 4) Electrical Control.

Hydrogen and oxygen gases are generated in the Water Electrolysis Subsystem at a selected pressure level. Oxygen gas is fed to the rebreather loop through the oxygen demand regulator. A blower in the rebreather loop circulates the oxygen gas through the carbon dioxide concentrator. The hydrogen gas from the electrolysis module is fed to the carbon dioxide concentrator where it reacts electrochemically with oxygen to remove carbon dioxide from the rebreather loop. The carbon dioxide is vented with excess hydrogen.

The pilot's exhalation enters the counter-lung which accommodates the pilot's tidal volume during breathing to maintain the loop at constant pressure during the breathing cycle. Inhalation oxygen is drawn from the circulating loop through a heat exchanger used as a dehumidifier.

The following sections describe each subsystem and the theory of operation in the Aircrew Oxygen System. Specifications for the system components are listed in Table I.

Water Electrolysis Subsystem. - Figure 10 shows the overall view of the ten-cell water electrolysis module. The basic cell construction and method of water supply is shown schematically in Figure 11. Potassium hydroxide electrolyte (25% by weight) is held in a porous asbestos matrix which is compressed between catalytically active (platinized) electrodes. By separating the electrodes physically with this asbestos matrix, the two gases are kept from mixing within the cell and can be drawn off separately. A water feed membrane separates the feed water cavity (containing electrolyte) from the gaseous hydrogen compartment. A DC current flowing through the electrolyte will cause oxygen to evolve at the anode (positive electrode) and hydrogen at the cathode (negative electrode).

When electrical power is applied to the electrodes, water from the cell electrolyte is decomposed. As a result, the concentration of the cell electrolyte increases and, therefore, its vapor pressure decreases to a level below that of the feed compartment electrolyte. This vapor pressure differential causes water vapor to diffuse from the feed membrane through the hydrogen cavity and hydrogen evolving electrode into the cell electrolyte. This process continues as long as the vapor pressure of the cell electrolyte is lower than that of the electrolyte in the feed matrix, i.e., as long as electrolysis is occurring. The transfer of water from the feed compartment to the cell matrix draws make-up water into the feed cavity from an external reservoir.

Removal of waste heat generated within the water electrolysis module due to cell inefficiencies is accomplished by air-cooling the metallic fins external to the module. The cooling loop incorporates a blower and temperature controller. The temperature controller is an ON-OFF control for the blower. Air is circulated in the module shroud by the blower and flows through the fins, thus providing cooling as required.

The Water Electrolysis Subsystem is composed of the electrolysis module, the water reservoir, oxygen pressure control, pressure balance regulation, the cooling loop, and water vapor condensers and traps. A solenoid valve, located between the water reservoir and the electrolysis module, is closed when the system is not in operation to prevent flooding of the cells. During operation this valve is open and the proper differential pressures are maintained by the

TABLE I

COMPONENT PERFORMANCE SPECIFICATIONS

Electrolysis Module Assembly	
Oxygen Generation Rate:	0.15 lb/hr, nominal 0.20 lb/hr, maximum
Oxygen Supply Pressure:	77 ±3 psia
Hydrogen Pressure:	0 to 5 psi below O_2 pressure
Water Supply Pressure:	0 to 5 psi below H_2 pressure
Operating Duration:	10 hrs, continuous
Power Input:	0 to 30 amps, 20 volts maximum
Coolant:	Air
Cooling Load:	400 BTU/hr, maximum
Operating Temperature:	150°F
Electrolysis Module Water Reservoir	
Useful Capacity:	1.9 lb water, minimum
Gas (O_2) Side Pressure:	72 ±8 psia
Gas (O_2) to Water Side Pressure Difference:	±0.5 psi
Carbon Dioxide Concentrator Module Assembly	
CO_2 Removal Rate:	0.12 lb/hr, minimum
Operating Temperature Range (after start-up):	100 to 140°F
O_2 Side Total Pressure:	3 to 15 psia
H_2 Side Total Pressure:	3 to 15 psia
O_2 Consumption:	0.05 lb/hr, maximum
O_2 Side Circulating Flow:	2.0 CFM, minimum
O_2 Side Pressure Drop:	4 inches H_2O at 3.5 CFM, 1 atm.
H_2 Side Inlet Flow:	0.018 lb/hr
CO_2 Partial Pressure at O_2 Exit:	7.6mm Hg, maximum
Operating Duration:	10 hrs, continuous
Coolant:	Air
Cooling Load:	300 BTU/hr, maximum
Operating Temperature:	100°F
Counter-Lung Assembly	
Useful Volume:	1 liter
Differential Pressure, container above Ambient:	1.0 psi, maximum
Vent Valve Cracking Pressure:	0.5 inches H_2O
Blower	
Pressure Flow:	6 inches H_2O at 3.5 CFM
Electrical Power:	115 volts, 400 Hz, 250 milliamps

continued-

Table I - continued

Dehumidifier Assembly	
Cooling Fluid:	Water or water-antifreeze solution
Oxygen Flow Rate:	0.5 CFM average, 2.0 CFM peak, flow vs time is a sine wave, positive flow only
Oxygen Inlet Temperature:	$100^{\circ}F$ to $140^{\circ}F$
Oxygen Outlet Temperature:	$40^{\circ}F$ to $60^{\circ}F$
Coolant Inlet Temperature:	$40^{\circ}F$ to $50^{\circ}F$
Oxygen Inlet Humidity:	Saturated
Coolant Flow Rate:	50 lb/hr, minimum
Electrolysis Module Power Control Unit	
Voltage Input:	28 ±4 volts DC, 750 watts, maximum 115 volts, 400 Hz, 5 watts
Voltage Output to Module:	10 to 20 volts DC
Current Output to Module:	0 to 30 amps
Current Regulation:	±0.5 amps
Pressure Control Shut-off:	80 psia
Pressure Control Proportional Band:	6 psi
CO_2 Concentrator Module Load	
Load Current:	Manual set point 0 to 10 amps
Current Regulation:	±0.12 amps
Load Voltage:	2 to 12 volts DC
Control Power Input:	115 volts, 400 Hz, 5 watts
Counter-Lung Air Pressure Control Regulator	
Air Flow Rate:	0.5 CFM, average 2.0 CFM, peak
Safety Pressure:	1 to 2 inches H_2O above ambient
Pressure Breathing:	MIL-R-19121D
Relief Pressure:	18 inches H_2O
Air Inlet Pressure:	50 psig, nominal
Oxygen Demand Regulator	
Oxygen Inlet Pressure:	50 to 100 psia
Oxygen Outlet Pressure:	3 to 15 psia
Cracking Pressure:	0.5 inches H_2O below dome loading pressure
Oxygen Flow Rate:	0 to 50 liters/min
Oxygen Differential Pressure Regulator	
Operating Pressure:	10 to 100 psia
Differential Pressure:	0 to 5 psi, adjustable
Oxygen Flow Rate:	0 to 0.2 lb/hr

continued-

Table I - continued

Hydrogen Pressure Control Regulator

Operating Pressure:	10 to 100 psia
Dome Loading Gas:	Oxygen
Diaphragm:	Double, with interspace vented for safety
Backpressure:	0 to 5 psi above dome loading, adjustable
Hydrogen Flow Rate:	0 to 0.02 lb/hr

Hydrogen Backpressure Regulator

Pressure Level:	3 to 20 psia
Operating Pressure:	0 to 5 psi above ambient, adjustable
Fluid:	Hydrogen-Carbon Dioxide mixture (30% CO_2 by vol.)
Gas Flow Rate:	1.6 standard liters/min.

Hydrogen Detector

Operating Fluid:	Oxygen
Operating Pressure:	0 to 100 psia
Oxygen Flow Rate:	0.15 lb/hr, nominal
Sensitivity:	0.5 percent H_2 by volume

Partial Pressure Sensor Assembly

Oxygen Partial Pressure Range:	100 t0 760mm Hg
Carbon Dioxide Partial Pressure Range:	2 to 100mm Hg

CO_2 Concentrator Cooling Fan

Input:	115 volts, 400 Hz, 16 watts
Output:	22.5 CFM free air

Electrolysis Module Cooling Fan

Input:	115 volts, 400 Hz, 18 watts
Output:	32 CFM free air

Water Feed Solenoid Valve

Fluid:	Water
Operating Pressure:	0 to 100 psia
Input Power:	20-30 VDC, 1.0 amp.

Oxygen Shut-Off Valve

Fluid:	Oxygen
Operating Pressure:	0 to 100 psia

Counter-Lung Vent Valve

Inhalation Cracking Pressure:	less than 0.1 inch H_2O
Exhalation Cracking Pressure:	0.5 inch H_2O, compensated for pressure breathing

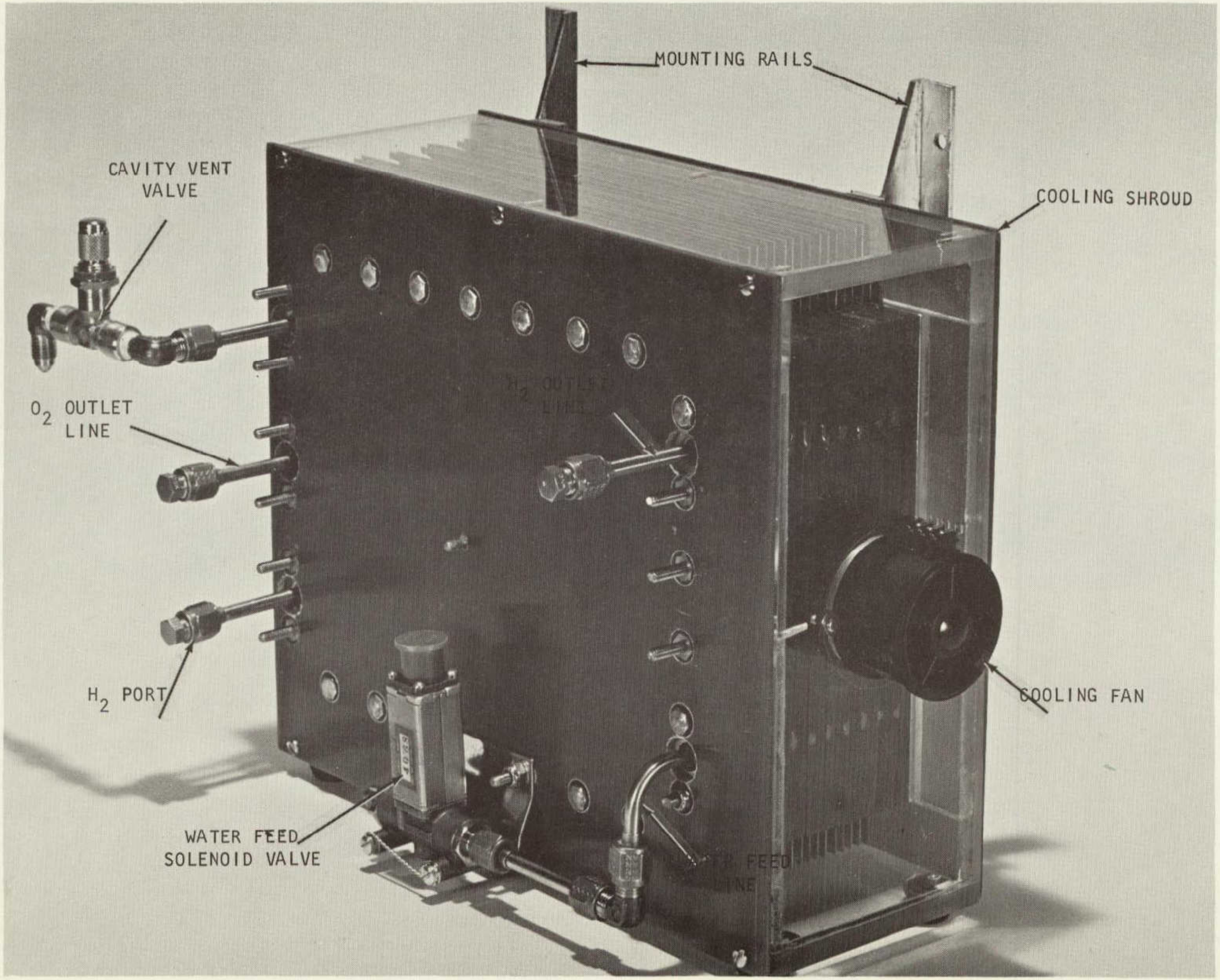


FIGURE 10 WATER ELECTROLYSIS MODULE

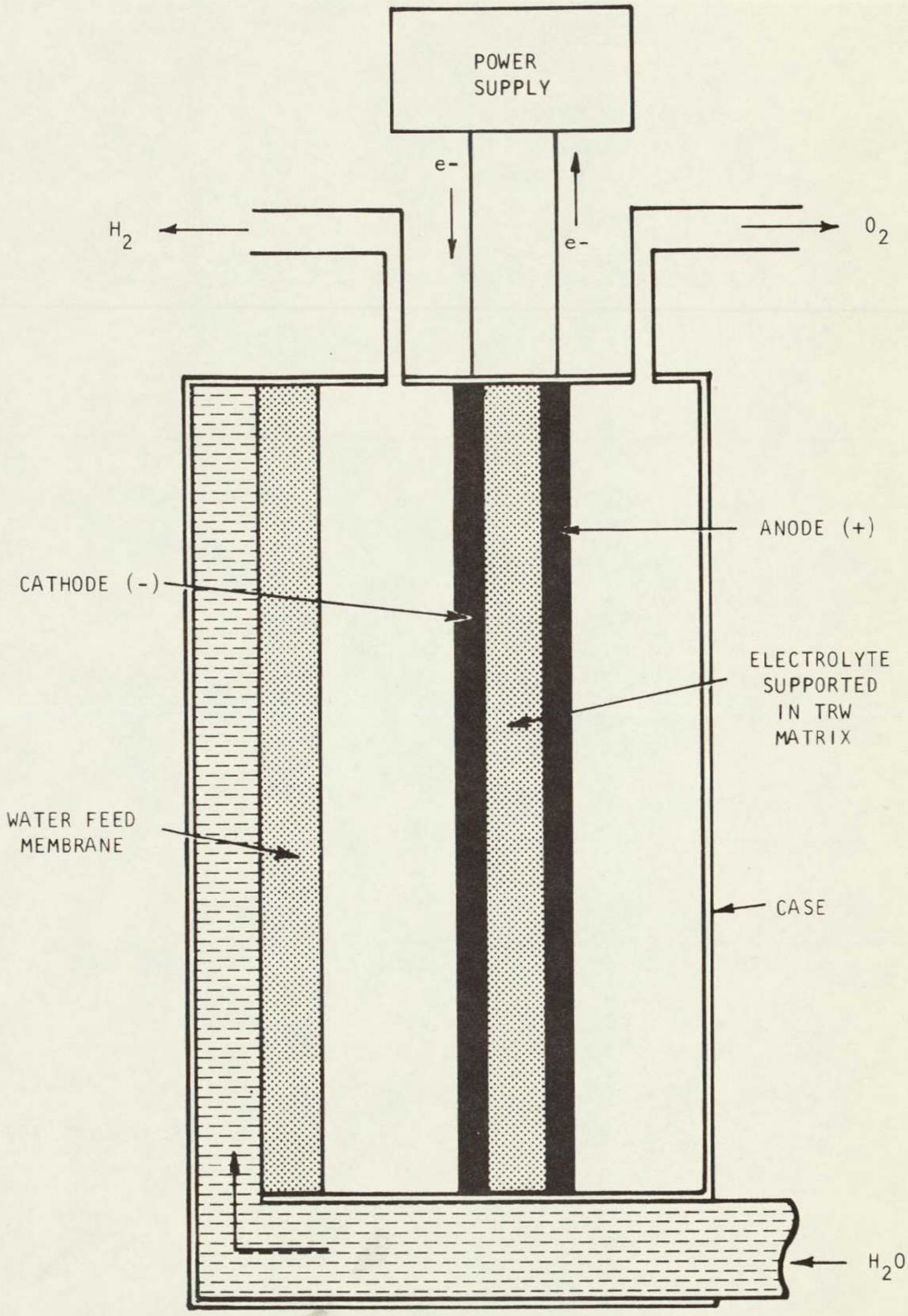


FIGURE 11 WATER ELECTROLYSIS CELL SCHEMATIC

differential pressure regulator in the oxygen line and the back-pressure regulator in the hydrogen line.

A pressure transducer located in the oxygen line provides a signal to an electronic controller which regulates the flow of electrical current into the electrolysis module. The characteristics of this controller are such that the current remains constant as the pressure increases to a preset value. At this pre-selected pressure level, the electrical current decreases linearly with pressure until the current is zero at the shutoff pressure.

A regulator in the oxygen line is used to drop the pressure level so that the water feed will be maintained at 1.0 psi below the oxygen pressure. The hydrogen pressure is maintained between these pressures by a dome-loaded back-pressure regulator. All pressures, therefore, are referenced to the oxygen pressure which in turn is controlled by electrical power to the electrolysis module.

The traps in the oxygen and hydrogen lines are used to contain the excess moisture and any aerosol generated. Check valves prevent backflow into the electrolysis module when the system is not operating. The shutoff valve in the oxygen line prevents oxygen loss through the demand regulator in the event that the rebreather loop is opened. The restriction and accumulator in the oxygen line damp out pulsations caused by the periodic operation of the demand regulator. Figure 12 is the WES mass and flow balance schematic.

Carbon Dioxide Concentrator Subsystem. - The Carbon Dioxide Concentrator Subsystem is composed of the carbon dioxide concentrator module, oxygen circulating loop including a blower and check valve, an electrical load control, and a cooling system. The circulating loop provides for continuous oxygen flow through the carbon dioxide concentrator independent of the periodic breathing flow rates.

The load control maintains a constant current flow through the concentrator and load resistors independent of the concentrator voltage. The cooling system incorporates a temperature controller which operates an air blower when the concentrator reaches a set temperature.

The Carbon Dioxide Concentrator is an electrochemical cell which concentrates or removes carbon dioxide from a mixture of oxygen/carbon dioxide. A single cell consists of two porous electrodes (anode and cathode) separated by an asbestos matrix. This asbestos matrix contains the electrolyte which is an aqueous solution of 52% weight concentration of cesium carbonate (Cs_2CO_3). Cell plates adjacent to the electrodes provide passageways for distributing the gaseous reactants over the surface of the electrodes. The cell plates consist of two parts--a polysulfone frame and a silver sheet. The polysulfone frame provides the internal manifolding for the gases, positions the electrodes and matrix and the current collectors which provide electrical and thermal paths between the electrodes and the silver sheets. The silver sheets act as electrical bipolar plates between each cell and conduct waste heat to the fin areas where the heat is dissipated to the cooling air stream.

The carbon dioxide concentrator module is shown in Figure 13 with the recirculating loop. The module is capable of transferring approximately 0.1 lb CO_2/hr. Figure 14 is a schematic of the Carbon Dioxide Concentrator Cell.

