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AIRCREW OXYGEN SYSTEM DEVELOPMENT FLIGHT TEST REPORT

by

R.A. KIRALY AND A.D. BABINSKY

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PREPARED UNDER CONTRACT NO. NAS2-4444

by

TRW INC.
CLEVELAND, OHIO

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

DECEMBER 1969

TRW
MECHANICAL PRODUCTS DIVISION

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FOREWORD

The flight test 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. E. 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.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

AIRCREW OXYGEN SYSTEM DEVELOPMENT
FLIGHT TEST REPORT

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R. J. Kiraly and A. D. Babinsky

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 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 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. The Aircrew Oxygen System FBS consists of four primary subsystems: 1) Water Electrolysis, 2) Carbon Dioxide Concentrator, 3) Rebreather and 4) Electrical Control. 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 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 actual flight testing took place at Point Mugu 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 required. 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 co-operation 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.

Major conclusions reached as a result of the Flight 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, and 5) no limitations or design flaws were found which would negate the concept of this system for further development.

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, thereby minimizing the need for ground support facilities and reduce the time and effort required for servicing.

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.

PURPOSE

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 co-ordination and working experience with a user service (Navy);

4. To identify interface problems between the aircraft and the FBS;

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.

TEST EQUIPMENT DESCRIPTION

Aircraft

The FBS was flight-tested aboard a Navy C-131F aircraft at the Pacific Missile Range, Point Mugu, California. The choice of this aircraft was due primarily to schedule and availability of the aircraft. Ease of installation and operation in the aircraft were also major considerations. The use of this aircraft met the objectives of the Flight Test Program.

Flight Breadboard System

Figure 1 is a photograph of the FBS. The prime consideration used in packaging the system is maximum component accessibility with secondary emphasis on minimizing package volume. No auxiliary equipment was located within the system package. The FBS is mounted in a tubular, aluminum frame, 26" wide, 25" deep and 25" high. The Aircrew Oxygen System as shown in Figure 2 (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. Figures 3 through 6 show the locations of the major components in the FBS.

Water Electrolysis Subsystem (WES). - The Water Electrolysis Subsystem (WES) is composed of the electrolysis module, the water reservoir, oxygen pressure control, pressure balance regulation, the temperature control, and water vapor 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 differential pressure regulator in the oxygen line and the back-pressure regulator in the hydrogen line.

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 with a blower. The temperature controller is an ON-OFF control for the blower. Air is circulated in the module shroud by the blower and flows

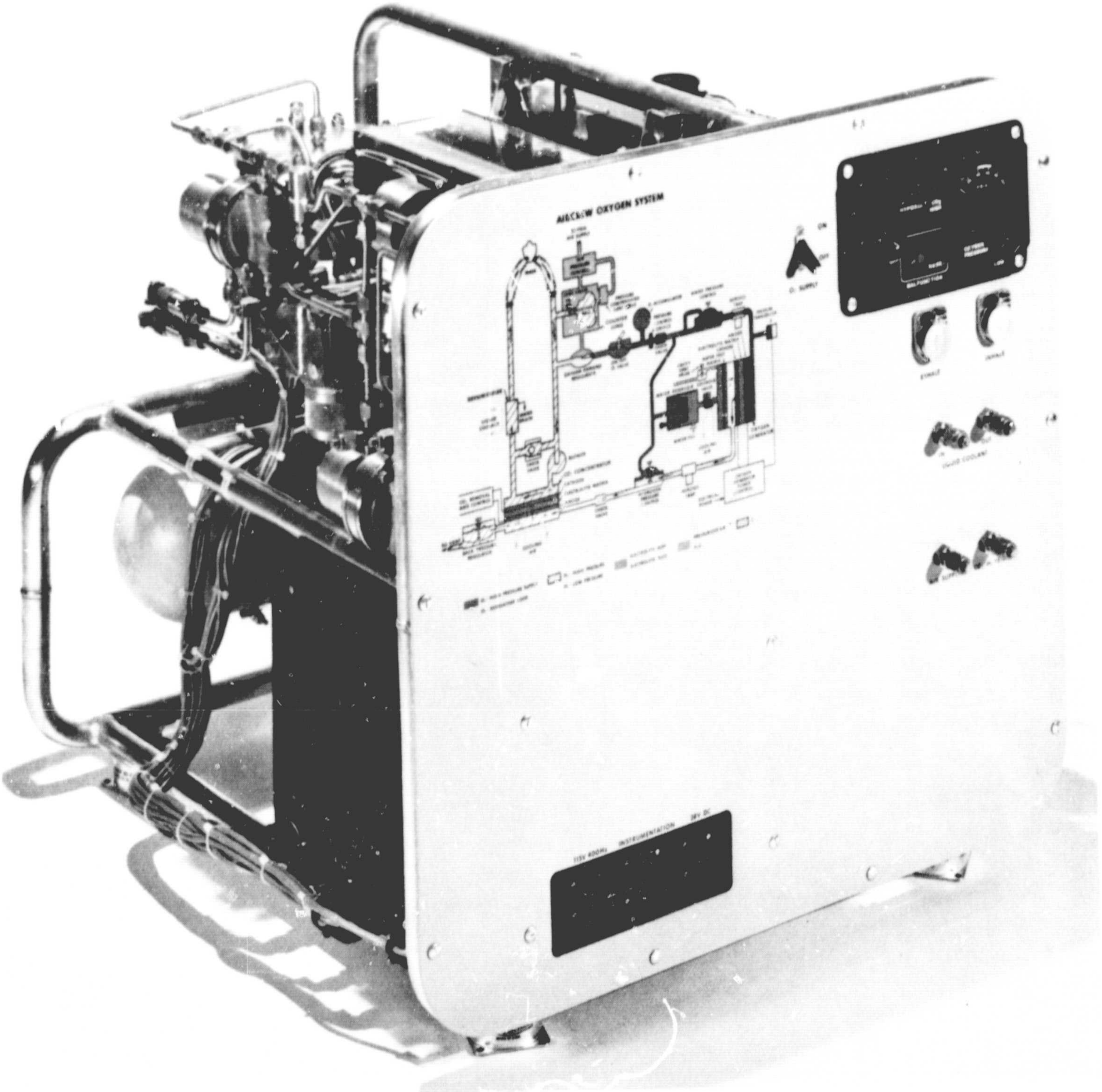

FIGURE 1 FLIGHT BREADBOARD SYSTEM