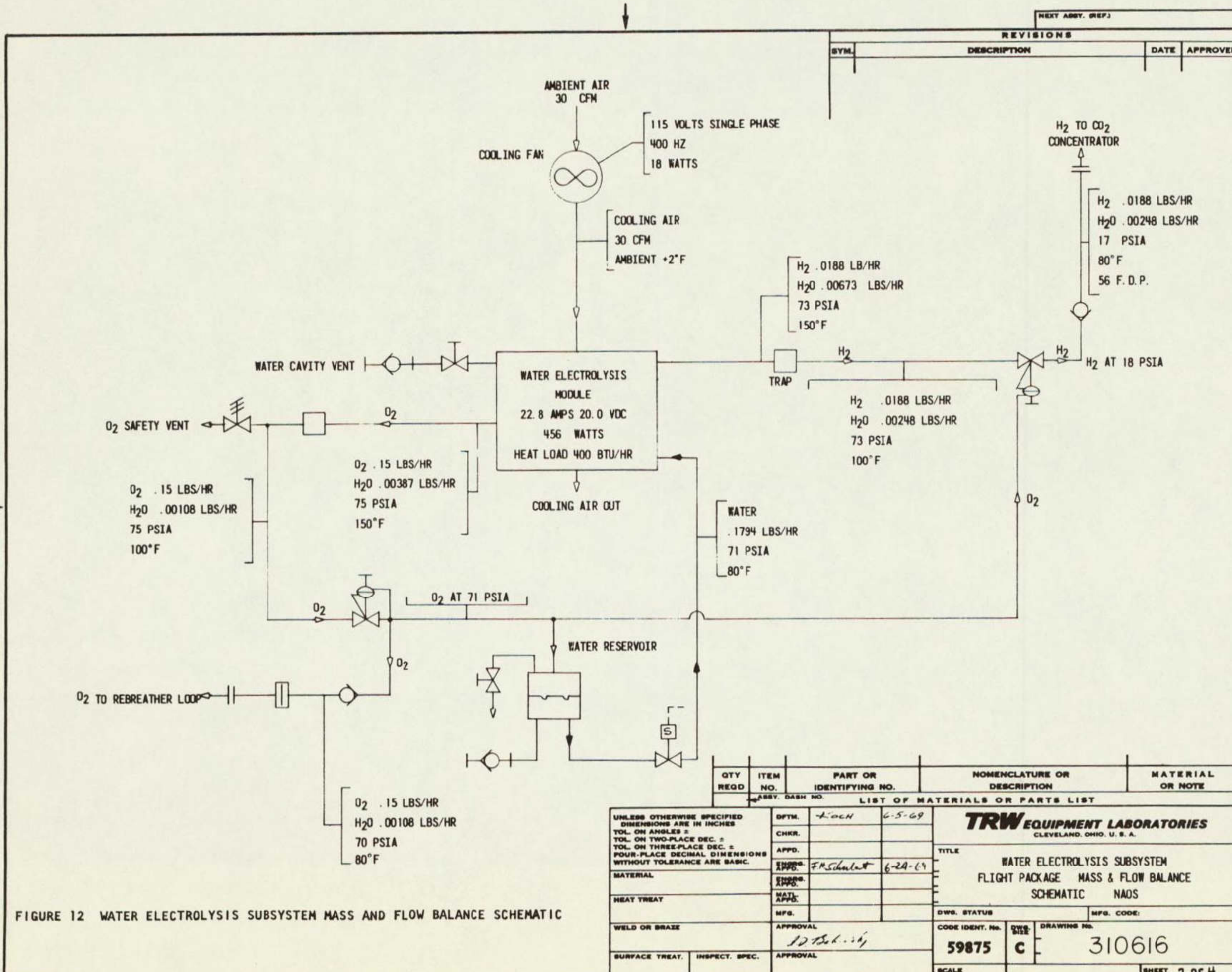


FIGURE 12 WATER ELECTROLYSIS SUBSYSTEM MASS AND FLOW BALANCE SCHEMATIC

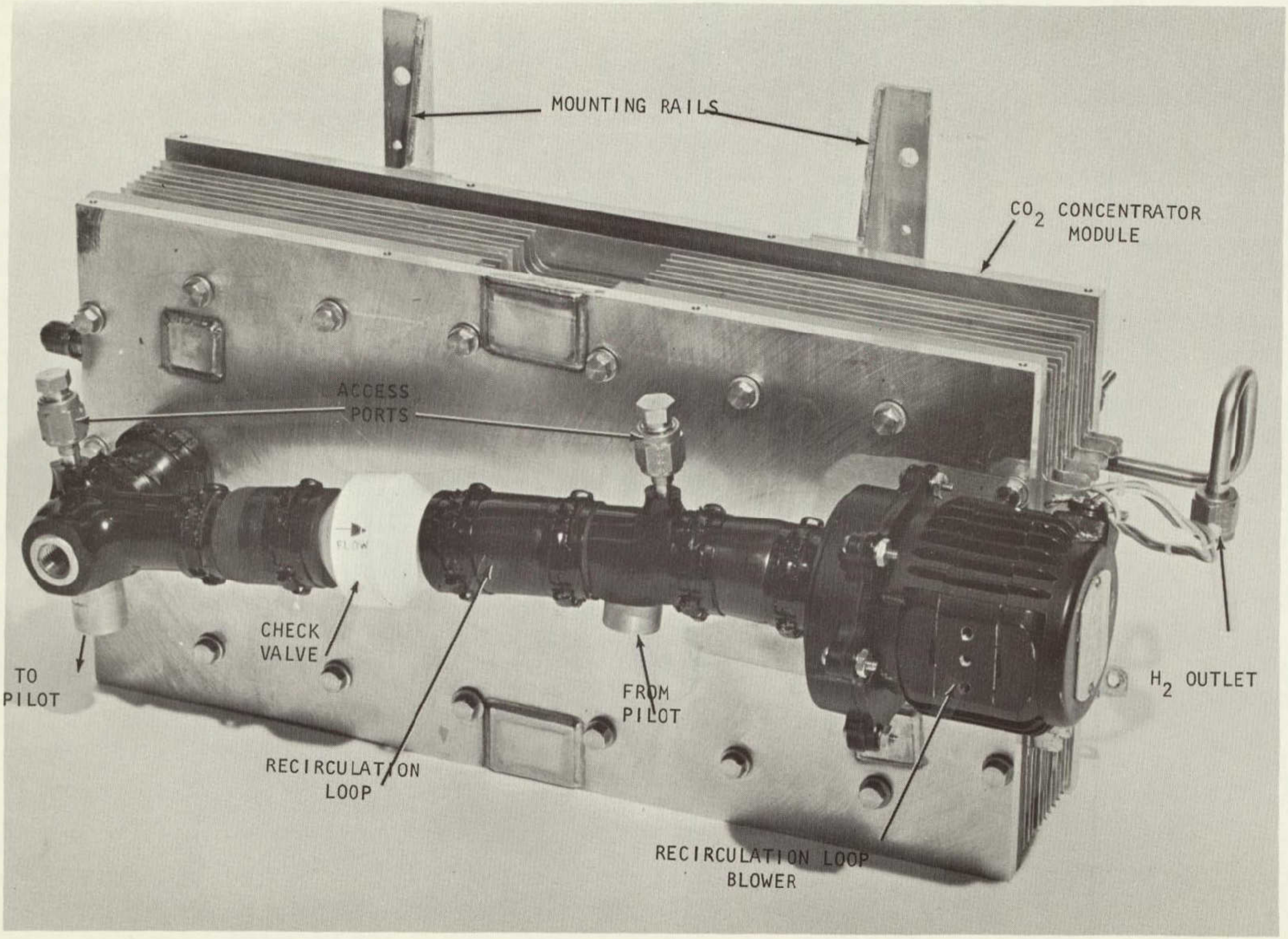
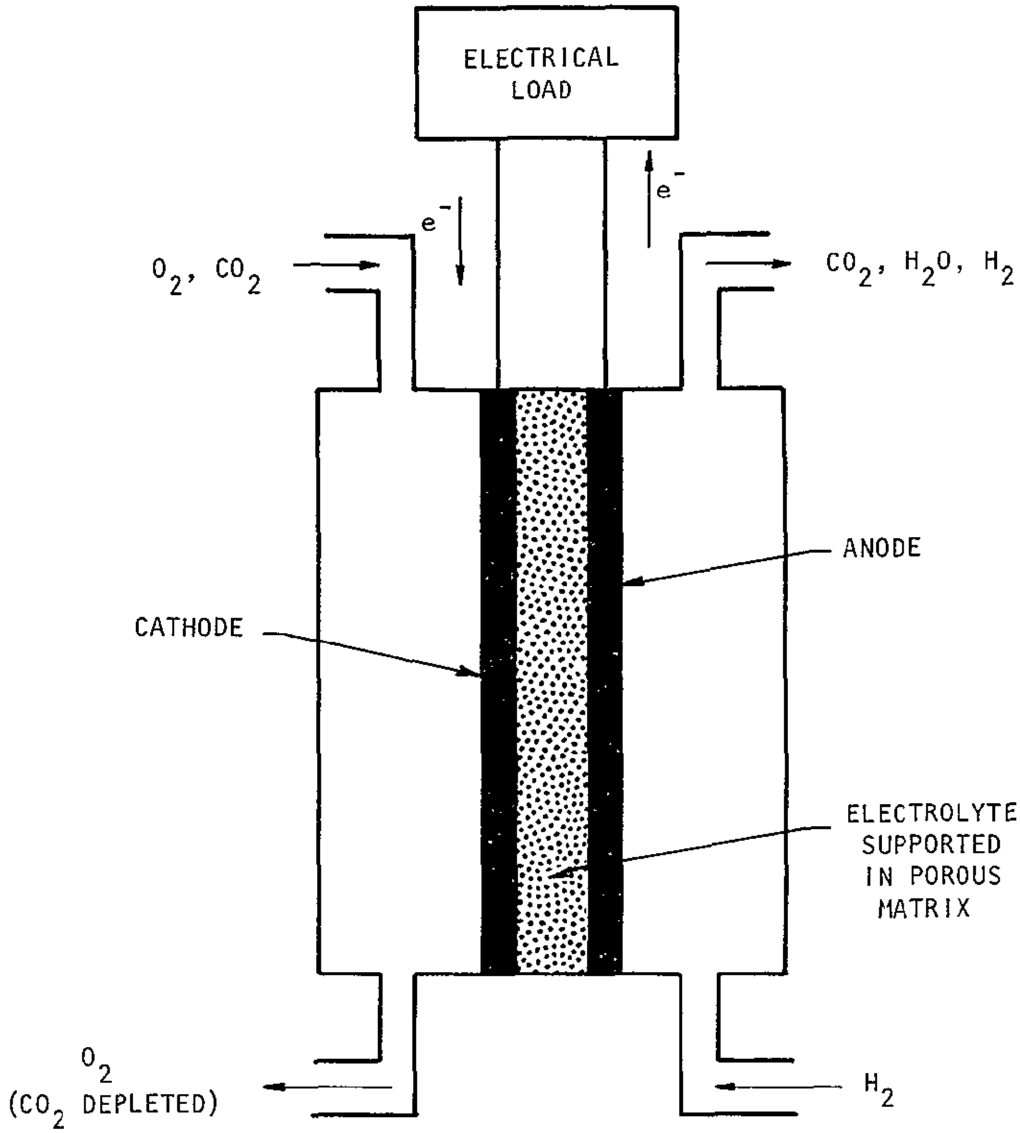


FIGURE 13 CARBON DIOXIDE CONCENTRATOR MODULE



REACTIONS

OVERALL	$H_2 + (1/2\ O_2 + CO_2) \longrightarrow H_2O + CO_2 + \text{POWER}$
CATHODE	$1/2\ O_2 + H_2O + 2\ e^- \longrightarrow 2\ OH^-$
	$CO_2 + 2\ OH^- \longrightarrow CO_3^{=} + H_2O$
ANODE	$H_2 + 2\ OH^- \longrightarrow 2\ H_2O + 2\ e^-$
	$CO_3^{=} + H_2O \longrightarrow 2\ OH^- + CO_2 \uparrow$

FIGURE 14 CO_2 CONCENTRATOR CELL SCHEMATIC

Figure 15 is a schematic of the carbon dioxide concentrator subsystem mass and flow balances.

Rebreather Subsystem. - The Rebreather Subsystem components include a rebreather bag and counter-lung with a pressure-compensated vent valve, a dehumidifier, and a circulating blower. The counter-lung functions as a volumetric gas reservoir to accommodate the variation in the breathing loop gas volume as the aviator inhales and exhales. The counter-lung is a flexible bag within a rigid container. The inside of the bag is connected to the breathing loop. The volume between the bag and the container is pressurized with air, normally about one inch of water pressure above cabin pressure. This prevents cabin air from leaking into the system. At altitudes requiring pressure breathing, the counter-lung is pressurized to the standard pressure breathing schedule starting at 38,000 feet cabin altitude.

Inhalation oxygen is drawn from the circulating loop through a heat exchanger used as a dehumidifier. This is required because the flow in the circulating loop is at approximately $100^{\circ}F$ and nearly saturated with water vapor. Oxygen from the electrolysis cell enters through the demand regulator to make up the oxygen consumed by the aviator, the carbon dioxide concentrator, and any system venting.

During inhalation, the counter-lung bag is collapsed by the air pressure within the counter-lung. A pressure regulator mounted on the counter-lung regulates this pressure. When the rebreather bag becomes fully collapsed and the loop pressure begins to fall below the air pressure, the demand regulator will open to supply oxygen from the Electrolysis Subsystem. During exhalation, if the pressure within the loop exceeds the pressure within the counter-lung, a vent valve will open and relieve the pressure in the loop. Figure 16 gives a schematic for the Rebreather Subsystem mass and flow balances.

Electrical Control Subsystem. - The Electrical Control Subsystem contains all the circuits required to power, control and monitor the operation of all the other subsystems in the FBS. It also contains malfunction detection and warning circuits with fault isolation capability.

Aircraft 28 volt DC power is converted to a controlled, constant current by means of an efficient switching regulator to power the WES module. The signal from an absolute pressure transducer in the module oxygen line is amplified and used to control the output of the constant current regulator. For pressures below a preset value, the current will be a constant maximum. The value of this maximum can be adjusted to any desired value. When the pressure exceeds the preset value, the current decreases linearly to zero as pressure increases. The slope of this decrease is adjustable. This slope sets the pressure variations for oxygen flow rate changes.

Oxygen flow rate from the module is determined only by module current. Thus, the oxygen pressure will change until the module current is the required value for the average oxygen demand. If the oxygen demand rate should decrease, the pressure will increase until the current drops to the value needed for the reduced oxygen flow rate and vice versa. A schematic representation of the WES current control characteristic is shown in Figure 17.

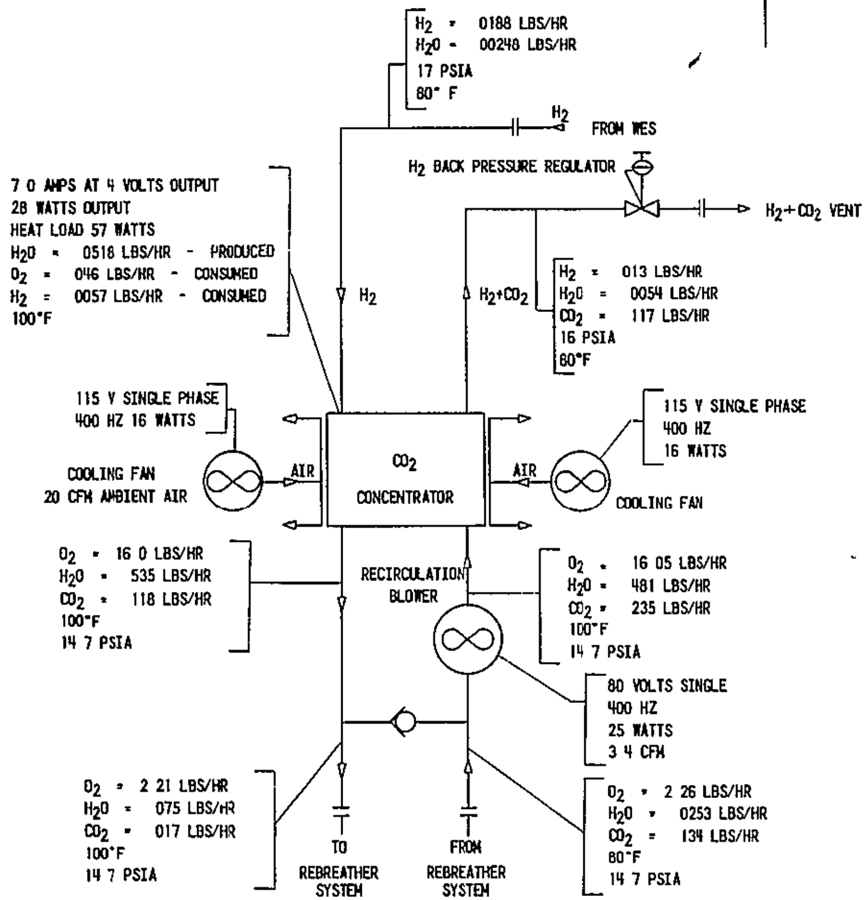


FIGURE 15 CO_2 CONCENTRATOR SUBSYSTEM MASS AND FLOW BALANCE SCHEMATIC

NEXT ASSY (REF)			
REVISIONS			
SYM	DESCRIPTION	DATE	APPROVED

QTY REQD	ITEM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL OR NOTE

LIST OF MATERIALS OR PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOL ON ANGLES ± TOL ON TWO-PLACE DEC ± TOL ON THREE-PLACE DEC ± FOUR PLACE DECIMAL DIMENSIONS WITHOUT TOLERANCE ARE BASIC

MATERIAL

HEAT TREAT

WELD OR BRAZE

SURFACE TREAT | INSPECT SPEC

DFTM	KOCH	6-5-69
CHKR		
APPD		
ENGRG APPD	R Kiraly	6/24/69
ENGRG APPD		
MATL APPD		
MFG		

APPROVAL
APPROVAL

TRW EQUIPMENT LABORATORIES
CLEVELAND OHIO U S A

TITLE
CO_2 CONCENTRATOR SUBSYSTEM
FLIGHT PACKAGE MASS & FLOW BALANCE
SCHEMATIC NAOS

DWG STATUS | MFG CODE

CODE IDENT No.	DWG SIZE	DRAWING No.
59875	C	310616

SCALE | SHEET 3 OF 4

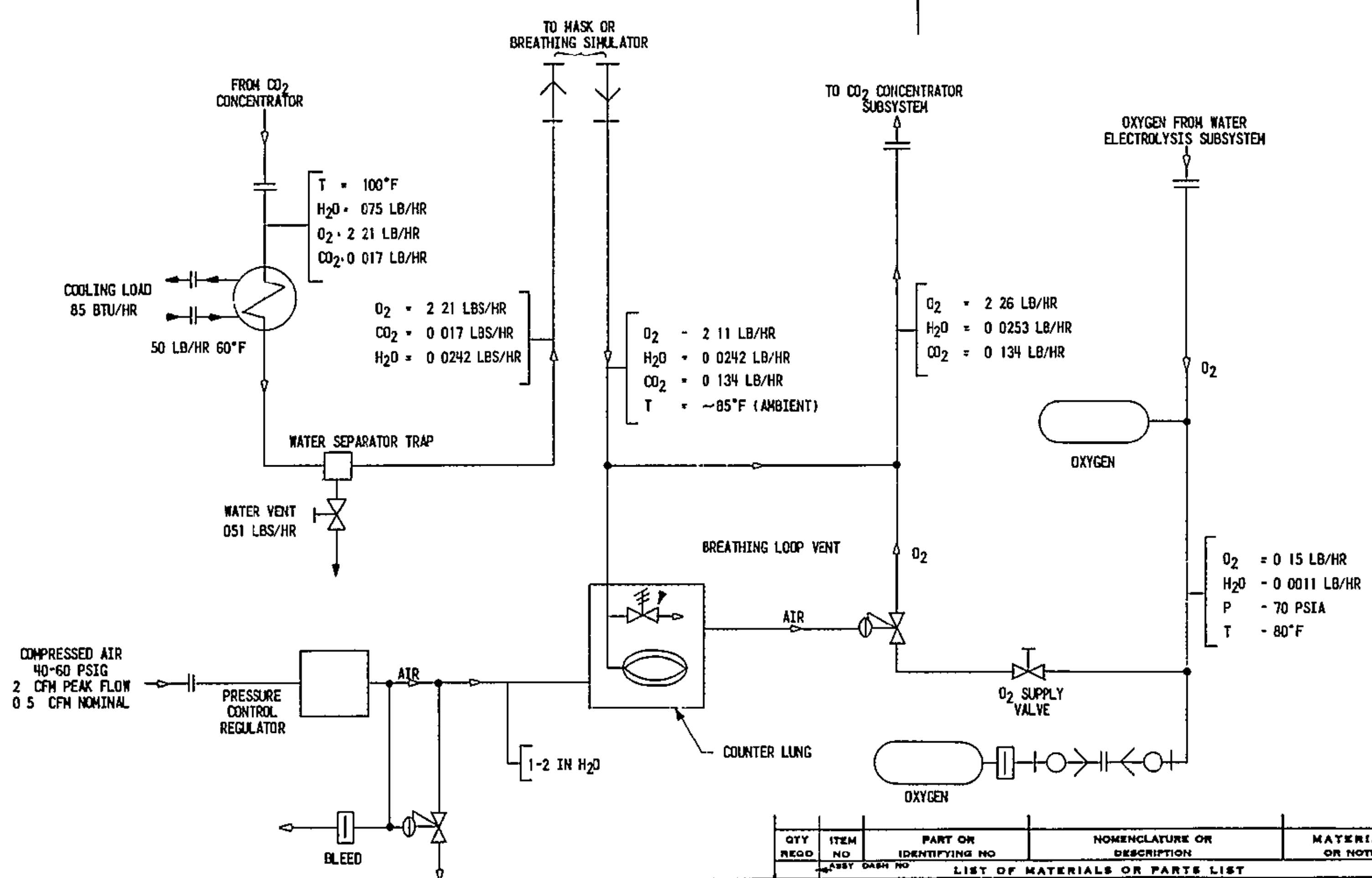


FIGURE 16 REBREATHER SUBSYSTEM MASS AND FLOW BALANCE SCHEMATIC

NEXT ASSY (REF)

REVISIONS

SYM.	DESCRIPTION	DATE	APPROVED

QTY REQD	ITEM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL OR NOTE

ASSY DASH NO — LIST OF MATERIALS OR PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOL. ON ANGLES ±
TOL. ON TWO-PLACE DEC. ±
TOL. ON THREE-PLACE DEC. ±
FOUR PLACE DECIMAL DIMENSIONS WITHOUT TOLERANCE ARE BASIC.
MATERIAL
HEAT TREAT
WELD OR BRAZE
SURFACE TREAT — INSPECT SPEC

DFTM	Koch	6-5-69
CHKR.		
APPD		
ENGRG. APPD	R Kudy	6/24/69
ENGRG. APPD		
MATL. APPD		
MFG		

APPROVAL: R D Bubinsky
APPROVAL

TRW EQUIPMENT LABORATORIES
CLEVELAND OHIO U S A.

TITLE
REBREATHER SUBSYSTEM
FLIGHT PACKAGE MASS & FLOW BALANCE
SCHEMATIC NAOS

DWG. STATUS — MFG. CODE:
CODE IDENT No. 59875 — DWG. SIZE C — DRAWING No. 310616
SCALE — SHEET 4 OF 4

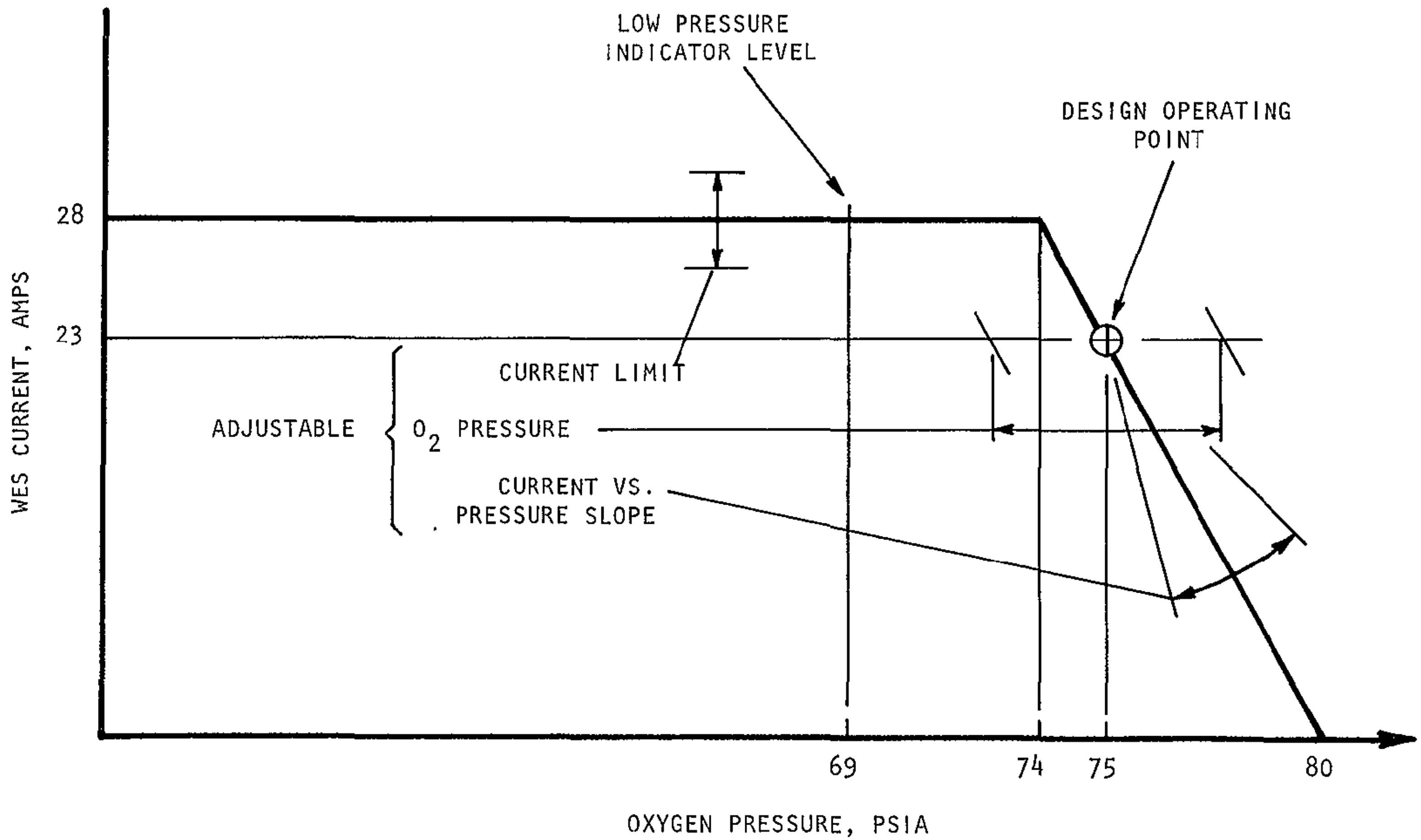


FIGURE 17 WES CONTROLLER CHARACTERISTICS

The CDCS module produces power as it operates. The ECS contains a DC constant current load for this module. The current can be manually set at any desired value from zero to 10 amps. Since there is no use for the power being generated by this module in this application, it is converted into heat in the load control transistor and removed with heat sinks.

The three additional controls contained in the ECS package are a temperature control (ON-OFF type) for each module and a speed control for the recirculation blower. These all have adjustable set points to allow variation of operating temperature and blower speed. All automatic control functions are summarized in Table II.

Pressure transducer amplifiers, low level AC/DC converters and thermistor amplifiers are contained in the ECS package as well as level detectors, logic gating and memory circuits and lamp drivers. These circuits are for operating system status readout equipment (meters, lamps and recorders) as well as malfunction detection and storage, isolation of faults and protective shutdown of the system. Table III summarizes the sensors used in the FBS.

All ECS adjustment controls are located in the eight plug-in circuit boards in the system and are accessible when the ECS side panel is removed. In addition, the WES and CDCS chassis can also be removed if required. The WES and CDCS chassis contain five and three control circuit boards, respectively. Figure 18 shows the ECS package with plug-in modules partially removed.

These circuit boards incorporate potentiometer adjustments for the controls and instrumentation calibrations.

Figure 19 is a schematic of the FBS instrumentation.

The failure or malfunction of selected areas of the system may be determined from indicator lights on the instrumentation panel. The locations and type of instrumentation used in the Flight Breadboard System are listed in Table IV. The pilot panel duplicates selected readout elements from the instrumentation package. In the eventual flight prototype system this pilot panel will be the only system status display available.

Manual controls are provided in the following areas. The pilot panel contains the system ON-OFF switch and a malfunction reset pushbutton. These two controls are duplicated on the flight instrumentation package. Located on the ECS package is a manual switch for operating the WES water feed solenoid valve and two circuit breakers, one for the 400 cycle AC and the other for the 28.0 volt DC power inputs.

There is also a pushbutton switch on the ECS package for testing all indicator lamps simultaneously in the pilot panel, the ECS package and flight instrumentation package.

Automatic shutdown of the system is provided in the ECS based on out-of-range values for four parameters (see Table V). Shutdown occurs when a measured value from a sensor (transducer, thermistor, etc.) is found to exceed preset

TABLE II

NAOS FLIGHT BREADBOARD AUTOMATIC CONTROLS

Parameter Controlled	Sensor Used*	Type of Control
WES Stack Temperature	5	On-Off
CDCS Stack Temperature	6	On-Off
WES O_2 Pressure	1	Proportional
WES Stack Current	13	Proportional
CDCS Stack Current	14	Proportional

*See Table III

TABLE III

SENSORS FOR NAOS FLIGHT BREADBOARD SYSTEM

Sensor No.	Type	Expected Range	Location
1	Absolute Pressure	0-100 psia	WES O_2 Out
2	Absolute Pressure	0-100 psia	Breathing Loop O_2 In
3	Differential Pressure	0-5 psid	WES H_2 Out, H_2O
4	Gage Pressure	0-5 psig	CDCS H_2 In
5	Thermistor	$70^{o}F$ to $150^{o}F$	WES Stack
6	Thermistor	$70^{o}F$ to $120^{o}F$	CDCS Stack
7	O_2 Partial Pressure	100 to 760mm Hg	Mask Inlet Tube
8	CO_2 Partial Pressure	2 to 20mm Hg	Mask Inlet Tube
9	Catalytic Bed and Thermistor	$50^{o}F$ to $200^{o}F$	WES H_2 Out
10	Shunt	0-30 amps DC	DC Input Line
11	AC-DC Converter	0-300 ma AC 0-120 volts AC	Recirculation Blower Power
12	AC-DC Converter	0-1 amp AC 0-120 volts AC	400 Hz Input Line
13	Shunt	0-30 amps DC	WES Stack Current
14	Shunt	0-10 amps DC	CDCS Stack Current

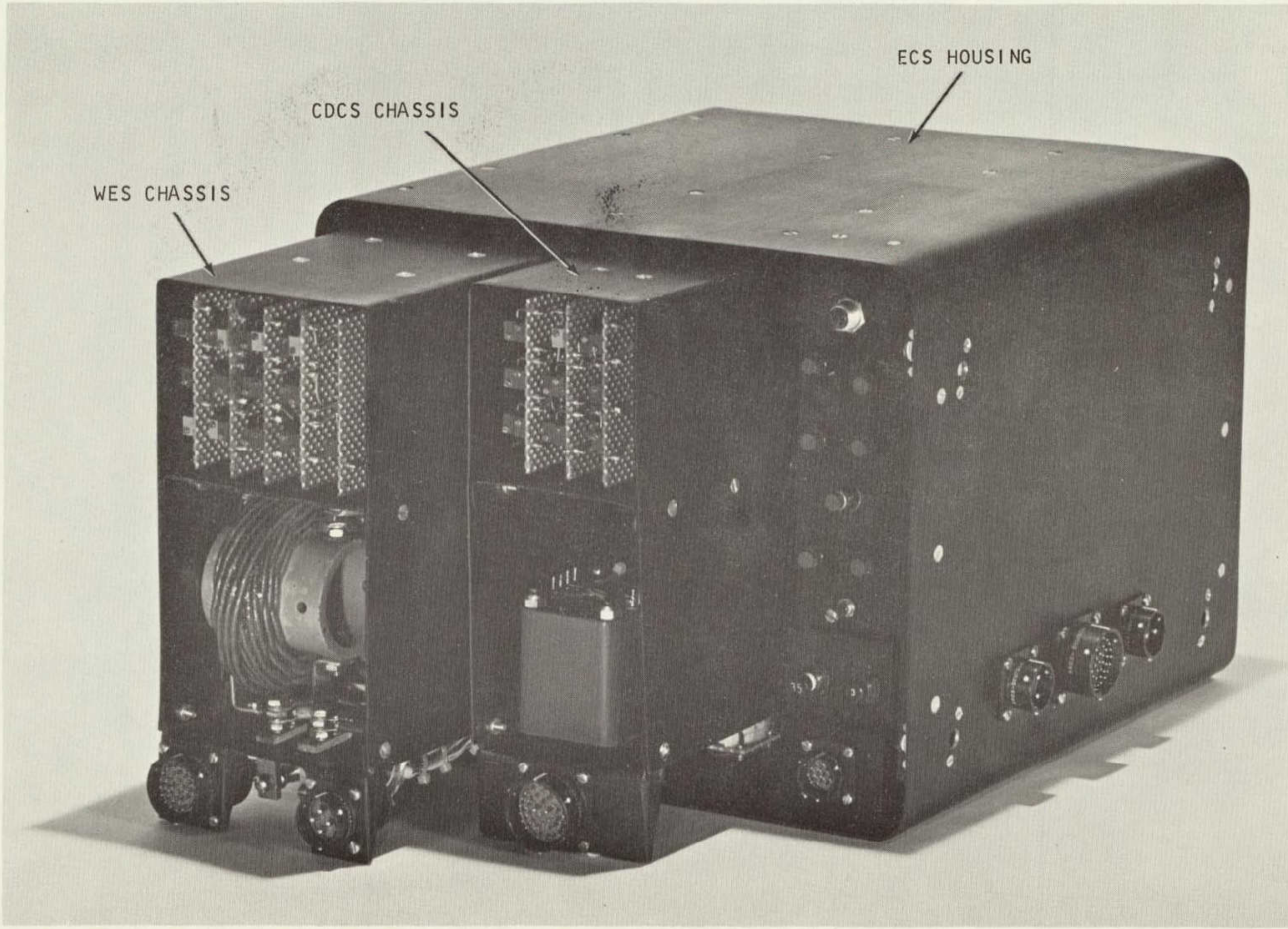


FIGURE 18 ECS PACKAGE COMPONENTS

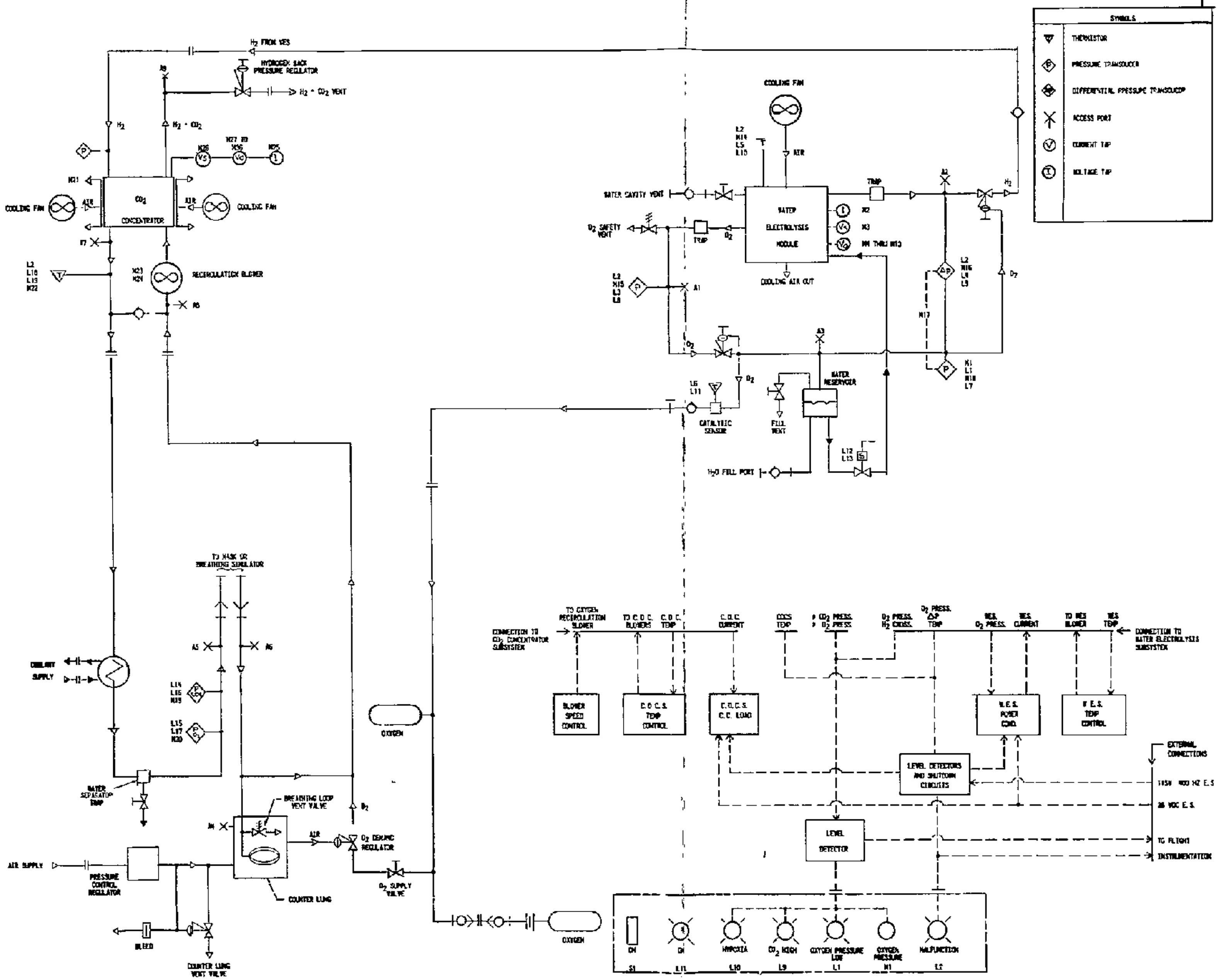


FIGURE 19 FLIGHT BREADBOARD SYSTEM INSTRUMENTATION

COCKPIT DISPLAY	
M1	OXYGEN PRESSURE
L1	OXYGEN PRESSURE LOW
L2	MALFUNCTION LIGHT
	1 OVER TEMP
	2. OVER PRESSURE
	3. ΔP OUT OF RANGE
L14	CO_2 HIGH
L15	HYPOXIA

FLIGHT INSTRUMENTATION	
M2	MODULE AMPS
M3	MODULE VOLTS
M4 TO M13	CELL 1 TO 10 (VOLTAGE)
M14	MODULE TEMP
M15	O_2 PRESS
M16	$H_2 - H_2O$ Δ PRESS
M17	H_2 PRESS
M18	O_2 SUP PRESS
M19	CO_2 PARTIAL PRESSURE
M20	O_2 PARTIAL PRESSURE
M21	H_2 PRESSURE
M22	MODULE TEMPERATURE
M23	RECIRC BLOWER VOLTS
M24	RECIRC. BLOWER AMPS
M25	MODULE AMPS
M26	MODULE VOLTS
M27 TO M36	CELLS 1 TO 10 VOLTS
L3	WES O_2 OVER PRESS
L4	WES ΔPRESS H_2-H_2O (OUT OF RANGE)
L5	WES OVER TEMP
L6	WES CROSSOVER
L7	WES O_2 UNDER PRESS
L16	HIGH % CO_2 — BREATHING GAS
L17	LOW % O_2 — BREATHING GAS
L18	CDCS OVER TEMP
A1	O_2 GAS ANALYSIS PORT
A2	H_2 GAS ANALYSIS PORT
A3	O_2 ACCESS PORT
A4	COUNTER LUNG PRESSURE ACCESS PORT
A5	INHALATION GAS SAMPLE PORT
A6	EXHALATION GAS SAMPLE PORT
A7	SAMPLE ACCESS PORT — O_2 EXIT FROM MODULE
A8	SAMPLE ACCESS PORT — O_2 INLET TO MODULE
A9	SAMPLE ACCESS PORT — H_2 EXHAUST FROM MODULE

FLIGHT BREADBOARD SYSTEM - ELECTRICAL CONTROL INDICATORS	
L8	WES O_2 OVER PRESS
L9	WES Δ PRESS H_2-H_2O (OUT OF RANGE)
L10	WES OVER TEMP
L11	WES CROSSOVER
L12	OPEN — SOLENOID MANUAL CONTROL MODE
L13	CLOSED — SOLENOID MANUAL CONTROL MODE
L19	CDCS OVERTEMP

TRW SYSTEMS
FLIGHT BREADBOARD SYSTEM INSTRUMENTATION SCHEMATIC
NAOS
59875
310589

TABLE IV

NAOS FLIGHT BREADBOARD SYSTEM READOUTS

No.	Function	Type[a]	Location[b]	Sensor Used[c]
1.	Malfunction	L	PP, FIP	1, 3, 5, 6
2.	Hypoxia (low O_2)	L	PP, FIP	7
3.	High CO_2	L	PP, FIP	8
4.	O_2 Pressure <65 psia	L	PP, FIP	2
5.	WES Crossover	L	FBS, FIP	9
6.	WES O_2 Pressure >80 psia	L	FBS, FIP	1
7.	WES H_2-H_2O ΔP <0 or ≥ 5 psid	L	FBS, FIP	3
8.	WES Temperature $> 170^\circ F$	L	FBS, FIP	5
9.	WES H_2O Valve Off Auto	L	FBS, FIP	Switch
10.	CDCS Temperature $> 130^\circ F$	L	FBS, FIP	6
11.	DC Input Current	M	FIP	10
12.	DC Input Voltage	M	FIP	None Needed
13.	AC Input Current	M	FIP	12
14.	AC Input Voltage	M	FIP	12
15.	Running Time	M	FIP	None Needed
16.	WES Stack Current	M	FIP	13
17.	WES Stack Total Voltage	M	FIP	None Needed
18.	WES Stack Cell Voltages (10)	M(10)	FIP	None Needed
19.	WES Stack Temperature	M	FIP	5
20.	WES O_2 Pressure	M	FIP	1
21.	WES H_2-H_2O Differential Pressure	M	FIP	3
22.	WES H_2 Pressure	M	FIP	2, 3
23.	Breathing Loop O_2 Supply Pressure	M	FIP, PP	2
24.	Breathing Loop Blower Voltage	M	FIP	11
25.	Breathing Loop Blower Current	M	FIP	11
26.	Breathing Loop O_2 Partial Pressure	M	FIP	7
27.	Breathing Loop CO_2 Partial Pressure	M	FIP	8
28.	CDCS Stack H_2 Inlet Pressure	M	FIP	4
29.	CDCS Stack Total Voltage	M	FIP	None Needed
30.	CDCS Stack Cell Voltages (10)	M(10)	FIP	None Needed
31.	CDCS Stack Temperature	M	FIP	6
32.	CDCS Stack Current	M	FIP	14

(a) M = meter, L = indicator light
(b) PP = pilot's panel, FIP = flight instrumentation package, FBS = flight breadboard system
(c) See Table III

TABLE V

NAOS FLIGHT BREADBOARD SYSTEM
Parameter Out-of-Range Indications and Automatic Shutdown

PARAMETER	SENSOR USED*	TRIP LEVEL
WES Stack Temperature	5	$>150^\circ F$
CDCS Stack Temperature	6	$>130^\circ F$
WES O_2 Pressure	1	>82 psia
WES H_2/H_2O ΔP	3	<0 psid or >5 psid

TABLE VI

NAOS FLIGHT BREADBOARD SYSTEM
Parameter Out-of-Range Indication

PARAMETER	SENSOR USED*	TRIP LEVEL
O_2 Partial Pressure in Mask Inlet	7	<135mm Hg
CO_2 Partial Pressure in Mask Inlet	8	>15mm Hg
Breathing O_2 Pressure	2	<65 psia
Excess H_2 in WES O_2 out (Crossover detector)	9	$>0.5\%$

*See Table III

limits. A storage circuit maintains the system in a shutdown mode until cleared by depressing a reset momentary contact switch. Indicator lamps are provided to aid in fault isolation and for determination of the parameter which is out of tolerance.

There are four additional sensors (see Table VI) which provide signals to warning lights which serve as indicators of off-design conditions.

AUXILIARY EQUIPMENT

Breathing Simulator

The breathing simulator, Figure 20, simulates the pilot's inputs to the system. A breathing machine simulates respiration and has adjustable tidal volume, inspiration ratio and breathing rate. A vacuum pump and valve are used to meter oxygen from the breathing loop at the metabolic consumption rate. Carbon dioxide is added to the system in the breathing loop at the metabolic generation rate. Both oxygen removal and carbon dioxide input rates are adjustable to simulate variable respiration profiles. Carbon dioxide is carried in a high pressure bottle containing 3 pounds of liquified gas. This bottle is enclosed in the breathing simulator and is easily removed and replaced. At the nominal input rate of 0.117 lb/hr, the supply contains enough carbon dioxide for approximately 25 hours of system operation. If laboratory testing is required, all system components are capable of operating from standard supplies of bottled carbon dioxide.

A rack capable of holding five 500 ml sample bottles is mounted on the rear of the package. A manifold and valving necessary for obtaining rebreather loop gas samples are provided. The procedure for rebreather gas sampling is covered elsewhere in this report. The electrical connector on the front panel provides input power (115V, 60 Hz $\sim$3 amps) for the operation of the vacuum pump and the breathing machine.

Aircraft Resources Adapter

The Flight Breadboard System requires 50 psig air at 3 CFM and liquid coolant. These services are provided by the aircraft resources adapter, Figure 21. Refrigerated coolant (33 1/3% ethylene glycol and 66 2/3% water) is provided by a refrigeration unit capable of removing 300 watts of heat at a coolant flow of 1/4 gallon a minute. An integral temperature controller maintains coolant temperature and is adjustable from $45^{\circ}F$ to $100^{\circ}F$. A pyrometer is provided to measure temperatures at six external points as required by testing operations. The air supply consists of a compressor, accumulator, pressure relief valve and pressure regulator. The compressor and accumulator are operated to provide 75 psi air to the regulator. This pressure is then dropped to 50 psi by the pressure regulator for use in the counter-lung. The aircraft resources adapter was chosen as the distribution point for 115V, 60 Hz power used in the system auxiliaries. Connectors are provided for input power (115V, 60 Hz, 35 amps) and outputs to the flight data acquisition system and breathing simulator. A spare output connector capable of providing approximately 5 amps for non-system use is also mounted in the cluster.

Flight Instrumentation Package

The Flight Instrumentation Package contains all the readouts, meters, indicators and controls to operate and monitor the operation of the Flight Breadboard System. The system condition readouts consist of thirty-nine (39) edgewise meters mounted in three groups; one group of sixteen (16) meters for the Carbon Dioxide Concentrator Subsystem, a second group of sixteen (16) meters for the

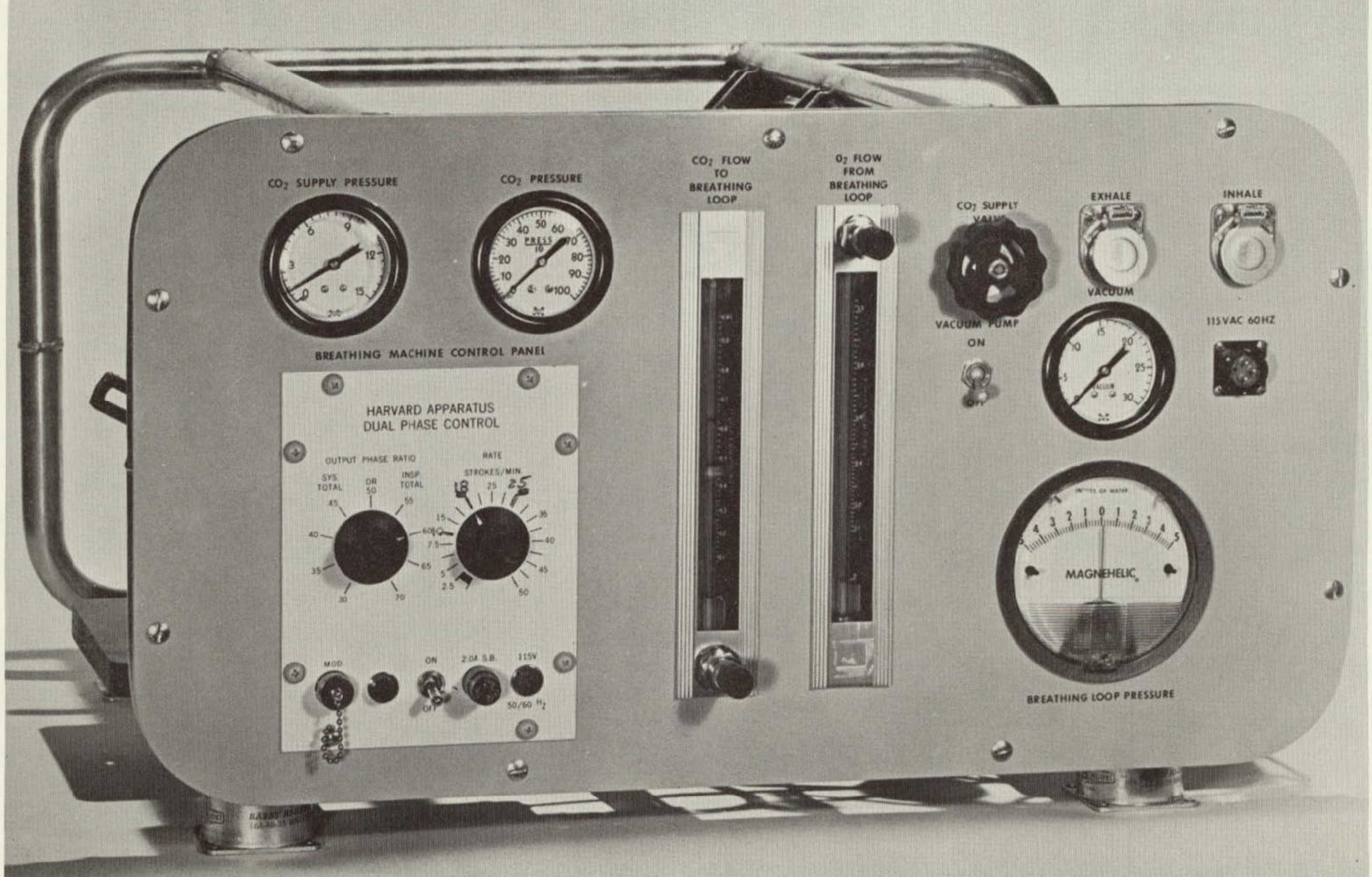


FIGURE 20 BREATHING SIMULATOR

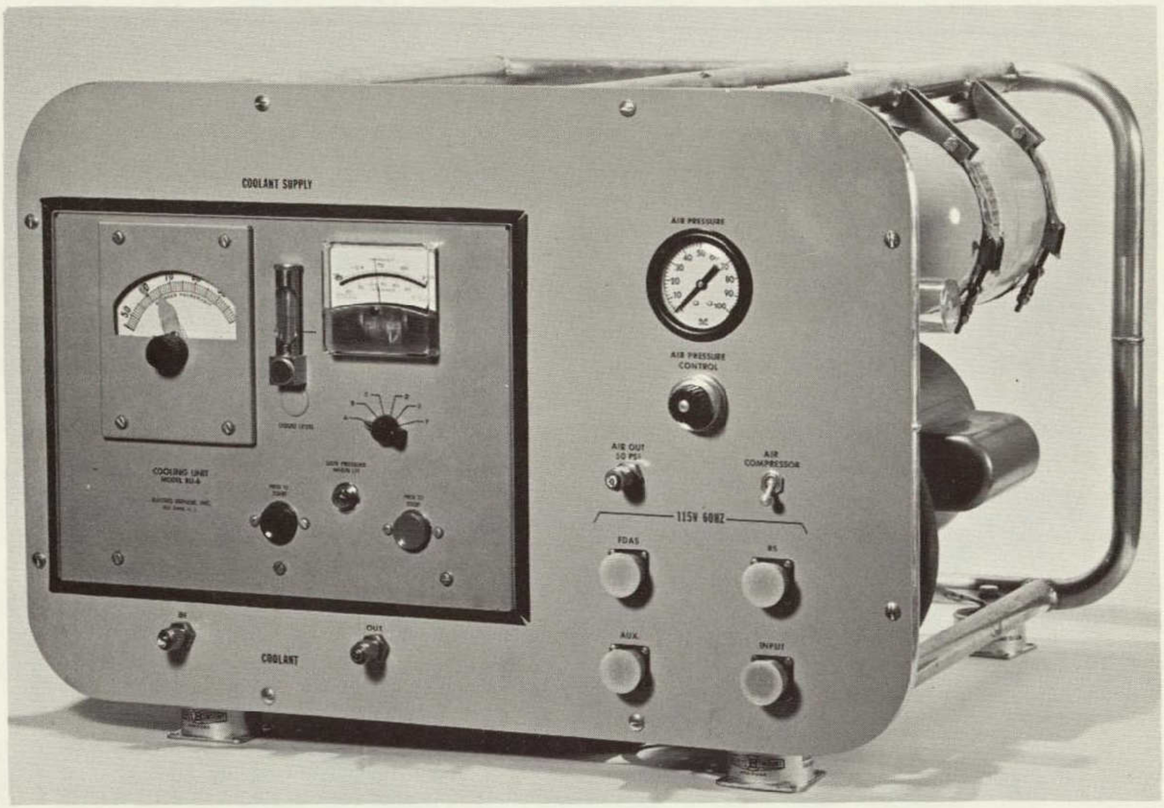


FIGURE 21 AIRCRAFT RESOURCES ADAPTER

Water Electrolysis Subsystem, and a third group of seven (7) meters for the system. There is a running time meter to keep track of operating hours and eight (8) system condition indicators. These indicators duplicate the lights that are contained on the pilot control panel and the Electronic Control Subsystem package. An ON/OFF switch and a malfunction reset pushbutton are also included. Thus, the complete Flight Breadboard System can be operated and monitored from this Flight Instrumentation Package. There are two 61-pin connectors on the package. One goes to the Flight Breadboard System and the other connector goes to the Flight Data Acquisition Unit.

Because all of the components and wiring for the Flight Instrumentation Package are mounted on a subpanel, the unit is very easily disassembled for repair or maintenance as required. The all-aluminum military transit case is used as a housing and a carrying case for the Flight Instrumentation Package. The cover of the case contains a compartment in which cables can be stored. When the flight instrumentation package is being used, this cover can be removed to allow easy access to the meters and controls. Figure 22 is a photograph of the Flight Instrumentation Package.

Flight Data Acquisition Unit

In order to obtain as much information as possible from the flight tests and any other tests performed on the Flight Breadboard System, it is desirable to have some method of automatically recording the various parameters from the Flight Breadboard System during its operation. Magnetic tape recording was chosen as the most desirable method because large amounts of data can be recorded and stored in a relatively small volume via the magnetic tape. It also can very conveniently be played back at a later time to evaluate the data.

The recorder selected was an AMPEX Model SP700 shown in Figure 23. This machine puts four tracks of analog information on ¼" tape. Any one of these four tracks can be used in a multiplex mode with up to thirty channels of information being put on this one track. The machine, thus, has thirty-three channel capability.

The machine was purchased with one voice track for running commentary during the test and two FM record/reproduce tracks. The fourth multiplexed track will reproduce frequencies up to five cycles per second if all thirty channels are used on independent signals. Since the highest frequency rexpected in the NAOS Flight Breadboard System is approximately one-half cycle per second, this is more than adequate. These multiplex channels accept 0 to 5 volt DC and can produce 0 to 5 volt DC out when played back. During recording and play-back, all thirty channels can be displayed simultaneously on an oscilloscope in a bar graph pattern. This will allow observation of recorded data as it is being recorded as well as surveying the data on play-back. During play-back, any five of the thirty channels can be selected by patch panel plug-in jumpers and played back on a sample and hold system. This provides a 0 to 5 volt DC output which corresponds to the 0 to 5 volt DC input originally put into the recorder. On play-back, the information is also available as a pulse amplitude and pulse width modulated signals for use in automatic data reduction systems. With 1 mil, 7" reel of tape running at 7½" per second, three-fourths of an hour of data can be recorded. With ½ mil tape and reducing the speed to 1 7/8" per second, this time can be extended by a factor of eight, up to six hours.

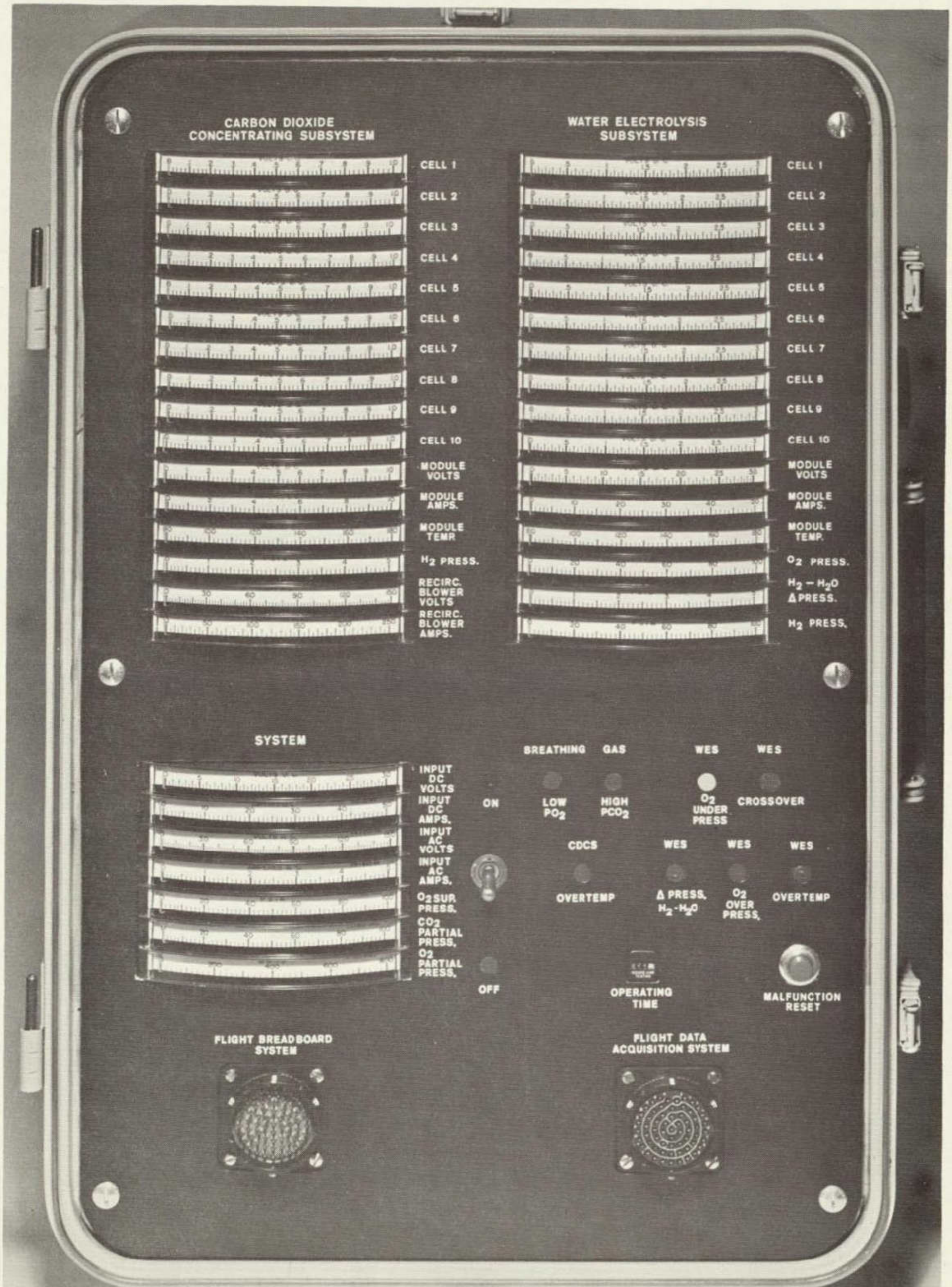


FIGURE 22 FLIGHT INSTRUMENTATION PACKAGE

FIGURE 23 FLIGHT DATA ACQUISITION UNIT

The signals from the Flight Breadboard System are fed to the tape recorder through an amplifier box which converts the signals from the Flight Breadboard System to the 5 volt level required by the tape recorder on the multiplex channels. This box contains seventeen (17) DC amplifiers constructed around integrated circuit operational amplifier modules. Some are single-ended inverting, some are single-ended non-inverting and some are differential. The signals from the Flight Breadboard System vary from 50 millivolts full scale up to 30 volts full scale. These are all converted to a 5 volt maximum signal in the amplifier box. This amplifier box is permanently wired into the cable which connects the Flight Data Acquisition Unit to the Flight Instrumentation Package. The power to operate these amplifiers is obtained from the 400 cycle power being used to operate the running time meter from the Flight Breadboard System.

Ground Power Conversion Unit

Because the Flight Breadboard System was designed to operate in an aircraft, it requires 28 volts DC at 30 amps and 115V, 400 Hz AC power. For this reason a ground power conversion unit was assembled using standard components. With this unit, the Flight Breadboard System can be operated anywhere in which there is 115V, 60 cycles available. The ground power conversion unit is plugged into a normal wall socket and the Flight Breadboard System is connected to the ground power conversion unit.

The ground power conversion unit consists of a 50 amp, 28 volt DC power supply and a 200Va, 115 volt, 400 cycle power supply. These are both off-the-shelf solid-state devices. These two units were assembled into a commercial case provided with a main power circuit breaker and pilot lights as well as a cooling fan. Figure 24 is a photograph of this assembly.

Spares, Maintenance and Service Equipment

Spares. - To support the pre-flight, flight and post-flight test programs of the Aircrew Oxygen Flight Breadboard System, a variety of spare parts and system components were purchased and/or fabricated. The primary criteria for the selection of spares was to insure minimum down-time of the system. As a result, the spectrum of spares includes replacements for miscellaneous hardware items through components at the subassembly level.

The major spare subassembly of the Water Electrolysis Subsystem is a full size, ten-cell electrolysis module. Thus, in case of an electrolysis module malfunction, the system down-time is only governed by the time required to exchange modules rather than by the time required to repair individual cells. Other spare parts for the Water Electrolysis Subsystem include such items as gas pressure regulators, safety vent and hand valves, cooling fan, solenoid valve, moisture trap with filter elements, and a variety of bolts, nuts, washers and plumbing components. Spare parts for the static water feed assembly of the Water Electrolysis Subsystem include spare plastic cylinders, spare belloframs and gaskets, and, again, miscellaneous hardware items.

The spare part concept for the Carbon Dioxide Concentrator Subsystem is similar to that of the Water Electrolysis Subsystem. Again, a complete ten-cell carbon

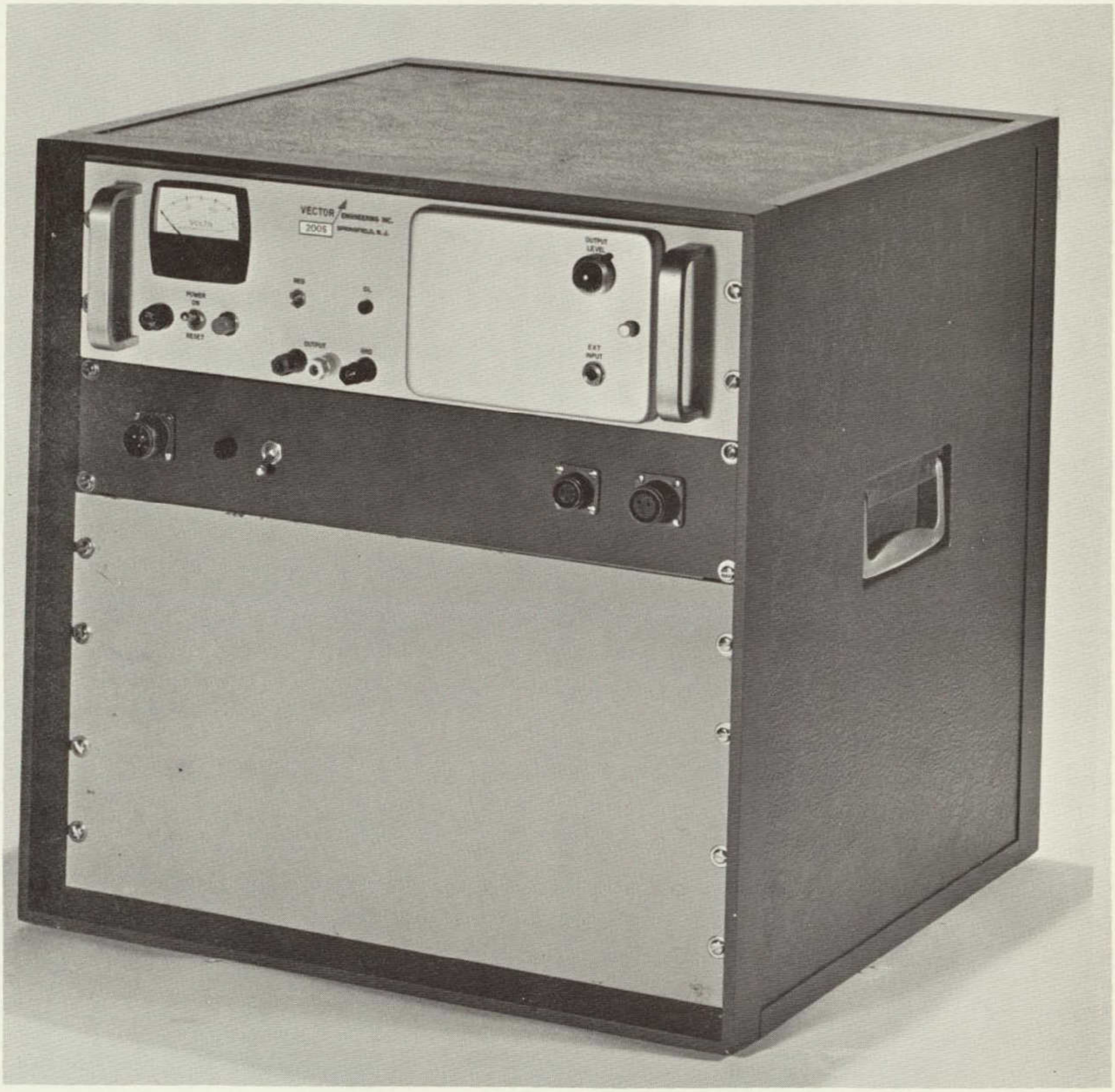


FIGURE 24 GROUND POWER CONVERSION UNIT

dioxide concentrator module has been assembled and is utilized as a spare. Other spare parts in the Carbon Dioxide Concentrator Subsystem include such items as spare cooling fans, backpressure regulator, check valve assembly, and a complete recirculating blower subassembly.

The spare parts for the Rebreather Subsystem consist mainly of the counter-lung unit with its rebreather bag, pressure control regulators, and vent valves. Therefore, in case of malfunction in the counter-lung unit, the spare unit can be utilized and the Flight Breadboard System can be returned to operation with a minimum down-time. The spare, minor components are then used to replace any malfunctioning items within the other lung unit. Here again, as noted above, the level of modularity used in the spare system is such as to return the Flight Breadboard System to operation in as short a time as possible and then repair subassemblies or subsystems with individual spare parts or components. Spares for other major components in the Rebreather Subsystem such as for the demand regulator, condensate sump, disconnects, vent valves and individual hose connectors and hose clamps are provided.

The major spare components for the Electrical Control Subsystem consist of a set of pressure transducers and a spare cooling fan for electronics. Spare parts for electronic circuits used within the Flight Breadboard System are kept at an individual part level. This means that the spares consist mainly of transistors, resistors, capacitors, diodes, switches, connectors, etc.

A variety of spare parts are also provided for the auxiliary flight hardware. This, in general, consists of valves, tubing and plumbing components, meters, switches, connectors, and wiring, etc. Some of the major spares provided for the Flight Test Program are shown in Figure 25.

Maintenance and Service Equipment. - To support and maintain the electrochemical modules of the Flight Breadboard System during the flight test program and subsequent test operations requires certain special items of servicing equipment.

The servicing equipment required for the Water Electrolysis Subsystem consists of an electrolyte charging stand, a source for distilled water and an apparatus to be used for refilling the water tank and venting the water feed cavity. The Carbon Dioxide Concentrator Subsystem requires only an electrolyte charging apparatus. The electrolyte charging stands for both electrochemical modules utilize an external vacuum source. This can be supplied by either an aspirator or a mechanical vacuum pump.

The charging stands were also designed to be used for crossleak checks across cell and feed matrices. Figure 26 is a photograph of the carbon dioxide concentrator electrolyte charging apparatus. The apparatus for the Water Electrolysis Subsystem is almost identical in construction. The distilled water source for the Water Electrolysis Subsystem can either be bottled, distilled water, or in case only tap water is conveniently available, a water purification stand was designed using a commercial water purification cartridge assembly. The water fill apparatus used to replenish that water which has been consumed by the water electrolysis module is simply a cylindrical container utilizing gravity feed to a quick disconnect coupling to refill the water tank. The quick disconnect coupling to the cavity vent connection is identical to that

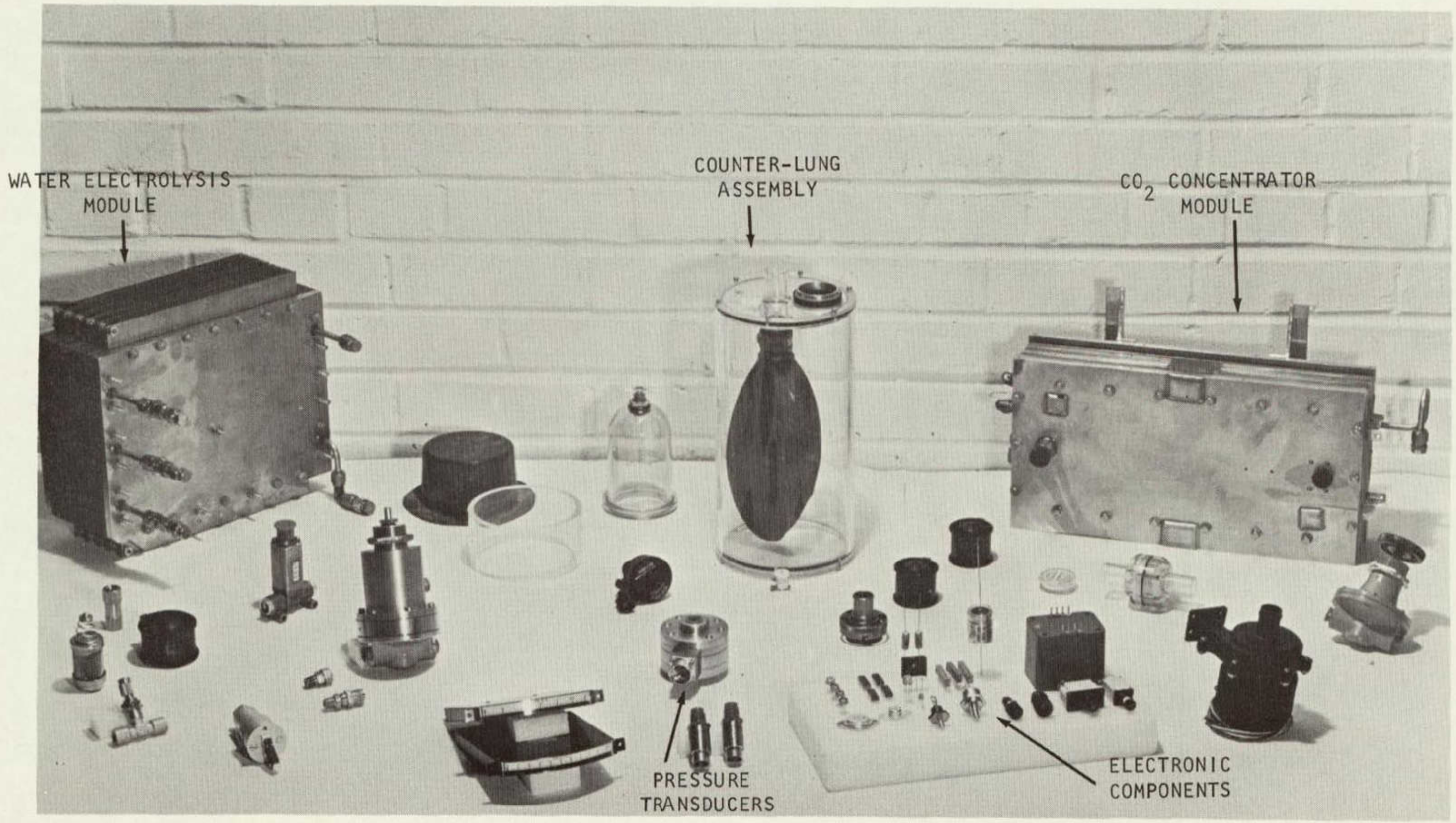


FIGURE 25 FBS - SPARE PARTS

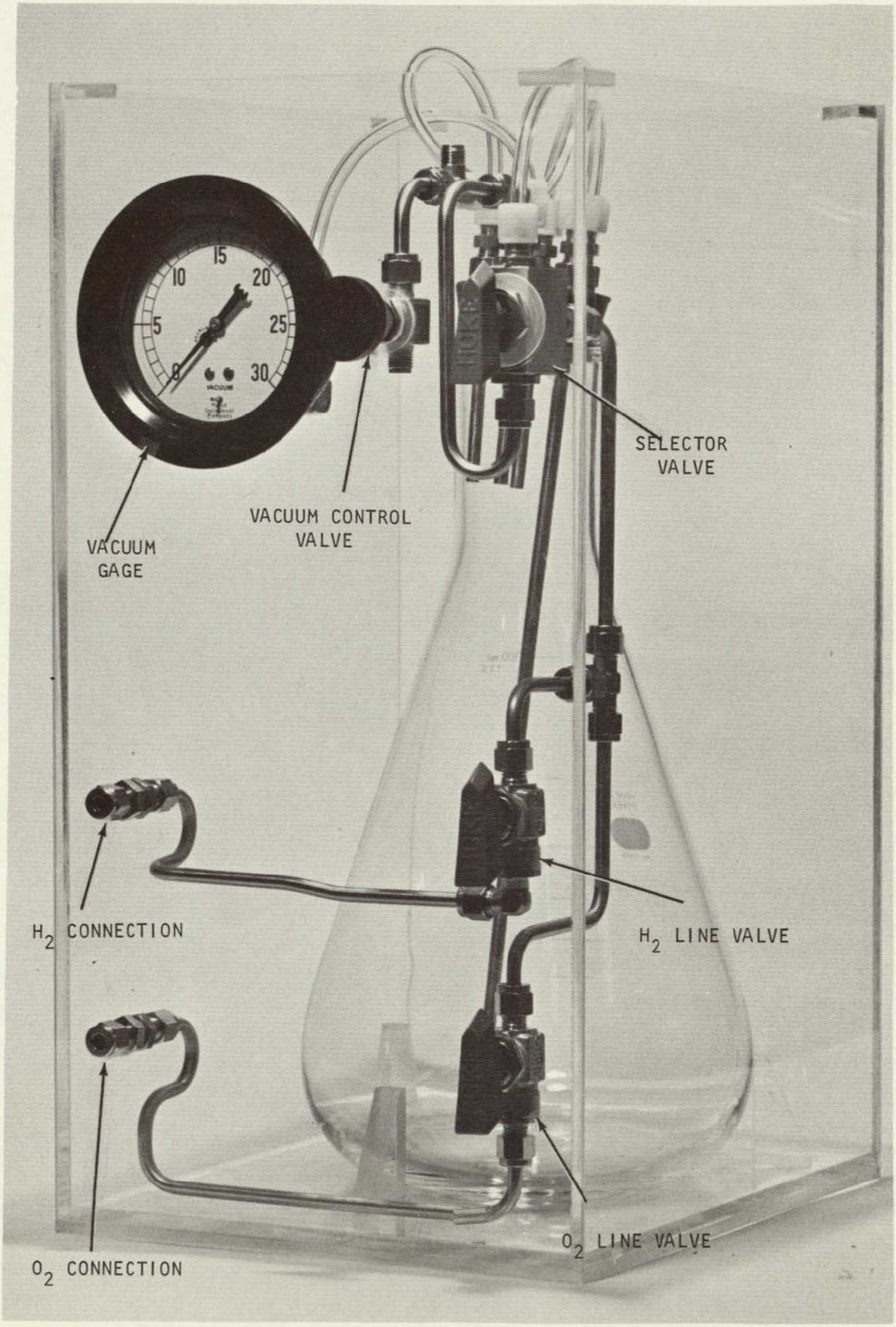


FIGURE 26 CDCM ELECTROLYTE CHARGING APPARATUS

2360D

used on the refilling apparatus and, therefore, the container also serves as the cavity venting apparatus. In utilizing the same container for filling and venting, any electrolyte that may be flushed out during a cavity venting procedure is trapped in the filling tank and will be subsequently returned to the module during water refilling.

Gas Analysis Provisions

The Flight Breadboard System incorporates several taps to facilitate removal of gas samples. The water electrolysis module subassembly has a gas sample tap in the high-pressure oxygen line and one in the hydrogen line. There are also sample taps in the rebreather system. The gas samples in the oxygen and hydrogen lines are taken with sample cylinders of a 150cc capacity. The sampling procedure is to evacuate the cylinders and then fill them with argon to a pressure of one atmosphere. The cylinders are then attached to the sample tap points on the system with the sample valves closed. At normal operating conditions, the pressure in the hydrogen and oxygen lines will be five atmospheres. When a sample is to be taken, the valve is opened at the cylinder, allowing the sample gas to flow into the cylinder. The sample cylinders, therefore, contain approximately 20% argon gas. Pressurizing the cylinders with argon precludes any air leakage into the cylinders. A small orifice is included in the line between the sample tap on the system and the cylinder to prevent a large flow rate entering the cylinder when the valve is opened causing a pressure disturbance in the system. After a sample bottle has been filled, the valve is closed and the sample cylinder is removed at the conclusion of the test.

The sample cylinders for the rebreather gases are located in the breathing simulator. The gas tap is located at the inhalation side of the breathing machine. Since low pressure is available to fill the cylinders from the rebreather system, these cylinders are evacuated prior to connection to the gas sample tap in the rebreather. These cylinders are 500cc capacity.

During any one flight test only one hydrogen gas sample was taken and, at the most, three oxygen samples and five rebreather gas samples taken. It was therefore necessary to install three oxygen sample bottles in parallel and five rebreather gas sample bottles in parallel for connection to the system. These could then be opened in turn to take the sample and fill any one cylinder at a time.

The purpose of the gas analyses is to determine the purity of the oxygen generated, determine if any oxygen has crossed over into the hydrogen stream, and to examine the rebreather gas samples for carbon dioxide content, oxygen content, and any contamination that may be in the system. The sampling cylinder arrangement is shown in Figure 27.

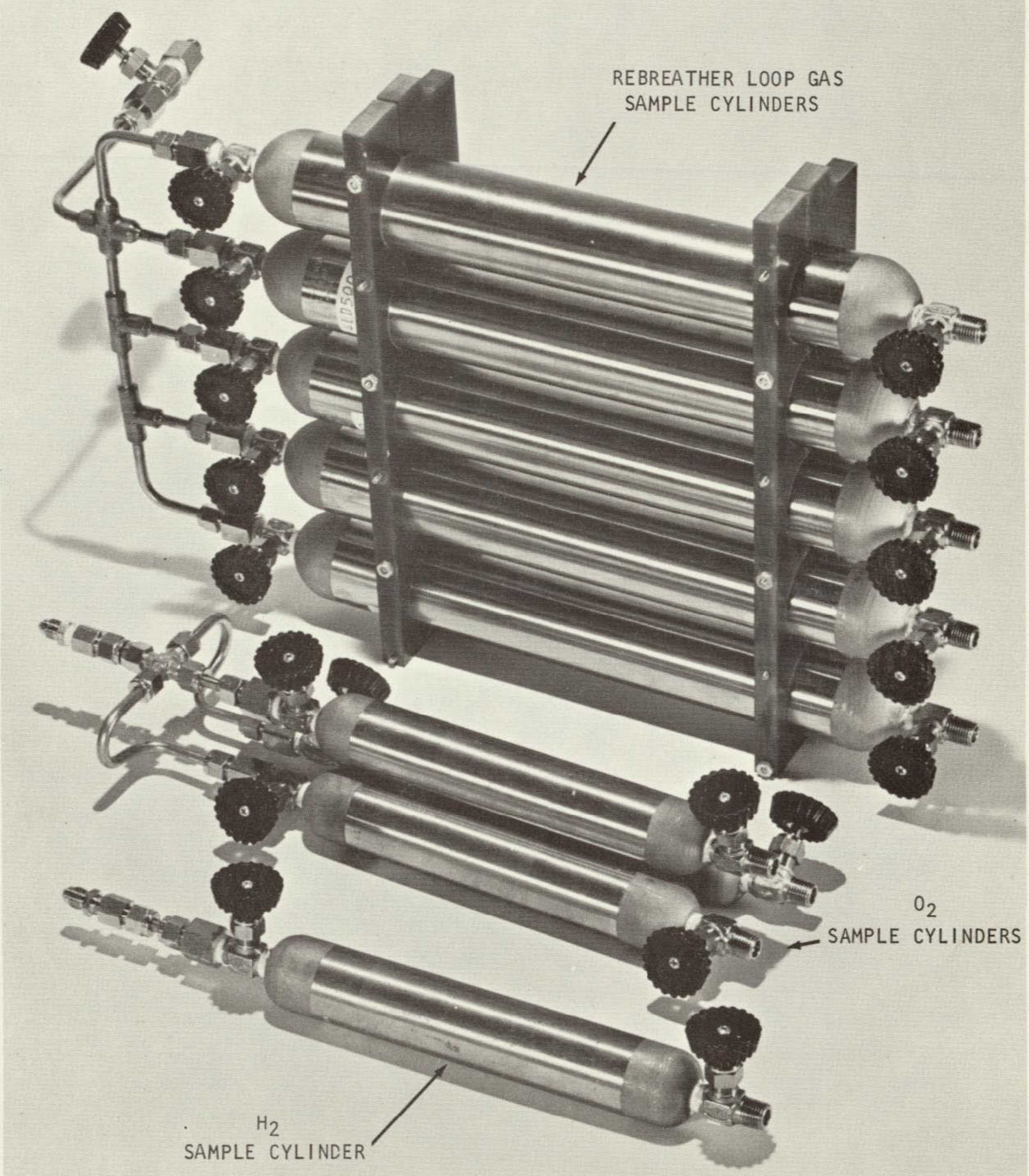


FIGURE 27 GAS SAMPLE CYLINDERS

PURPOSE OF FLIGHT TEST PROGRAM

The purpose of the Flight Test Program was:

1. To demonstrate independent operation of an integrated system without support of laboratory equipment;

2. To provide a first packaging experience of an oxygen system;

3. To provide coordination and working experience with a user service (Navy);

4. To identify interface problems between the aircraft and the Flight Breadboard System;

5. To identify effects of environmental factors such as gravitational changes, vibration, and aircraft orientation;

6. To provide preliminary flight operation reliability information to identify design limitations; and

7. To indicate areas for improvement regarding operation, maintenance and servicing the system when installed in an aircraft.

FLIGHT TEST PLAN AND PROCEDURES

The complete Flight Test Program is summarized in Table VII giving the purpose and location of each element.

As a means of checking performance, aligning the test equipment, and establishing baseline operating characteristics, two complete run-throughs of the flight test sequence were conducted in the laboratory prior to shipment of the equipment to Point Mugu.

At Point Mugu, a checkout test of the FBS and support equipment was made after installation in the aircraft racks. In addition, another checkout test was conducted after installation in the aircraft using the ground power supply.

Four flight tests of nominally 4 hours duration each were planned. The first test at design conditions was intended to establish baseline performance. The second test was a variation in breathing rates from 10 to 25 breaths per minute at a constant tidal volume of 780cc. The third test was to examine variations in tidal volume between 420 and 900cc at constant breathing rate of 18 breaths per minute. The last test was to examine abnormal conditions of high carbon dioxide input rate, high oxygen consumption, a simulated circulating blower failure, and a short period of simulated non-use of the system.

After return of the equipment to the laboratory, a run-through of the flight test sequence was again made as a final check and comparison of system performance.

Appendix A-1 gives the details of the sequence followed in performing the flight test program.

During all of the testing, the data was recorded continuously on the tape recorder. In addition to this, steady-state data was tabulated periodically from the observed instrument readings. Gas samples were taken at three locations in the system at each different operating condition. Hydrogen and oxygen samples were taken at the electrolysis module and rebreather gas samples were taken at the inhalation side of the breathing simulator.

TABLE VII

NASA AIRCREW OXYGEN SYSTEM
FLIGHT BREADBOARD SYSTEM - FLIGHT TEST PROGRAM

PROGRAM ELEMENT	PURPOSE	LOCATION
1. GROUND DUPLICATION OF FLIGHT TESTS	CHARACTERIZATION OF BASE-LINE PERFORMANCE	CLEVELAND
2. PRE-FLIGHT GROUND CHECKOUT	POST-SHIPMENT CHECK AND SYSTEM ALIGNMENT	PT. MUGU
3. FLIGHT TESTING		PT. MUGU
TEST NO. 1 - 4-HOUR FLIGHT	BASELINE PERFORMANCE	
TEST NO. 2 - 4-HOUR FLIGHT	VARIATION OF BREATHING RATES	
TEST NO. 3 - 4-HOUR FLIGHT	VARIATION OF BREATHING VOLUMES	
TEST NO. 4 - 4-HOUR FLIGHT	OFF DESIGN OPERATION	
4. POST-FLIGHT GROUND CHECKOUT	CHECK OF SYSTEM DESIGN POINT PERFORMANCE	PT. MUGU
5. POST-FLIGHT GROUND DUPLICATION OF FLIGHT TESTS	DETERMINE DEVIATION FROM INITIAL BASELINE PERFORMANCE	CLEVELAND

FLIGHT TEST PROGRAM

Pre-Flight Tests

The pre-flight testing of the Flight Breadboard System was initiated in May 1969. The purpose of these tests was to duplicate the flight test procedures on the ground to establish baseline performance. The complete flight test procedures were performed twice prior to packing and shipping to Point Mugu. During the ground testing, the water feed cavities in the electrolysis module required frequent venting to eliminate gas which seemed to accumulate at a much faster rate than observed in the life and parametric test rigs. In addition, cell voltages were measured which were higher than observed in the other test stands. The electrolysis module was replaced between the first and second series of tests and again halfway through the second series due to high cell voltages. This was attributed to dryout of the cells caused by the gas accumulation in the water feed cavity. The test procedure was then changed to include a thorough cavity venting after each test.

Other problems which were minor included a failure of the carbon dioxide concentrator module thermistor which required replacement, the oxygen partial pressure sensor which required frequent recharging, and electrical noise generated in the indicator lamp circuits which required filtering in the circuits to eliminate interference with the instrumentation.

Flight Tests

After completing the ground tests in the laboratory, the equipment, spares and operating supplies were packaged and shipped to Point Mugu for the flight tests. Figure 28 shows the shipping cases containing the major equipment items. In addition to these, four other cases containing the spare parts, electrolyte charging apparatus, gas sample cylinders, tools and miscellaneous test equipment were packed and shipped.

Upon arrival at Point Mugu on July 7, 1969, the equipment was checked visually for shipping damage and no damage was evident. During the week, the equipment was installed in two racks which were used to mount equipment in the aircraft. The breadboard system and the breathing simulator were mounted in one rack shown in Figure 29 while the resources adapter, the instrumentation package and the tape recorder were mounted in the second rack shown in Figure 30. At the start of the ground checkout tests, the cooling system in the resources adapter package was found to have a bound-up refrigerant compressor. A replacement compressor was purchased locally and installed by the refrigeration maintenance shop on the base at Point Mugu.

A four-hour ground checkout test was conducted. During this test all components operated satisfactorily except for the last two hours of the test. The water electrolysis module cell voltages began to rise and an abnormal amount of gas was vented from the water feed cavities. This module was then replaced with the spare unit. A brief checkout test indicated satisfactory performance of the system with the spare module.

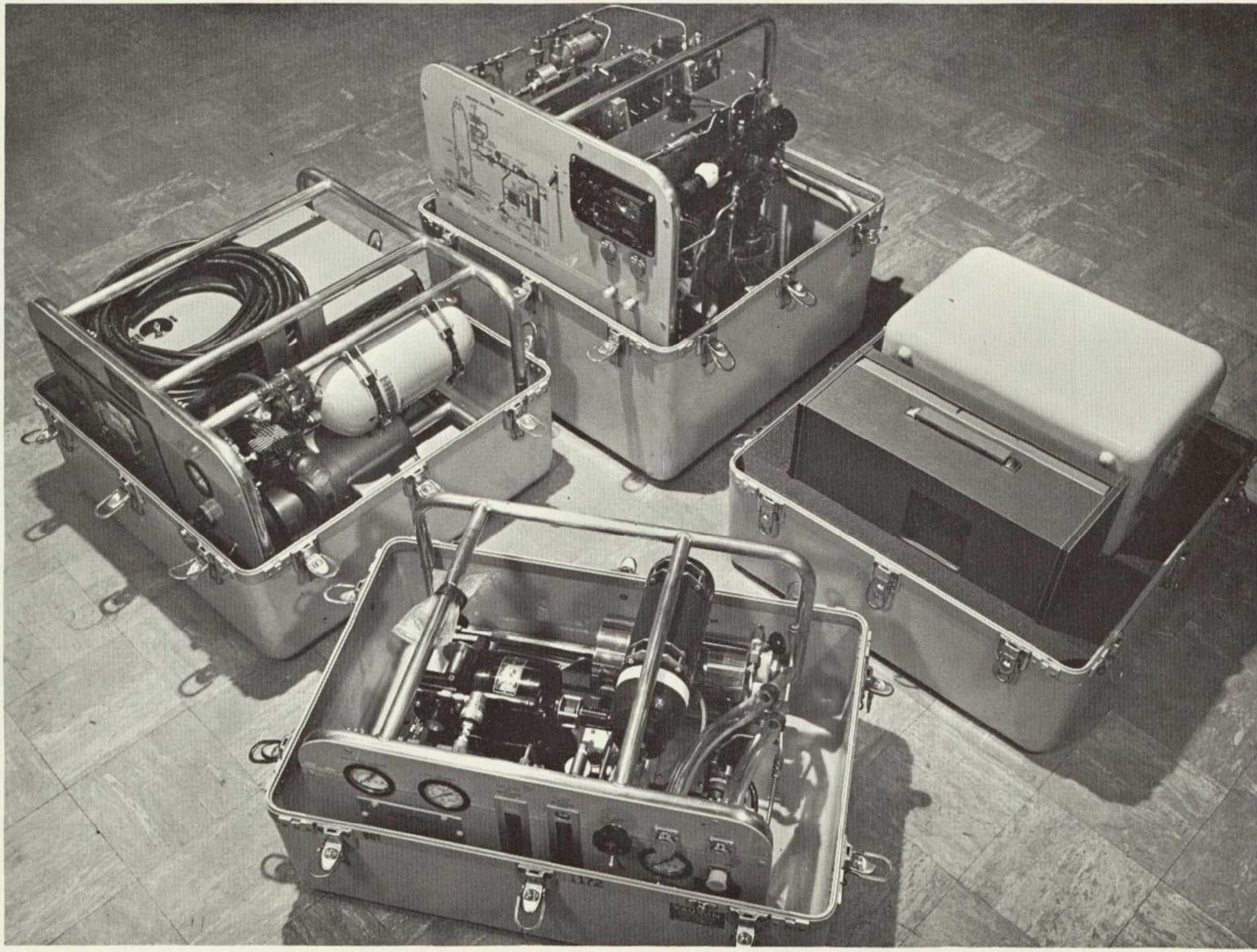


FIGURE 28 FLIGHT BREADBOARD SYSTEM AND AUXILIARY EQUIPMENT IN SHIPPING CONTAINERS

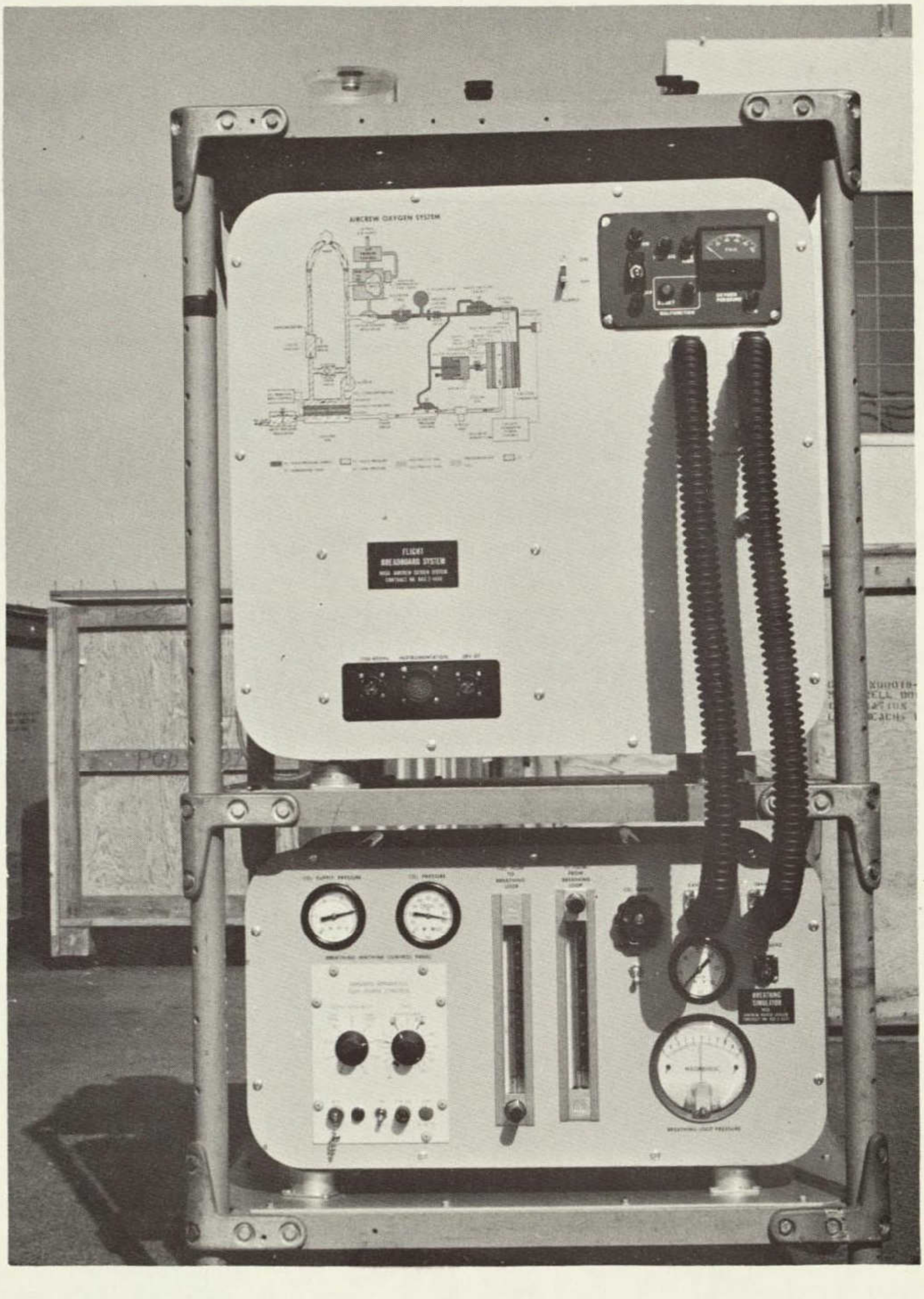


FIGURE 29 FLIGHT BREADBOARD SYSTEM AND BREATHING SIMULATOR MOUNTED IN AIRCRAFT RACK

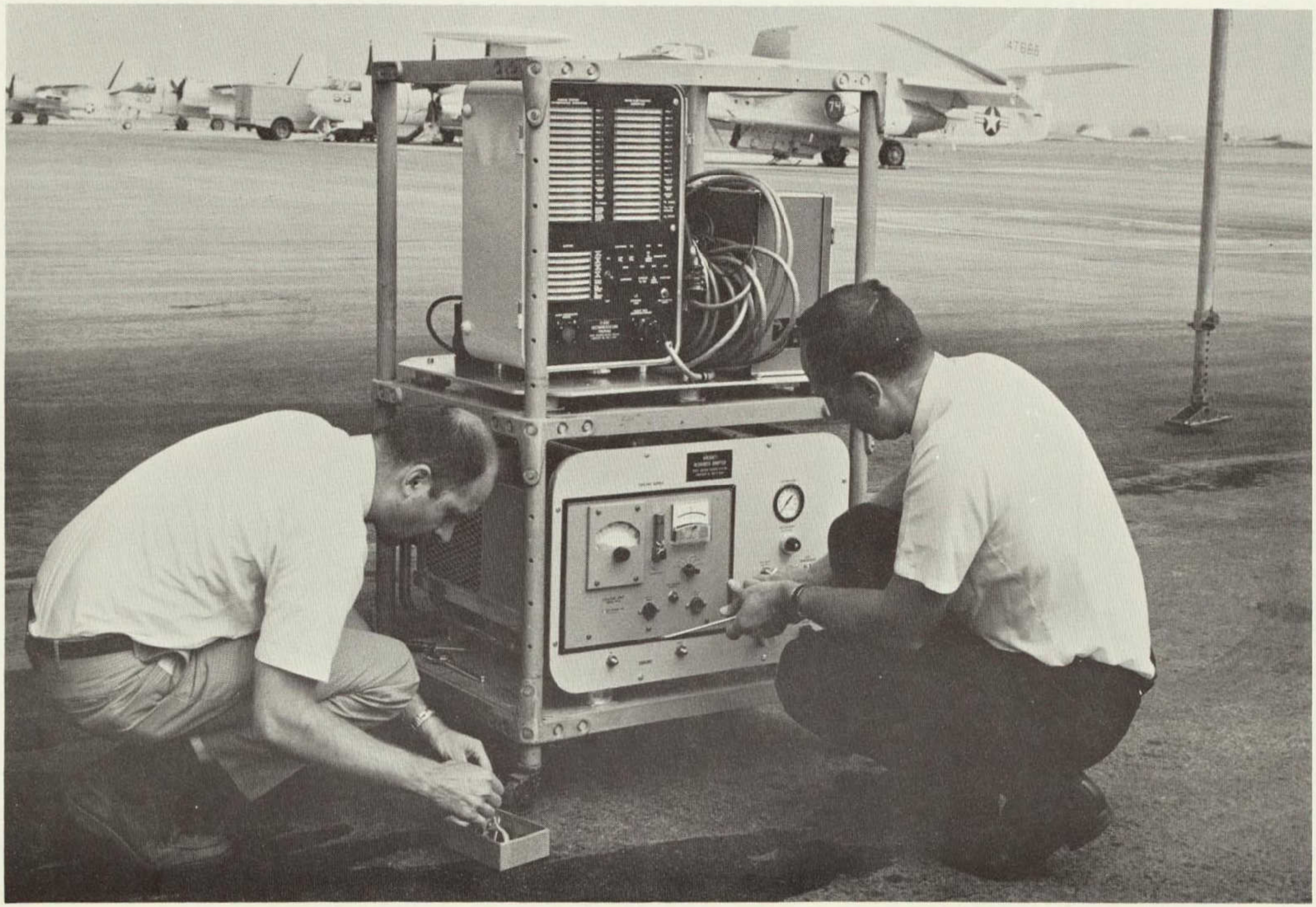


FIGURE 30 INSTALLATION OF INSTRUMENTATION AND AIRCRAFT RESOURCES ADAPTER IN AIRCRAFT RACK

The racks containing the Flight Breadboard System and auxiliary equipment were installed in the C-131F aircraft on July 15. Figure 31 shows the racks being lifted into the aircraft. Figure 32 is a view towards the rear of the aircraft showing the racks installed. Figure 33 is a forward view showing the instrumentation. A checkout test in the aircraft using ground power identified a problem. The aircraft electrical system has a common ground for the 28 volt DC, 400 cycle AC and 60 cycle AC. This grounding arrangement resulted in erroneous instrumentation readings which were traced to the tape recorder case touching the aircraft frame and completing a ground loop. This problem was solved by electrically insulating the tape recorder case from the equipment rack.

In the course of the checkout test, the ground power to the aircraft was turned off in the hangar. When the power was returned, the electrolysis current control circuits were damaged apparently by a momentary high voltage surge. The circuits were repaired and checked. The first flight test was conducted on July 17, 1969 for a period of 2.85 hours. This test was at steady design conditions. The second test of three hours duration was conducted on the following day. This test was to examine variations in breathing rates. The aircraft was grounded with an oil filter problem until July 25 when test three was conducted to examine variations in breathing volume. This test lasted 3.5 hours and was terminated due to high voltages on the water electrolysis module and a hydrogen to oxygen crossover malfunction indication due again to gas in the water feed cavities of the module. The water feed cavities were flushed out and the fourth test started on July 28. After 0.8 hours a crossover again was indicated and the system was shut down. The original water electrolysis module was recharged and installed in the system. On July 29 tests four and five were conducted at off-design conditions for 4.7 hours. The five flight tests accumulated 14.85 operating hours. At the conclusion of these tests the equipment was removed from the aircraft racks and placed in their respective shipping containers for shipment to Cleveland.

The significant problem identified was that of gas generation by electrolysis in the water feed plumbing. This was caused by stray electrical currents flowing through the electrolyte to ground in the system frame. The result of the gas generation was the gradual accumulation of gas in the water feed cavities which then decreased the area available for water feed to the cell and consequent cell dryout having symptoms of high cell voltages and eventual crossover.

Another minor problem identified was the instrumentation problem due to common grounds in the tape recorder. All other system components functioned satisfactorily with the exception of the oxygen and carbon dioxide partial pressure sensors in the rebreather loop which periodically gave erratic readings, and an oxygen differential pressure regulator which developed a small leak during the last test.

Post-Flight Tests

The post-flight ground tests were initiated upon arrival of the Flight Breadboard System and auxiliary equipment at Cleveland. The equipment was inspected, interconnected and given a brief checkout test. This test revealed an inoperative thermistor in the electrolysis module and a dead battery in the carbon

FIGURE 31 LOADING EQUIPMENT INTO C-131 AIRCRAFT

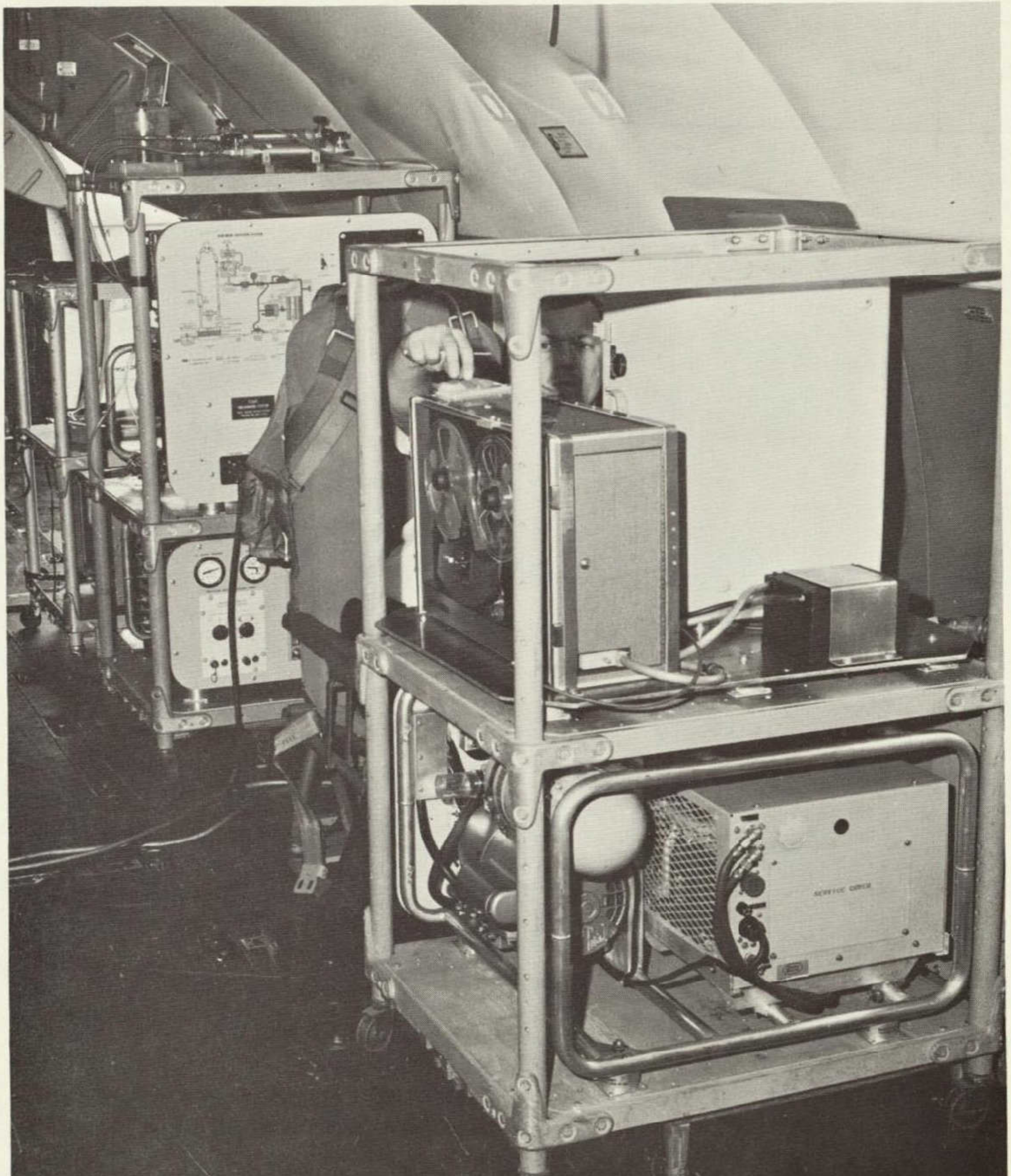


FIGURE 32 AFT VIEW OF EQUIPMENT INSTALLATION IN AIRCRAFT

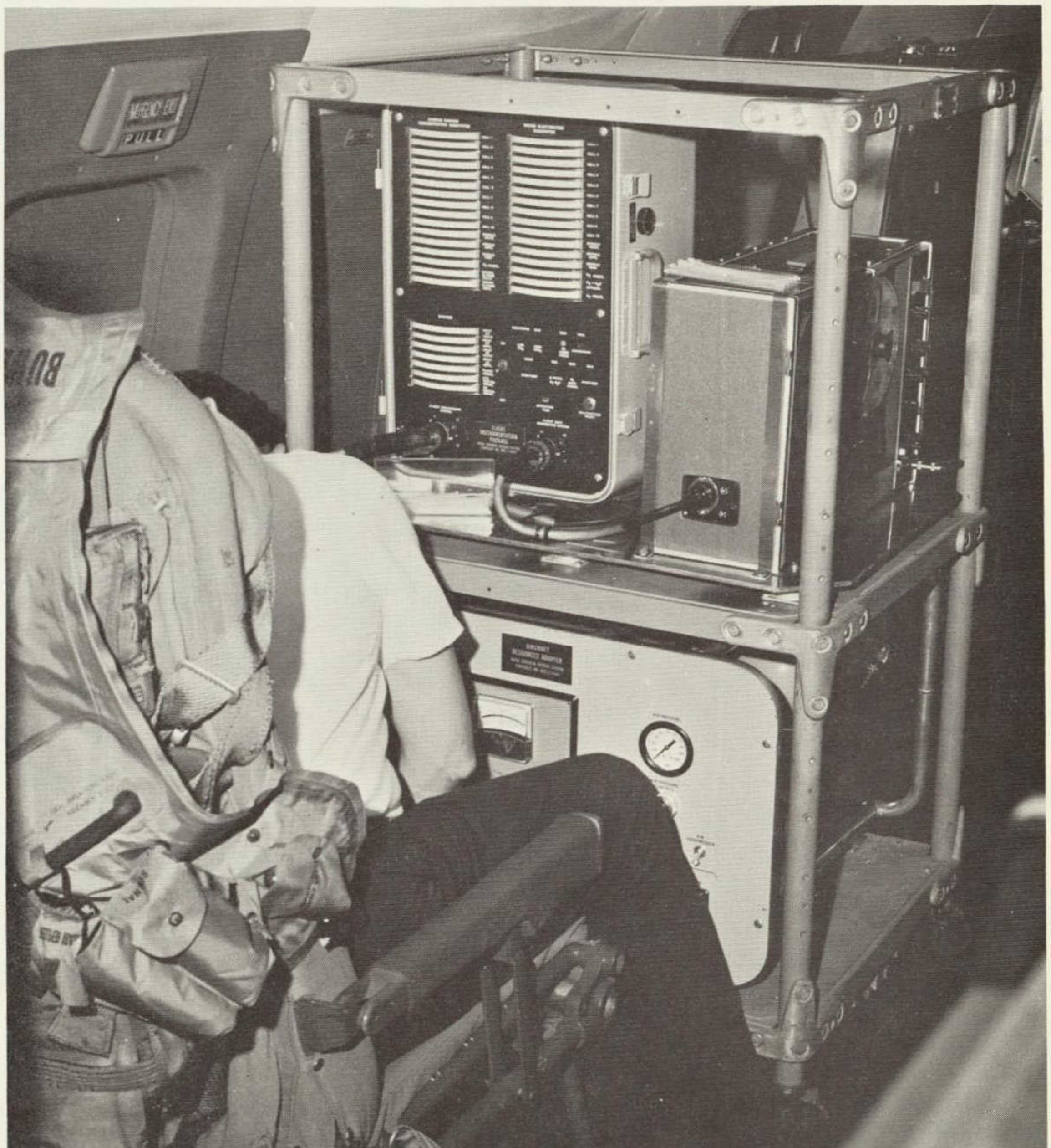


FIGURE 33 FORE VIEW OF EQUIPMENT INSTALLATION IN AIRCRAFT

dioxide partial pressure sensor amplifier. The thermistor and battery were replaced as well as the oxygen differential pressure regulator which was found to have a leak in the rubber diaphragm. The ground tests duplicating the flight test plan were then started.

While the post-flight tests were being conducted, efforts were made to locate the electrical current leakage path through the electrolysis module. One leg of the circuit was known to start at a hydrogen electrode and along the electrolyte wetted walls, through the water feed cavity and finally into the steel water feed tubing. Gas would be evolved at the steel-electrolyte interface and would then gradually accumulate in the water feed cavities. The gas in the water feed cavity would reduce the water evaporation surface area and thus allow the cell to dry out with the observed high cell voltages and eventual crossover between the hydrogen and oxygen gas compartments.

This situation, however, required a return path of current from the metal frame back to some part of the electrical circuitry. Examination of the electrolysis module which gave the crossover indication during the flight tests on July 25 and 28 showed that a short circuit existed between the endplate and the first cell oxygen current collector. Disassembly of the module showed a discoloration in the plastic insulation between the current collector and the endplate. The discoloration was localized around a bolt hole. The plastic insulation sheet was 0.010 inch thick. It was postulated that a film of electrolyte in this location could have completed the electrical circuit.

Two changes were made in the electrolysis module to solve this problem. First, a plastic insulation sheet of 1/8 inch thickness was added between the end cell current collector and endplate, and second, the bolt holes in the end cell current collector were enlarged to further increase the path between the current collector and endplate. This module was then installed in the Flight Breadboard System for the last test in the post-flight sequence. During this test the electrolysis module cell voltages were all uniform and significantly lower than observed previously. In addition, the water cavity venting revealed very low gas accumulation in the module. It appears, therefore, that the problem in the electrolysis module was correctly identified and solved.

An additional problem was discovered just prior to the last post-flight test. After running a brief checkout test following the installation of the reworked electrolysis module, the solenoid valve in the water feed line failed to close after shutting the system off. The valve was removed from the Flight Breadboard System and a bench check showed that the valve would occasionally stick open when de-energized. A manual valve was installed in the water feed line and will remain until a suitable replacement solenoid valve can be obtained.

TEST RESULTS

The data which was tabulated at each step in the test sequence is shown in Tables VIII through XI. The data and performance of the Flight Breadboard System indicated that no performance change was evident over the pre-flight, flight, or post-flight testing. The problem associated with the water electrolysis module having gas accumulation in the water feed cavities has already been discussed. The symptoms were evident during the pre-flight tests but the severity was not recognized until the crossover indication was observed in the flight test. A decrease in electrolysis module voltage and the elimination of the gas accumulation in the water feed cavities was observed in the last post-flight test after the change was incorporated in the module. This indicated that this problem has been solved.

The operation of the carbon dioxide concentrator module has been excellent all through the test program. A decrease in voltage was evident in the flight tests. This was attributed partially to the inability to maintain the design cell temperature using ambient air circulation during the flight tests due to high cabin temperatures in the aircraft. This caused a change in water balance; in this case a drying of the electrolyte. Even with a decrease in voltage, the current was maintained to transfer the carbon dioxide; and the carbon dioxide partial pressure in the rebreather loop was maintained at design levels.

All other components functioned normally except for the oxygen differential pressure regulator on the Water Electrolysis Subsystem which developed a small leak in the diaphragm in the last flight test.

All instrumentation functioned satisfactorily except for the oxygen and carbon dioxide partial pressure sensors which periodically gave erratic readings. The carbon dioxide partial pressure sensor circuit employs a battery in the bias off-set circuit for the amplifier. At the conclusion of the flight tests, the battery was found to be dead, explaining the problems with this sensor. After replacement of the battery, the sensor operated satisfactorily throughout the post-flight tests. The oxygen sensor, however, frequently gave erratic readings.

Throughout the test program, gas samples were taken at selected steady state operating conditions as specified in the Flight Test Sequence in Appendix A-1. The gas sample numbers are given for each operating condition in Tables VIII through XI. Some of the gas samples were unfortunately sent to a commercial testing laboratory whose procedures and results proved to be questionable. Data on these analyses are given in Table XII with reservations as to accuracy. The remainder of the samples were analyzed at Battelle Memorial Institute and are reported in much greater detail in Table XIII.

The samples in Table XIII were analyzed by gas chromatography which gave values for carbon monoxide and methane with a 7 ppm lower limit of detection. These gas chromatography results also gave a double check for oxygen-argon content and nitrogen content. The samples were then analyzed using a mass spectrometer. The gas was run through an evacuated liquid-nitrogen trap, the non-condensables pumped away, and the condensable material measured and analyzed by the mass spectrometer.

TABLE VIII

FBS LABORATORY TESTS - PRE-FLIGHT FIRST SERIES

Date	5/23	5/23	5/23	5/23	5/23	5/26	5/27	5/27	5/27	5/29	5/29	5/29	5/29	5/29	5/29	5/29	5/29
Sequence Step No	4	6	7	8	9	11	13	14	15	18	19	20	21	23	24	25	26
Operating Time - Hrs.	5 35	7 3	7 8	8 3	10.35	15.5	17.6	18 5	19 6	23 0	24.0	25.0	26.0	26.5	27.5	28.0	29 0
WES Module Volts	19.8	18	18 8	19 4	19.0	22	20.5	20.5	20	20	19 6	19 8	19.8	19.8	20.4	21.5	21.2
Module Amps	20	17 5	22	26	21	22	21	21	22	21 5	21	21	22	23	20.5	21.0	10.5
Module Temp. - ^oF	149	146	149	149	149	149	138	149	149	149	149	149	149	149	149	149	149
O_2 Press. - psia	75 5	76	74	74	75	75	75	75	75	74 5	75	74.5	74.5	74	74.5	74.5	77
H_2-H_2O ΔP - psi	1 7	1 5	1 6	1.65	1.7	1.8	1.7	1 75	1 8	1 65	1 65	1 7	1.7	1.5	1.25	2.0	1.0
H_2 Press - psia	76	76 5	75	74	76	74.5	75 5	75	74.5	75	75	74.5	74.5	74.5	74.5	75	76.5
CDCS Module Volts	4.9	5 0	5 0	5 0	5 0	4.8	4.9	4.9	5.0	4.9	5.0	4.9	4 8	5.1	5.6	4.8	4.8
Module Amps	7 0	7 0	7 0	7 0	7 0	7.0	7.0	7.0	7.0	7.0	7.0	7 0	7.0	7.0	7.0	7.0	7.0
Module Temp. - ^oF	108	109	109	109	109	109	108	109	102	109	109	109	109	109	109	109	109
H_2 Press. - psig	65	70	6	85	5	.75	.70	.70	.60	.45	75	.8	.8	.65	.9	.85	2.2
Blower Volts	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	57
Blower Current - ma	170	168	170	170	170	170	170	170	170	168	170	170	170	170	170	170	88
System Input DC Volts	28	28	28	27 7	28	27.8	28	28	28	28	28	28	27.8	27.8	27.9	27.9	28.5
Input DC Amps	17	15	20	24 5	18	23	21	21	21	20	20.5	20.5	21	22	20	22	11
Input AC Volts	116	116	116	116	116	116	117	117	116	112	115	115	115	116	115	115	114
Input AC Amps	.85	85	85	1 0	85	85	.85	1.3	85	1.1	.85	1.1	.85	1.1	.85	1.1	1.3
O_2 Supply Press. - psia	73.5	74	73	72	73	71	73	73	72	72.5	72.0	71	71	71	72	72	75
CO_2 Partial P - mm Hg	3.8	3.5	5.8	8 1	14.0	4.9	4.0	6.1	6.3	3.5	3.3	4.1	4 4	3.4	14.5	4.6	4.6
O_2 Partial P - mm Hg*	320	660	740	780	700	690	375	760	580	200	320	140	680	700	660	700	470
Coolant Temp. - ^oF	65	65	65	65	65	65	65	65	65	65	65	66	66	64	64	65	65
O_2 Bleed Rate - SLPM	50	40	57	71	57	57	57	.57	57	57	57	57	57	.57	.57	.57	.15
CO_2 Flow Rate - SLPM	.46	46	46	46	.48	49	.49	.49	49	49	49	49	.49	.49	.64	.49	.49
Breathing Rate - Cycles/min	18	18	18	18	18	18	18	10	25	18	18	18	18	18	18	18	18
Tidal Volume - cc	780	780	780	780	780	780	780	780	780	780	420	900	780	780	780	780	780
Breathing Loop Press.-in H_2O min/max	-1/5	-1/5	-1/5	-1/5	-1/5	-1/5	-1/5	0/4	-3/5+	-1/4 5	5/3 9	-2/5+	-1/4.2	-1/4	-1/5	-1/4.5	-4.5/4
Gas Samples H_2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O_2	1	-	-	-	-	2	3	4	-	6	-	-	-	9	-	-	-
Rebreather	1	-	-	-	-	2	3	4	5	6	-	-	-	9	-	-	12

*O_2 partial pressure instrumentation erratic

TABLE IX

FLIGHT BREADBOARD SYSTEM TESTS - PRE-FLIGHT SECOND SERIES

Date		6/9	6/10	6/10	6/10	6/10	6/13	6/16	6/16	6/16	6/16	6/16	6/16	6/17	6/17	6/17	6/17	6/17	6/17
Sequence Step No		4	6	7	8	9	11	13	14	15	18	19	20	23	24	25	26	27	29
Operating Time - Hrs		37 5	39 5	40 0	40.4	41 5	50 5	52 3	53.3	54.3	56 4	57.3	58.3	59 7	60.7	61.2	62.2	62.7	63.0
WES	Module Volts	21 1	20 4	21 0	21 6	21.4	20 4	21 5	21 6	21 6	20 6	21.4	22.5	20 4	20 8	21 0	21 2	22.0	21 5
	Module Amps	23 0	17 0	22 0	25 5	21.9	20 5	21 0	21 0	21 0	21.8	22.0	21.2	21 3	21.5	22.0	21 5	26 0	20.5
	Module Temp - °F	149	115	142	149	149	149	149	149	148	149	149	149	103	149	140	149	149	149
	O_2 Press - psia	75	76	75	74	75	75	75.5	75 8	75.5	75	75	75	75 5	75 5	75	75	74	75.5
	H_2-H_2O ΔP - psi	1.5	1 9	2 1	2.1	2 0	1 95	1.8	0.95	0 95	0 95	1 0	1 0	0.85	0 90	0.90	0.90	0.95	0 90
	H_2 Press - psia	76	77 5	76	75 5	76	74	76.5	75 8	75 7	75 5	75	76	75 5	75	74.8	75	74	75
CDCS	Module Volts	4 7	4 7	4 7	4.8	4 7	4 6	4.6	4 6	4 6	4.6	4.4	4 4	4 2	4.9	4.4	4 6	4.3	4.5
	Module Amps	7 0	7 0	7 0	7 2	6 9	7 0	7 0	7.2	6 9	7.5	7.55	7 0	71.	7.05	7 05	7 1	7.0	7 0
	Module Temp - °F	108 5	106	109	109	108 5	109	108	108	109	109	109	109	99	109	109	109	109 5	109
	H_2 Press - psig	1.0	0	0 2	0.5	0.55	0 6	0.5	0.5	0 4	0.45	0 45	0 45	0.42	0.40	0 50	0.50	0.60	0.45
	Blower Volts	90	90	90	90	89	91	93	92	90	90	90	90	90	91	90	10	90	90
	Blower Current - ma	190	188	185	193	190	185	186	190	188	184	185	184	187	184	183	35	183	184
System	Input DC Volts	27 8	28.2	27 9	27 5	27.8	27 5	27 5	27.5	27 5	27 5	27.5	27 5	27 7	27.5	27.5	27 5	27.2	27 5
	Input DC Amps	22	17.5	21 5	26	21 5	20	21	22	21 5	21	22	22	20.5	21	22	22	27	20.5
	Input AC Volts	116	116	116	116	116	114	116	115	115	114	114	114	116	115	115	114	114	114
	Input AC Amps	0.8	0 75	0.70	0.95	0.75	0.65	0.70	0.68	1 5	1 5	1.25	0 70	0.70	0.95	0.68	0.65	0.65	0.65
	O_2 Supply Press - psia	74	75	74	72	73	71	74	74	74	73 5	73.5	74	73.5	73	73	73	72	73
	CO_2 Partial Press-mm Hg	4 4	13.5	18 5	11 5	8 5	4 9	7.7	12 5	10.0	15 5	14	8	7 7	24	7 5	8.5	8	4.3
	O_2 Partial Press -mm Hg*	490	620	540	460	390	700	400	800	630	400	420	420	360	300	620	470	435	425
Coolant Temp - °F		65	65	65	65	65	65	64	64	64	64	64	63 5	64	64	64	64	64	64
O_2 Bleed - SLPM		57	.39	57	70	57	.57	57	57	57	57	57	57	.57	57	57	57	.70	57
CO_2 Flow - SLPM		45	49	49	59	59	48	49	49	.49	49	49	49	.48	64	48	.49	.49	.49
Breathing Rate - Cycles/min		18	18	18	18	18	18	18	10	25	18	18	18	18	18	18	18	18	18
Tidal Volume - cc		780	780	780	780	780	780	780	780	780	780	420	900	780	780	780	780	780	780
Breathing Loop Press - in H_2O (min/max)		-1/5	-1/5	-1/5	-1/5	-1/5	-1/5	-1/5	0/4	-3/5+	-1/5	1/4	-1.5/5	-1/5	-1/5	-1/5	-4/3	-1/5	-1/5
Gas Samples	H_2	6	-	-	-	-	-	7	-	-	8	-	-	9	-	-	-	-	-
	O_2	10	-	-	-	-	-	11	-	-	14	15	-	17					-
	Rebreather	13	-	-	-	-	14	15	16	17	18	19	20	21	22	23	24	25	-

* O_2 partial pressure readings erratic

TABLE X

FLIGHT BREADBOARD SYSTEM DATA - FLIGHT TESTS

				INSTALLED IN C-131 - 7/15/69				FLIGHT TEST #1			FLIGHT TEST #2			
Date	7/11	7/11	7/11		7/15	7/17	7/17		7/17	7/17		7/13	7/18	7/18
Sequence Step No	4	4	4		6	6	8		2	2		4	5	6
Operating Time - Hours	69 6	70 7	71 9		75 7	76 9	77 9		79 0	80		81 6	82 5	83 4
WES Module Volts	22 4	24 8	21 6		17 8	20 1	18		19	19 6		21 3	21 3	23 4
Module Amps	21	21	11		14	14 5	23		18	19		17 5	19	25 5
Module Temp - °F	149	149	149		98	123	131 5		134	149		126	149	150
O_2 Press - psia	75	75	77 5		77	75	73		74	73 5		74	73 5	71
H_2-H_2O ΔP - psi	0 9	0 9	0 8		0 7	1 1	1 0		1 1	1 1		1 15	1 15	1 2
H_2 Press - psia	74 5	74 5	77		76	77	74		75 5	75		75 5	75	72
CDCS Module Volts	4 7	4 6	4 4		4 4	4 5	5 2		4 5	4 4		4 3	4 3	4 4
Module Amps	7	7	7		7 9	7 2	7 2		7 2	7 2		7	7	7
Module Temp - °F	109	109	109		105	109	109		109	109		109	110	113
H_2 Press - psig	0 5	0 5	0 4		0 5	0 4	0 5		0 6	0 7		0 55	0 70	0 70
Blower Volts	90	90	90		90	84	80		83	82		84	82	84
Blower Current - ma	182	185	176		210	195	195		187	178		170	175	173
System Input DC Volts	26	28 5	30		27 5	27	26 5		27 4	27 2		27 4	26 9	26 5
Input DC Amps	23 5	24	12		16	18	25		20	21		20	21	26 2
Input AC Volts	118	117	117		118	114	112		109	109		110	109	109
Input AC Amps	0 8	0 8	0 8		0 7	0 7	0 9		1 0	0 9		0 7	1 0	1 1
O_2 Supply Press - psia	73	72	75 5		72	73	71		72	71		72 [illegible]	72	70
CO_2 Partial Press - mm Hg*	-	-	-		3 5	7 0	2 9		4 8	4 9		5 4	6 3	5 4
O_2 Partial Press - mm Hg*	735	740	735		300	370	520		300	600		340	585	560
Coolant Temp - °F	67	53	63		75	67	68		69	65		66	65	91
O_2 Bleed - SLPM	57	57	17		40	41	70		54	57		57	57	57
CO_2 Flow - SLPM	49	49	49		49	49	49		47	48		48	48	50
Breathing Rate - Cycles/min	18	18	18		18	18	18		18	18		18	10	25
Tidal Volume - cc	780	780	780		780	780	780		780	780		780	780	780
Breathing Loop Press - in H_2O (min/max)	-1/5	-1/5	-1/5		-1/5	-1/5	-1/5		-1/5	-1/5		-1/5	-1/5	-2/2
Aircraft Altitude	———	———	———	GROUND	———	———	———		7300	7300		7500	GROUND	
Ambient Temperature	-	-	-		85	85	90		98	100		90	100	105
Gas Samples H_2	-	10	-		-	-	-		-	11		12	-	-
O_2	-	16	-		-	-	-		-	17A		18	19	20
Rebreather	-	26	-		-	-	-		-	27		28	29	30

	FLIGHT TEST #3					FLIGHT TEST #4						FLIGHT TEST #5			
Date		7/25	7/25	7/25	7/25		7/28	7/29	7/29	7/29	7/29		7/29	7/29	7/29
Sequence Step No		9	9	10	11		14	14	14	16	17		-	18	-
Operating Time - Hours		84 3	84 6	85 3	86 3		88 3	89 7	90 2	90 7	91 2		92 1	92 6	93 5
WES Module Volts		20 1	21	21	21 2		20 4	20 4	21	21 5	21 3		20 6	23 2	21 6
Module Amps		22 5	22 5	18	18		19	19	19	19	17		17	23 5	16
Module Temp - °F		115	134	149	149		111	107	132	149	149		139	149	149
O_2 Press - psia		73	73	74	74		74	74	74	74	74		74	65	74
H_2-H_2O ΔP - psi		1 2	1 2	1 2	1 1		1 0	0 8	0 8	0 85	0 85		0 70	0 9	0 75
H_2 Press - psia		74	74	75	75		-	75 5	75 5	75 5	75 5		76	66 5	74
CDCS Module Volts		4	4 3	4 2	4 1		4 1	4 1	4 4	4 1	4 7		4 5	4 2	3 9
Module Amps		7 2	7	7	7		7 2	7	7	7	7		7	7	7
Module Temp - °F		102	109	109	109		102	100	109	109	109		109	109	109
H_2 Press - psig		0 60	0 50	0 50	0 55		0 6	0 3	0 5	0 5	0 5		0 4	0 5	0 55
Blower Volts		82	81	81	81		82	82	82	82	10		80	80	81
Blower Current - ma		185	182	180	180		185	180	180	174	35		177	178	178
System Input DC Volts		27	26 8	27 4	27 5		26 8	27 2	27	27 4	27 4		27 5	26 9	27 5
Input DC Amps		26	26	20	20		22	19	20	21	18		18	26	16 5
Input AC Volts		110	110	110	109		110	110	110	110	109		108	108	108
Input AC Amps		0 65	0 80	0 85	1 1		0 65	0 65	1 0	1 0	0 8		1 1	1 1	1 0
O_2 Supply Press - psia		69	73	72	72		70	71	71	71	71		71	62	72
CO_2 Partial Press - mm Hg*		-	-	-	-		-	-	-	-	-		-	-	-
O_2 Partial Press - mm Hg*		350	340	310	320		200	200	200	200	200		220	220	260
Coolant Temp - °F		66	65	67	65		65	65	67	66	67		66	66	65
O_2 Bleed - SLPM		57	57	37	37		57	17**	26**	36**	36**		36**	69**	36**
CO_2 Flow - SLPM		50	49	49	49		49	49	63	49	49		49	49	49
Breathing Rate - Cycles/min		18	18	18	18		18	18	18	18	18		18	18	18
Tidal Volume - cc		780	780	420	900		780	780	780	780	780		780	780	780
Breathing Loop Press - in H_2O (min/max)		-1/5	-1/5	0/4	-2/5		-1/5	-1/5	-1/5	-1/5	-1/5		-1/5	-1/5	-1/5
Aircraft Altitude		8000	8000	8000	5300		CLIMB	8400	8400	8400	8400		5200	5200	5200
Ambient Temperature		82	84	97	104		78	75	90	95	95		82	95	105
Gas Samples H_2		-	13	-	-		14	-	-	-	-		-	-	-
O_2		-	21	22	23		24	-	-	-	-		-	-	-
Rebreather		-	31	32	33		34	-	35	36	37		-	38	-

*Partial pressure instrumentation erratic

**Bleed set low to offset regulator leak

TABLE XI

FLIGHT BREADBOARD SYSTEM TESTS - POST-FLIGHT

Date		8/12	8/13	8/13	8/14	8/14	8/14	8/15	8/15	8/15	9/15	9/15	9/15	9/15	9/15	9/15
Sequence Step No		-	2	2	4	5	6	9	10	11	14	15	16	17	18	19
Operating Time - Hrs.		95.6	97 9	99.9	100.9	101.9	102.9	105.7	106.7	107.7	117.6	118.5	119 0	120.0	120.5	120.9
WES	Module Volts	22 6	22.6	24	21 5	23 5	24 5	21.1	23	23.8	19.8	19.0	19.4	19 8	21.0	19.5
	Module Amps	21.5	21 5	21	21.3	21	21	21	21.5	20.2	21.5	20.0	21.0	19.0	24	21 8
	Module Temp - ^{o}F	149	149	149	134	149	149	142	149	149	113	146	149	149	149	149
	O_2 Press. - psia	72 5	73	73	73	73	73	73	73	73	73	73	73	73	72	73
	H_2-H_2O Δ P - psi	0.75	0175	0 75	0.9	0.9	0 95	0.7	1 0	1.0	1.3	1.2	1.5	1.2	1.1	1.1
	H_2 Press - psia	73	73	72.5	73	73	72	72	72	73	72	72	72	73	71	72
CDCS	Module Volts	4.2	3.8	3.7	3.9	3.7	3.6	3.8	3.6	3.5	3.8	2.2	3.1	1.9	3.7	2.9
	Module Amps	7.0	6.9	6.95	7.0	6.9	6.95	6 9	7.0	7.0	7.0	6.5	6.9	4.2	7.0	7.0
	Module Temp - ^{o}F	108	107	108	108	109	108	108	109	109	107	108.5	108	108	108	108
	H_2 Press - psig	0.4	0.3	0.5	0.4	0.4	0 5	0.4	0.4	0.5	0.7	0.8	0.8	0.8	0.8	0 9
	Blower Volts	82	81	81	82	82	81	82	82	82	82	81	80	OFF	81	81
	Blower Current - ma	177	178	178	177	176	177	176	178	176	176	176	180	-	175	176
System	Input DC Volts	27.2	27 4	27 2	27.5	27.3	27.3	27 5	27.3	27.3	27.5	27.5	27.5	27 6	27.0	27.5
	Input DC Amps	23	23	23.5	22	23	23.5	21	23	22.5	20	18.5	19.5	17	25.5	20
	Input AC Volts	109	110	109	111	110	109	110	109	109	110	109	109	109	109	108
	Input AC Amps	1.2	1.3	1.3	1 1	0.9	1.1	0.9	0.9	0.9	1.3	1.0	1.3	1.1	1.1	1.3
	O_2 Supply Press - psia	71.5	72	70	71	71	70	70	70	70	70	70	70	71	69	70
	CO_2 Partial Press-mm Hg	6 0	4.9	4 7	3.9	4 3	4.0	3 3	3.4	4.0	3.9	18.5	5.6	12 5	4.1	5.1
	O_2 Partial Press-mm Hg*	550	410	370	800	750	730	710	710	690	690	710	710	700	680	695
Coolant Temperature - ^{o}F		66	66	71	71	70	71	71	67	67	65	66	65	74	75	75
O_2 Bleed - SLPM		.57	.57	.57	57	.57	57	57	.57	.54	.57	.57	.57	.57	.70	.57
CO_2 Flow - SLPM		49	.49	.49	.49	49	.49	.49	.49	.49	.49	64	.49	.48	.49	.49
Breathing Rate - Cycles/min		18	18	18	18	10	25	18	18	18	18	18	18	18	18	18
Tidal Volume - cc		780	780	780	780	780	780	780	420	900	780	780	780	780	780	780
Breathing Loop Press - in H_2O (min/max)		-1/5	0/5	0/5	0/5	1/4	-1/5	-1/5	1/4.5	-1/5	-1/5	-1/5	-1/5	-4/3	-1/4.5	-1/4.5
Gas Samples	H_2	-	15	-	16	-	-	17	-	-	18	-	-	-	-	-
	O_2	-	25	-	26	27	28	29	30	31	32	-	-	-	-	-
	Rebreather	-	39	-	40	41	42	43	44	45	46	47	48	49	50	-

*O_2 partial pressure readings erratic

Normal procedure in collecting the oxygen and hydrogen samples results in gas samples with a nominal 20 percent argon content. The data in Table XII has been corrected to reflect the composition of the hydrogen and oxygen gases which are obtained from the system, not the content of the bottle which includes initial argon charge. In addition, the gas sample lines are purged with argon prior to each test which explains the presence of argon in the rebreather gas samples.

The compounds identified in the gas samples are indicated in Table XIII. These compounds in the concentrations found are not known to be toxic.

At system design operating conditions, the carbon dioxide level in the rebreather loop is within acceptable limits. Samples R-22, R-35 and R-47, which show abnormally high carbon dioxide levels, were obtained at carbon dioxide input rates to the system which were 30 percent higher than the design rate. Gas samples R-39, R-40 and R-41 also exhibit carbon dioxide levels higher than the others in the table. These samples were the first ones taken early in the post-flight tests. The condition of the carbon dioxide concentrator is believed to have been affected by the high ambient temperatures in the flight test as mentioned previously. This could explain the relatively high carbon dioxide levels during this period while the carbon dioxide concentrator recovered in water balance. Sample R-49 was obtained during the period while the recirculating blower at the carbon dioxide concentrator was not operated. The high indicated carbon dioxide level may not be representative since without the blower, the carbon dioxide tends to flow through the system as high concentration pulses due to the method of carbon dioxide addition in the breathing simulator. This sample, therefore, may be one of these pulses.

The TRW personnel received excellent cooperation from the personnel at the Naval Missile Center, Point Mugu, California. A genuine interest and enthusiasm was displayed which made the flight test program a successful effort. The only comment concerning similar programs in the future would be that if possible, a non-classified area be used. On a few occasions it was necessary to have permission and escorts for overtime activities in the hangar which would have been much easier to accomplish in a non-classified area.

The flight test program accomplished all of the objectives originally set for this effort. The experience gained will contribute significantly to future development of aircrew oxygen systems.

TABLE XII

GAS SAMPLE COMPOSITIONS
COMMERCIAL TEST LABORATORY

Sample No.	Total Hydrocarbons	CO_2	CO	H_2
H_2-1	2ppm	3ppm	<1ppm	-
O_2-1	3ppm	13ppm	-	475ppm
-2	7 "	17 "	-	785 "
-3	6 "	17 "	-	383 "
-4	2 "	13 "	-	675 "
-6	3 "	15 "	4ppm	-
-9	2 "	7.5 "	2 "	-
R-1	NO ANALYSIS			
-2	NO ANALYSIS			
-3	148ppm	-	-	
-4	145 "	0.53 vol%	18ppm	
-5	145 "	0.26	8 "	
-6	430 "	0.26	8 "	
-7	770 "	0.32	8 "	
-9	410 "	-	16 "	
-12	300 "	0.45	4 "	
-14	300 "	0.35	< 5 "	
-15	1460 "	0.37	< 5 "	
-17	87 "	0.32	< 5 "	
-21	116 "	0.34	< 5 "	
-23	114 "	0.36	< 5 "	
-24	84 "	0.49	< 5 "	
-26	1470 "	0.64	< 5 "	
-27	520 "	0.83	< 5 "	
-28	310 "	0.38	< 5 "	
-29	520 "	1.58	< 5 "	
-30	490 "	0.54	< 5 "	
-31	340 "	0.24	< 5 "	

NOTE: Above data obtained by gas chromatography. Sample handling procedures are questionable and therefore accuracy of results are suspect.

TABLE XIII

GAS SAMPLE COMPOSITIONS

Sample No	Volume Percent O_2	Volume Percent N_2	Parts Per Million CH_4	Parts Per Million CO_2	Parts Per Million CH_2Cl_2	Parts Per Million $(CH_3)_3SiOH$
H_2-6	0 01	0 30		8		10
H_2-7	0 02	0 76	15	5		12
H_2-8	0 02	0 17	13	4		5
H_2-9	0 08	0 69		5		4
H_2-10	0 41	2 30	21	4	4	2
H_2-11	0 09	0 95	20	1		5
H_2-12	0 09	1 57	10	6	1	
H_2-13	0 06	1 05	10	6	2	
H_2-14	0 05	0 93	10	5		
H_2-15	0 05	0 51		5	8	5
H_2-16	0 02	1 31	14	31	6	5
H_2-17	< 0 01	0 07		13	6	1
H_2-18	0 05	1 15			4	1

Sample No	Volume Percent H_2	Volume Percent N_2	Parts Per Million C_2H_4	Parts Per Million CO_2	Parts Per Million $(CH_3)_3SiOH$
O_2-10	12	1 00		20	7
O_2-11	20	1 75		4	5
O_2-14	14	0 70		11	2
O_2-15	21	0 61		16	
O_2-16	34	2 00		124	
O_2-17	15	0 78	11	12	10
O_2-17A	20	1 63		7	
O_2-18	23	1 65		7	
O_2-19	04	0 71		4	
O_2-20	55	0 60		15	
O_2-21	48	0 48		6	
O_2-22	32	0 77		18	
O_2-23	41	0 65		12	
O_2-24	14	0 52		6	
O_2-25	< 01	1 03		49	2
O_2-26	< 01	1 13		15	
O_2-27	< 01	0 71		44	
O_2-28	< 01	0 10		74	
O_2-29	< 01	< 0 01		107	
O_2-30	< 01	< 0 01		38	
O_2-31	< 01	< 0 01		180	
O_2-32	<.01	1 02		320	

Sample No	Volume Percent CO_2	Volume Percent N_2	Volume Percent H_2	Volume Percent Ar	Parts Per Million C_2H_4	Parts Per Million $(CH_3)_3SiOH$
R-13	.29	96	20	.23		6
R-16	47	50	27	41		3
R-18	29	1 73	20	06	2	2
R-19	31	92	30	07	2	1
R-20	36	83	80	05	1	
R-22	1 12	41	30	31		
R-25	36	29	17	14		
R-32	29	45	25	06		
R-33	20	62	32	06		
R-34	41	1 83	28	14		
R-35	3 31	4 15	10	24		
R-36	93	93	23	12		
R-37	86	.43	22	06		
R-38	.64	48	14	05		
R-39	1 00	72	02	14		
R-40	1 17	1 03	03	10		
R-41	1.53	2 29	01	24		
R-42	70	22	< 01	18		
R-43	.93	2 11	18	25		
R-44	.61	65	21	18		
R-45	.76	23	35	21		
R-46	.34	4 47	< 01	10		
R-47	2 95	.40	< 01	16		
R-48	38	29	10	17		
R-49	2 10	23	76	17		
R-50	.22	32	1 50	15		

Unless otherwise stated, all samples contain less than the concentration stated below in parts per million.

CO	< 7	C_2H_4	< 1
SO_2	< 1	CH_4	< 7
H_2S	< 5	CH_2Cl_2	< 1
C_2H_6	< 1	CO_2	< 1
COS	< 1	$(CH_3)_3SiOH$	< 1
HCl	< 1	CS_2	< 1
NOx	< 1		

ENVIRONMENTAL TESTING

The purpose of the environmental tests were to examine the effects of low temperature and high altitude on system performance. This task was directed towards identifying problem areas associated with these two conditions.

Low Temperature Test

Water Reservoir. - One of the components definitely affected by a low temperature environment (less than 32°F) is the feed water tank for the water electrolysis module. To investigate the behaviour of this tank in such a low temperature environment prior to system exposure, a tank similar to that used in the Flight Breadboard System was exposed to a -5°F environment for a 24-hour period. The water tank was introduced into a pre-cooled test chamber. The positioning of the tank was similar to that in the system with the gas compartment up. The tank was only partially filled to allow for the change in volume occurring during the freezing and thawing process.

After completion of the 24-hour low temperature test, the tank was removed from the test chamber. Upon inspection it was noted that the eight drawbolts of the tank were loose. By calculation the difference between the thermal expansion coefficients for acrylic plastic and stainless steel could account for a 0.019" difference for a height of 8" of plastic and a temperature change of 80°F. No ice was noted at the sealing surface however, hence, no leakage had apparently occurred prior to freezing. After removing the tank from the cold chamber, it was located in a vertical position, gas compartment up, in an ambient environment of approximately 70-75°F and the ice was allowed to thaw. Thawing required approximately 24 hours. No leakage was noted as the water tank went to ambient temperature levels. After the tank reached ambient temperature levels, several drawbolts required retightening. The water tank was then used for a water electrolysis module checkout test at a pressure level of 65 psia. The tank performed its required function throughout this test.

Based on this test it was concluded that the two basic problems in subjecting a water tank to a low temperature environment are expansion of the water/ice and loss of compression if the water tank is constructed of materials having dissimilar coefficients of thermal expansion. To modify the tank and to allow for the 8 percent expansion, a foam-rubber pad sufficiently sized for a particular water tank capacity could be inserted into the gas compartment side and thus expansion of a full water tank could take place through compression of the foam rubber. In this manner the water tank could always be readily filled to the uncompressed foam rubber height and no special precautions as to filling levels would have to be taken. Since a prototype water tank would most likely be constructed from items such as spun stainless steel cylinders, differential expansion would be no problem. However, the tank, utilizing the present construction of acrylic plastic cylinders and stainless steel endplates and drawbolts would have to use thicker gaskets or possibly belville washers to maintain a relatively constant compression load during the freezing process.

Flight Breadboard System. - Two low temperature tests were conducted to examine the effects of 1) low temperature storage and 2) start-up at low temperature.

The first test involved placing the Flight Breadboard System in a cold chamber at -5°F for 24 hours. The length of time was chosen to assure that the entire system had been cooled to -5°F. The only precaution taken was to fill the water tank three-quarter full to allow for expansion of the water on freezing. At the conclusion of this soaking period, the system was removed from the chamber and allowed to equilibrate with the ambient temperature (75°F) for another 24 hours. The Flight Breadboard System was then connected to the breathing simulator and auxiliary equipment. A four-hour test at design operating conditions was conducted to determine if any change in performance was attributable to a low temperature storage condition. The system performance was normal and no change from previous test data was observed. The data from this test is shown in Table XIV.

At the conclusion of the test, electric resistance heaters were strapped on the bottom of the electrolysis module water reservoir and around the water feed line leading from the reservoir to the module. This was done in preparation for the low temperature startup test so that the heaters could be turned on at startup to aid in thawing the water feed plumbing.

The Flight Breadboard System was again placed in the cold chamber at -5°F for 24 hours. At the conclusion of this period, the Flight Breadboard System was removed from the chamber and quickly connected to the breathing simulator, resources adapter and instrumentation. A thermocouple was inserted into a center cell of the electrolysis module. The heaters on the water tank and feed line were turned on and the Flight Breadboard System was started. A heat gun was also used to warm the tubing in the system to prevent blockage due to freezing of the condensed moisture in the hydrogen and oxygen lines. Startup occurred thirty minutes after removal of the Flight Breadboard System from the cold chamber. This time was required to move the Flight Breadboard System from the cold chamber, in another building, to the NAOS Laboratory and make the necessary plumbing and electrical connections.

Figure 34 shows the electrolysis module voltage, current and temperature with time. Module voltage was lower than expected at the cold startup condition. The voltage did not change significantly due to temperature. The small variations could be caused by the current changes during the startup transient. All components functioned normally during the test except for the carbon dioxide partial pressure sensor which read full scale for the first half of the four-hour test. At the conclusion of the test all components were at normal operating temperature, except for the electrolysis module water reservoir which had a large lump of ice floating in the water. The data from this test is shown in Table XIV.

The cold startup test indicates that the electrochemical modules function normally at least to near 0°F and that heating of the plumbing to prevent plugging with ice may be the only cold start requirement.

Altitude Chamber Tests

The Flight Breadboard System and auxiliary equipment was installed in an altitude chamber to examine system performance with changes in ambient pressure. Figure 35 shows the installation inside the chamber. The instrumentation package,

TABLE XIV

FLIGHT BREADBOARD SYSTEM DATA - ENVIRONMENTAL TESTS

AFTER 24 HRS AT -5°F PLUS 24 HRS AT ROOM TEMPERATURE

IN COLD BOX FOR 24 HRS AT -5°F

START UP IMMEDIATELY AFTER REMOVING

INSTALLED IN ALTITUDE CHAMBER

ALTITUDE TEST

Date		9/24	9/24	9/26	9/26	10/16	10/20	10/20	10/20	10/20	10/20	10/20	10/20	10/20
Operating Time		123.2	125.4	127.3	129.0	131.0	131.8	132.4	132.9	133.7	134.2	134.5	134.7	135.0
WES	Module Volts	20.2	20.4	21.8	21.5	20.5	20.8	21.0	20.0	19.9	19.2	19.6	19.8	20.0
	Module Amps	21.5	22.0	21.5	21.8	21.0	20.5	20.0	20.0	21.8	20.0	18.8	16.5	21.8
	Module Temp. - °F	149	149	149	149	133	110	144	149	119	134	142	146	149
	O_2 Pressure - psia	73	73	73	73	73	73	73	73	73	73	74	74	73
	H_2 - H_2O ΔP - psi	1.8	1.4	1.25	1.3	1.6	1.4	1.9	2.1	1.7	2.3	2.5	2.5	3.1
	H_2 Pressure - psia	74.5	75.0	71.0	71.0	72.0	72.0	72.0	72.5	72.0	73.0	74.0	74.5	73.0
CDCS	Module Volts	4.2	4.3	4.2	4.1	4.4	4.1	4.1	3.9	4.7	3.7	3.3	2.9	4.1
	Module Amps	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
	Module Temp. - °F	108	108	107	109	108	103	108	108	101	108	110	112	108
	H_2 Pressure - psig	0.7	0.7	1.4	0.6	0 5	0.4	0.6	0.9	0.4	1.2	1.9	2.0	0.7
	Blower Volts	82	82	82	82	83	82	85	90	82	94	95	95	82
	Blower Current - ma	178	175	177	176	175	176	160	135	178	112	106	106	176
System	Input DC Volts	27.5	27 5	27.4	27.5	27.5	27.6	27 5	27.5	26.0	26.0	26.2	26.5	25.7
	Input DC Amps	21.0	21.2	22.5	22.0	20.5	20.0	20.0	19.5	21.0	20.0	18.5	15.5	23.0
	Input AC Volts	110	109	110	110	110	110	110	109	110	110	110	109	109
	Input AC Amps	1.0	1.1	1.3	1.0	1.0	0.7	0.9	0.9	0.7	0.8	0.8	0.8	1.0
	O_2 Supply Press. - psia	70.0	70.0	69.0	69.0	70.0	69.5	69.0	69.0	69.0	70.0	71.0	71.0	69.0
	CO_2 Partial Press. - mm Hg*	3.0	3.6	-	3.0	2.1	2.4	-	-	1.5	-	-	-	3.6
	O_2 Partial Pressure - mm Hg*	710	720	780	780	640	380	250	210	240	110	400	430	260
Coolant Temperature - °F		65	65	65	65	65	65	65	65	65	65	65	65	65
O_2 Bleed - SLPM		0.62	0.63	0.63	0.63	0.60	0.60	0.60	0.60	0.60	0.60	-	-	0.60
CO_2 Flow - SLPM		0.49	0.48	0.49	0.49	0.45	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Breathing Rate - cycles/min		18	18	18	18	18	18	18	18	18	18	18	18	18
Tidal Volume - cc		780	780	780	780	780	780	780	780	780	780	780	780	780
Breathing Loop Pressure - in H_2O (min/max)		-1/4.8	-1/4.8	-1/4.8	-1/4.8	0/5.0	0/5	0/5	.5/4.5	0/5	1/4	3.5/6	5/7	0/5
Altitude - Feet		-	-	-	-	-	S.L.	5100	14300	S.L.	24800	36000	38500	S.L.
Ambient Temperature		75	75	75	75	65	66	66	66	62	62	62	62	62

*Partial pressure sensor readings erratic.

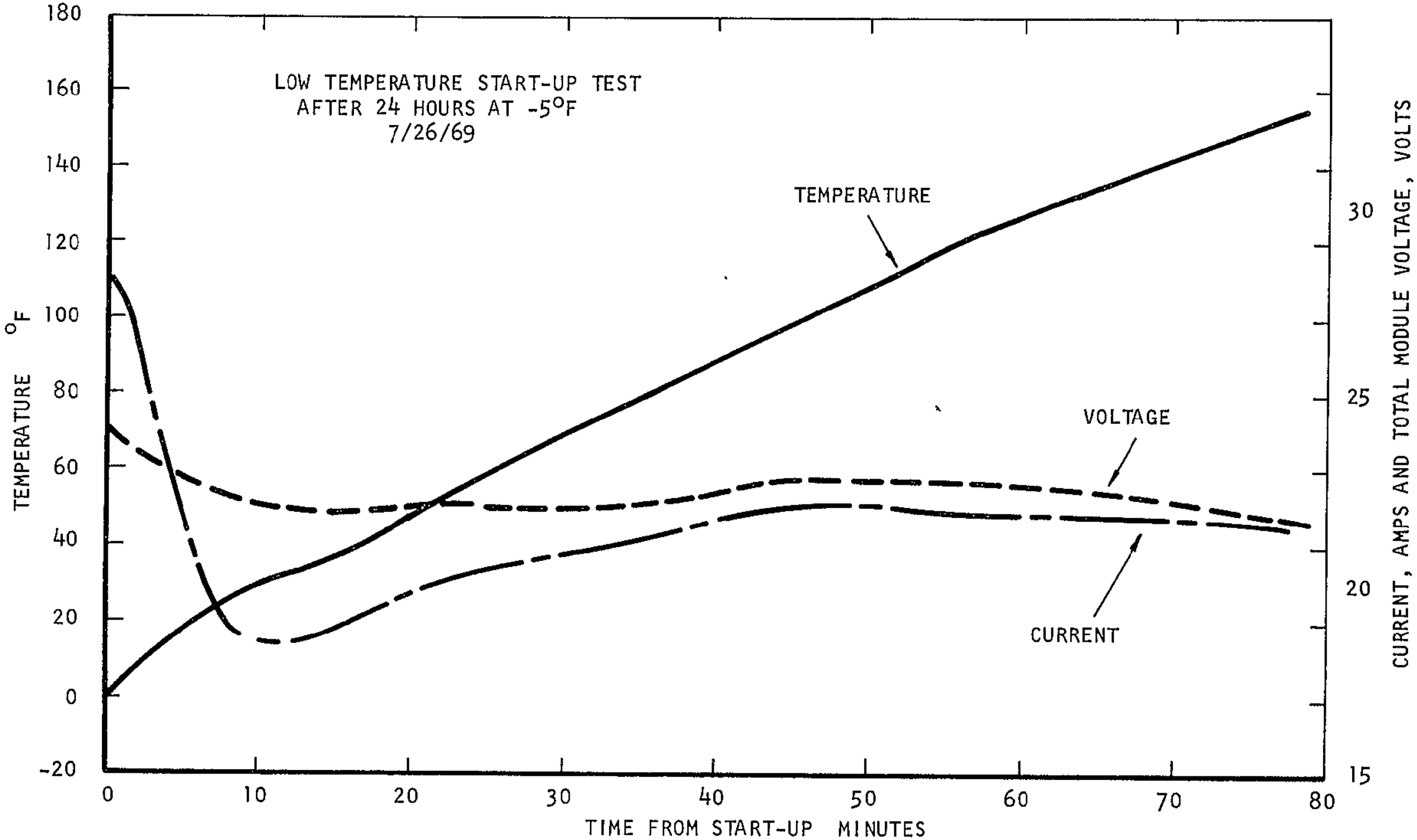


FIGURE 34 FLIGHT BREADBOARD SYSTEM - LOW TEMPERATURE TEST - ELECTROLYSIS MODULE PARAMETERS

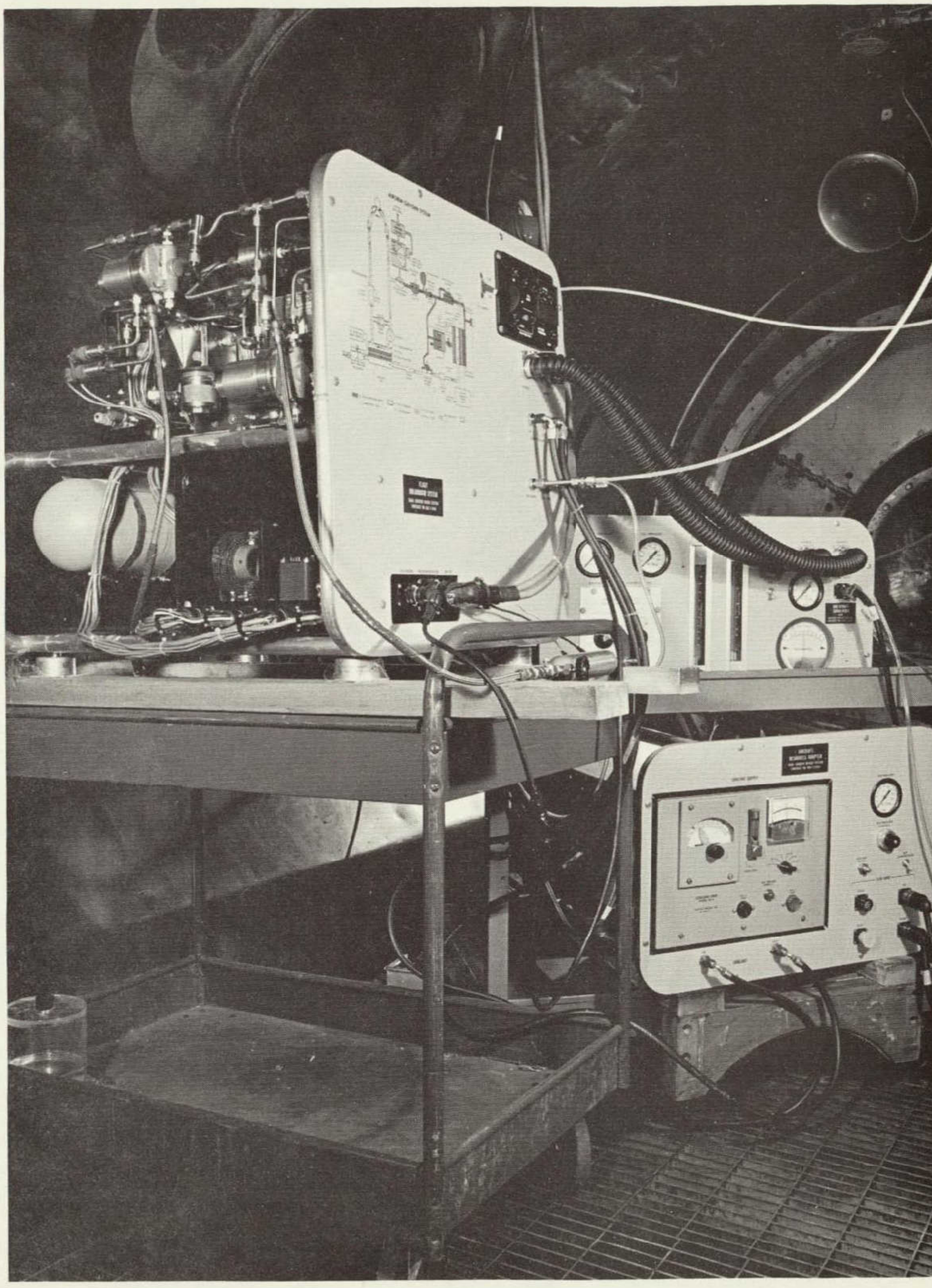


FIGURE 35 FLIGHT BREADBOARD SYSTEM INSTALLED IN ALTITUDE TEST CHAMBER

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tape recorder, and gas sample bottles were located outside the chamber. A one-hour sea level test was run to check out the installation in the chamber. The system was started and operated at sea level pressure for one-half hour. The pressure was lowered to an altitude of 5,100 feet and held for twenty minutes. The altitude then was increased to 14,300 feet for twenty minutes. On increasing altitude to 25,000 feet, the ground power conversion unit tripped on and off several times, apparently due to overheating caused by the low density of air. The system was shutdown and the ground power unit was moved to outside the chamber for the rest of the test. Again, the system was started at sea level and then raised to 24,800 feet and then to 36,000 feet altitudes. The maximum chamber altitude reached was 38,500 feet due to the capacity of the chamber vacuum system. The chamber was returned to sea level for twenty minutes and then the system shut down.

Table XIV shows the steady-state data at each operating condition. Note that at 36,000 feet the counter-lung pressure control is beginning to operate on the pressure breathing schedule as indicated by the increase in the breathing loop pressure. The partial pressure sensors were apparently affected by the change in total pressure as indicated by the abnormal readings. One cell of the carbon dioxide concentrator module decreased in voltage to near zero at the maximum altitude of 38,500 feet but recovered promptly upon return to sea level.

Rebreather gas samples were taken at each altitude. Table XV gives the results of the gas analysis. The oxygen and hydrogen samples were taken during the first sea level operating condition. Although the volume percent of carbon dioxide in the rebreather loop increases with altitude, the partial pressure of carbon dioxide rises to a value which is considered safe for short exposure times.

High Altitude Effects Analysis

Consideration was given to effects of low ambient pressure on the system performance. As the ambient pressure is reduced with rising cabin altitude, the oxygen partial pressure in the rebreather loop will also decrease since the counter-lung pressure control will maintain the rebreather loop at a value equal to ambient pressure plus the safety pressure of nominally one inch of water. Starting at an altitude of 38,000 feet, the normal pressure breathing schedule is controlled by the counter-lung pressure control regulator. This control allows a maximum of 18" of water above ambient in the rebreather loop. Thus, in a non-pressure suit application, the system can be used to a maximum cabin altitude of 43,000 feet.

To use the system at low ambient pressures requires that the oxygen in the rebreather loop is not diluted by ambient air leaking into the system. This requirement is met by always maintaining the safety pressure in the system so that any leakage would be outward rather than inward. Therefore, in order to conserve oxygen, mask leakage must be minimized. Mask leakage is a serious problem in rebreather systems since even small leaks could be the same magnitude as metabolic oxygen requirements, whereas in open loop systems the oxygen use rates are 20 to 30 times that of the closed system rates. The mask leakage problem would also be amplified at cabin altitudes above 38,000 feet where

TABLE XV

GAS SAMPLE COMPOSITIONS
ALTITUDE TESTS

Sample No.	Altitude, Ft.	Volume Percent			PPM
		O_2	N_2	H_2	CO_2
O_2-33	S.L.	99.00	1.00		14
H_2-19	S.L.	0.12	1.65	98.20	16

Sample No.	Altitude, Ft.	Volume Percent				CO_2 Partial Press
		CO_2	Ar	N_2	H_2	mm Hg
R-51	5,100	1.31	1.94	0.58	0.29	8.2
R-52	14,300	2.92	0.72	0.47	0.30	12.9
R-53	24,800	5.10	0.20	0.47	0.32	14.4
R-54	36,000	9.84	0.31	0.62	0.53	16.7
R-55	38,500	10.9	0.37	0.72	2.11	16.4

Unless otherwise stated, all samples contain less than the concentration stated below in parts per million.

CO	< 7	C_2H_4	< 1
SO_2	< 1	CH_4	< 7
H_2S	< 5	CH_2Cl_2	< 1
C_2H_6	< 1	CO_2	< 1
COS	< 1	$(CH_3)_3SiOH$	< 1
HCl	< 1	CS_2	< 1
NO_x	< 1		

the pressure breathing schedule results in pressure differences between the mask and ambient which are several times higher than at the lower altitudes.

As altitude increases, the gas density in the rebreather loop decreases, resulting in lower pressure drops in the rebreather circuitry. The net effect would be that the pressures would tend to fluctuate less during the breathing cycle. The greatest rebreather loop pressure fluctuations would occur at sea level, assuming that the aviator's respiration pattern does not change significantly with cabin altitude changes.

The carbon dioxide concentrator may be affected by altitude for two reasons. The first is that the concentrator performance may suffer some degradation as the partial pressure of oxygen and hydrogen is reduced with increasing altitude to about one-sixth of the sea level values. Parametric testing of a carbon dioxide concentrator in an altitude chamber would be required to examine this condition. The second effect would be the large increase in hydrogen volume flow as altitude is increased. Since the oxygen and hydrogen generation rate is on a mass flow basis independent of altitude, as the density decreases, the volume flow increases. On the oxygen side of the carbon dioxide concentrator, the recirculating flow produced by the blower and the aviator's respiratory flow will not change significantly with altitude. Between sea level and 43,000 feet the hydrogen volume flow will increase by a factor of six.

This change would affect the water balance on the carbon dioxide concentrator since the water carried away by the hydrogen is proportional to the volume flow of hydrogen. Therefore, whatever water balance control method is employed in the Carbon Dioxide Concentrator Subsystem, it must be designed with this effect in mind. In addition, if the hydrogen at the inlet to the concentrator has a lower dew point than the concentrator electrolyte, the large volume flow of relatively dry hydrogen could dry out the first cell or cells of the concentrator. Again, this possibility must be considered in the design of the carbon dioxide concentrator module and the overall system. Parametric tests of the concentrator module under these conditions would determine the existence and magnitude of this problem. Note that in the altitude test the first cell of the carbon dioxide concentrator dropped in voltage at 38,500 feet altitude. The cause is not known, however, the rapid recovery on returning to sea level indicates that the problem was not dry-out of the cell alone. It may have been due to a combination of a relatively dry cell and the low oxygen partial pressure.

Another significant effect of ambient pressure is the cooling of the system components. In the Flight Breadboard System, the carbon dioxide concentrator, electrolysis module, and electrical control subsystem package are all cooled by ambient air circulated by blowers. If the blowers are relatively constant speed machines, then the volume flow rate will not change appreciably with air density. Therefore, the cooling capacity of the blowers will decrease with altitude. Since the temperature controls are of an ON-OFF type we can expect the ON time to increase with altitude with a constant heat load. If the cooling system is found to be insufficient at the high altitude condition, then either the blower size must be increased or a variable speed blower must be used. Variable speed blowers with high slip motors are used for similar applications involving variable density. At the lower densities, the motor speed increases to pump a larger volume flow.

In the altitude test, the carbon dioxide concentrator module temperature was out of control at the high altitude condition but returned to the normal value upon return to sea level conditions. This blower, therefore, would require replacement for high altitude application. It is probable, however, that in an actual aircraft application, coolant would be supplied from the aircraft pneumatic system or a liquid cooling system which would not be sensitive to altitude.

CONCLUSIONS

1. The objectives of the Flight Test Program were successfully met.

2. System operation during the entire flight test program is considered satisfactory. Some of the problems identified and solved can be considered as de-bugging of the system.

3. The electrical leakage path in the electrolysis module was found and eliminated. This by-product of the Flight Test Program is very important to the performance of the water electrolysis module and the system.

4. No performance change in the system was evident over the course of the Flight Test Program.

5. Interfacing problems with the aircraft involved electrical grounding. In the future, the electrical circuitry in the laboratory should duplicate that of the aircraft as much as practically possible.

6. Gas sample analyses give no indication that the system would be unsafe for a man-in-the-loop test.

7. Maintaining water balance in the carbon dioxide concentrator module remains a condition requiring close control.

8. Servicing of the system (draining traps, filling the water tank, water cavity venting) presented no problems in the aircraft.

9. Replacement of major components (electrolysis module) and repair of components (Electrical Control Subsystem) were demonstrated to be rapidly and easily performed.

10. Preparations and planning for the Flight Test Program were totally adequate as evidenced by the lack of coordination and scheduling problems.

11. The design of the Flight Breadboard System and auxiliaries was satisfactory as evidenced by the satisfactory performance of the system.

12. At the conclusion of the test program the only unreliable components identified are the oxygen and carbon dioxide partial pressure sensors in the rebreather loop and the water feed solenoid valve.

13. The experience gained in the Flight Test Program is invaluable to the continuing development of electrochemical aircrew oxygen systems.

14. The Flight Test Program has successfully demonstrated the operation of an electrochemical aircrew oxygen system.

15. No limitations or design flaws were found which would negate the concept of this system for further development.

16. Long-term low temperature exposure ($-5^{\circ}F$) is not harmful to the operation of the Flight Breadboard System.

17. Low pressure (high altitude) does not adversely affect operation of the Flight Breadboard System.

RECOMMENDATIONS

1. Based on the overall results and experience of the Flight Breadboard System test program, continued development of electrochemical systems is recommended. Specifically, refinements in water electrolysis for oxygen generation and concentrators for carbon dioxide removal are recommended to reduce the size and weight of these components and to increase their capacities.

2. The design and development of control methods for maintaining water balance in the carbon dioxide concentrator is recommended.

3. The development of miniature pressure regulators for use in electrochemical systems is recommended.

4. Reliable miniature partial pressure sensors are needed as warning devices for rebreather type systems. These sensors should be identified as to reliability or special units developed.

5. Low temperature system problems (freezing) should be investigated and preheating or startup methods developed.

6. For any rebreather system, oxygen generation capacity may depend mainly on the aviator's mask leakage which could be a much larger magnitude than metabolic oxygen requirements. Therefore, the mask leakage problem warrants a significant effort towards solution.

7. Although no toxic level of substances have been found in the system, investigations to verify that the gases are free of toxic levels should be made. This could conveniently be done with animal exposure to the breathing gases in the system.

8. In order to increase system reliability and simplicitv a method to eliminate the water feed solenoid valve should be found. This could be done by locating the water reservoir below the electrolysis module so that gravity would keep the electrolysis module from flooding when the system is not in operation.

APPENDIX A-1

FBS FLIGHT TEST SEQUENCE

I. LABORATORY TESTING PRIOR TO DELIVERY FOR FLIGHT TESTING

1. Prior to startup, install one gas sample bottle at each sample tap: H_2, O_2 and rebreather lines. Have breathing machine set for 780cc tidal volume, 18 breaths/minute (40% inspiration ratio for all tests). The water coolant temperature should be adjusted to 65^oF.

2. Follow operating instructions in Flight Breadboard System instruction manual for system startup.

3. After startup, use normal O_2 bleed rate of 570cc/minute and CO_2 flow rate of 480cc/minute.

4. Operate system for four (4) hours. Monitor all meters and indicator lights for normal operating ranges. When system is in steady-state condition open valves to sample cylinders to obtain the gas samples.

5. Shut system down. Remove sample cylinders and cap up the sample ports on the system. Allow system to cool down to ambient temperature.

6. Start system. Maintain CO_2 flow rate of 480cc/minute. Set O_2 bleed rate at 430cc/minute and hold for 30 minutes.

7. Change O_2 bleed rate to 570cc/minute and hold for 30 minutes.

8. Change O_2 bleed rate to 710cc/minute and hold for 30 minutes.

9. Change O_2 bleed rate to 570cc/minute and hold until a total of four (4) hours of operation is obtained on this test. Shut system down.

10. Install one gas sample cylinder at each tap: H_2, O_2 and rebreather.

11. Start system. Set CO_2 flow rate at 480cc/minute and O_2 bleed rate at 570cc/minute. Operate for four (4) hours at these steady conditions. At three (3) hours after startup, open valves to the three sample cylinders to obtain gas samples. Shut system down after four (4) hours of operation.

12. Remove sample cylinders. Install a cylinder on the H_2 tap, three cylinders on the O_2 tap and three cylinders on the rebreather tap.

13. Start system. Set O_2 fleed rate for 570cc/minute and CO_2 flow rate at 480cc/minute. Turn on breathing machine adjusted to 18 breaths/minute (780cc tidal volume). Take the H_2 gas sample, one O_2 and one rebreather gas sample at end of the one-hour period.

14. Change breathing machine rate to 10 breaths/minute and hold for one hour. Take one O_2 and one rebreather gas sample at the end of the one-hour period.

15. Change breathing machine rate to 25 breaths/minute and hold for one hour. Take one O_2 and one rebreather gas sample at end of one-hour period.

16. Change breathing machine rate to 18 breaths/minute and hold until a total of four (4) hours has been accumulated since startup. Shut system down.

17. Remove gas sample cylinders and install a cylinder on the H_2 tap, three cylinders on the O_2 tap and three cylinders on the rebreather tap.

18. Start system. Set O_2 bleed rate for 570cc/minute and CO_2 flow rate at 480cc/minute. Operate for one hour. Take the H_2 gas sample, an O_2 sample and a rebreather gas sample.

19. Shut off CO_2 flow and breathing machine. Change tidal volume on breathing machine to 420cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480cc/minute. Operate for one (1) hour. Take an O_2 and a rebreather gas sample.

20. Shut off CO_2 flow and breathing machine. Change tidal volume to 900cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480cc/minute. Operate one hour. Take an O_2 and a rebreather gas sample.

21. Shut off CO_2 flow and breathing machine. Change tidal volume to 780cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480cc/minute. Operate until four (4) hours have been accumulated since startup. Shut down system.

22. Remove gas sample cylinders. Install a cylinder on the H_2 tap, one cylinder on the O_2 tap, and five cylinders on the rebreather tap. Have tools prepared for disconnecting the power to the recirculating loop blower during the next test.

23. Start system. Set O_2 bleed rate at 570cc/minute and CO_2 flow rate at 480cc/minute. Operate for 30 minutes. Take a H_2 gas sample, an O_2 sample and a rebreather gas sample.

24. Increase the CO_2 flow rate to 620cc/minute and hold for one (1) hour. Take a rebreather gas sample.

25. Return CO_2 flow rate to 480cc/minute. After 30 minutes take rebreather gas sample.

26. Disconnect power to recirculating blower and hold this condition for one (1) hour. Take a rebreather gas sample.

27. Reconnect the recirculating blower. Increase the O_2 bleed rate to 710cc/minute and hold for 30 minutes. Take a rebreather gas sample.

28. Return O_2 bleed rate to 570cc/minute. Shut off CO_2 flow and breathing machine for 5 minutes. Restart breathing machine and CO_2 flow.

29. Operate until four (4) hours have been accumulated since startup. Shut system down.

30. Repeat Steps 1 through 29.

31. Laboratory testing is completed.

II. PRE-FLIGHT GROUND CHECKOUT AT POINT MUGU

1. Assemble and interconnect Flight Breadboard System with auxiliaries and ground power conversion unit. Prior to startup install one gas sample bottle at each sample tap: H_2, O_2 and rebreather lines. Have breathing machine set for 780cc tidal volume, 18 breaths/minute and 40 percent inspiration ratio. The water coolant temperature should be adjusted to $65^{o}F$.

2. Follow operating instructions in Flight Breadboard System instruction manual for system startup.

3. After startup, use normal O_2 bleed rate of 570cc/minute and CO_2 flow rate of 480cc/minute.

4. Operate system for four (4) hours. Monitor all meters and indicator lights for normal operating ranges. When system is in a steady-state condition, open valves to sample cylinders to obtain the gas samples.

5. Shut system down. Remove sample cylinders and cap up the sample ports on the system.

6. Install Flight Breadboard System and accessories in aircraft and connect system to aircraft power. Start system. Maintain CO_2 flow rate of 480cc/minute. Set O_2 bleed rate at 430cc/minute and hold for 30 minutes.

7. Change O_2 bleed rate to 570cc/minute and hold for 30 minutes.

8. Change O_2 bleed rate to 710cc/minute and hold for 30 minutes. Shut system down.

III. FLIGHT TESTING

1. Install one gas sample cylinder at each tap: H_2, O_2 and rebreather.

2. Flight Test 1: Start aircraft. Start system. Set CO_2 flow rate at 480cc/minute and O_2 bleed rate at 570cc/minute. Set breathing machine for 780cc tidal volume, 18 breaths/minute and 40 percent inspiration ratio. Operate system for four (4) hours at these steady conditions. At three (3) hours after startup, open valves to the three sample cylinders to obtain gas samples. Shut system down after four (4) hours of operation.

3. Remove sample cylinders. Install a cylinder on the H_2 tap, three cylinders on the O_2 tap, and three cylinders on the rebreather tap.

4. Flight Test 2: Start system, set O_2 bleed rate for 570cc/minute and CO_2 flow rate at 480cc/minute, set breathing machine for 780cc tidal volume (18 breaths/minute and 40 percent inspiration ratio), and operate system for one (1) hour. Take the H_2 gas sample, one O_2 and one rebreather gas sample at end of the one-hour period.

5. Change breathing machine rate to 10 breaths/minute and hold for one (1) hour. Take one O_2 and one rebreather gas sample at the end of the one-hour period.

6. Change breathing machine rate to 25 breaths/minute and hold for one (1) hour. Take one O_2 and one rebreather gas sample at end of one-hour period.

7. Change breathing machine rate to 18 breaths/minute and hold until a total of four (4) hours has been accumulated since startup. Shut system down.

8. Remove gas sample cylinders and install a cylinder on the H_2 tap, three cylinders on the O_2 tap and three cylinders on the rebreather tap.

9. Flight Test 3: Start system. Set O_2 bleed rate for 570cc/minute and CO_2 flow rate at 480cc/minute, set breathing machine for 780cc tidal volume (18 breaths/minute and 40 percent inspiration ratio), and operate system for one (1) hour. Take the H_2 gas sample, an O_2 sample and a rebreather gas sample.

10. Shut off CO_2 flow and breathing machine. Change tidal volume on breathing machine to 420cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480cc/minute. Operate for one (1) hour. Take an O_2 and a rebreather gas sample.

11. Shut off CO_2 flow and breathing machine. Change tidal volume to 900cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480cc/minute. Operate one (1) hour. Take an O_2 and a rebreather gas sample.

12. Shut off CO_2 flow and breathing machine. Change tidal volume to 780cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480cc/minute. Operate until four (4) hours have been accumulated since startup. Shut down system.

13. Remove gas sample cylinders. Install a cylinder on the H_2 tap, one cylinder on the O_2 tap, and five cylinders on the rebreather tap. Have tools prepared for disconnecting the power to the recirculating loop blower during the next test.

14. Flight Test 4: Start system. Set O_2 bleed rate at 570cc/minute and CO_2 flow rate at 480cc/minute, set breathing machine for 780cc tidal volume (18 breaths/minute and 40 percent inspiration ratio), and operate system for thirty (30) minutes. Take a H_2 gas sample, an O_2 sample and a rebreather gas sample.

15. Increase the CO_2 flow rate to 620cc/minute and hold for one (1) hour. Take a rebreather gas sample.

16. Return CO_2 flow rate to 480cc/minute. After 30 minutes, take rebreather gas sample.

17. Disconnect power to recirculating blower and hold this condition for one (1) hour. Take a rebreather gas sample.

18. Reconnect the recirculating blower. Increase the O_2 bleed rate to 710cc/minute and hold for 30 minutes. Take a rebreather gas sample.

19. Return O_2 bleed rate to 570cc/minute. Shut off CO_2 flow and breathing machine for five (5) minutes. Restart breathing machine and CO_2 flow.

20. Remove gas sample cylinders. Remove Flight Breadboard System and auxiliaries from aircraft. Install a sample cylinder in the H_2 tap, one cylinder on the O_2 tap and one cylinder on the rebreather tap. Connect the ground power unit to the Flight Breadboard System.

21. Post-flight ground test: Start up and operate the system at design conditions for one (1) hour. Obtain the three gas samples. Shut system down.

22. Remove the gas sample cylinders and cap the sample ports.

23. Flight testing is completed.

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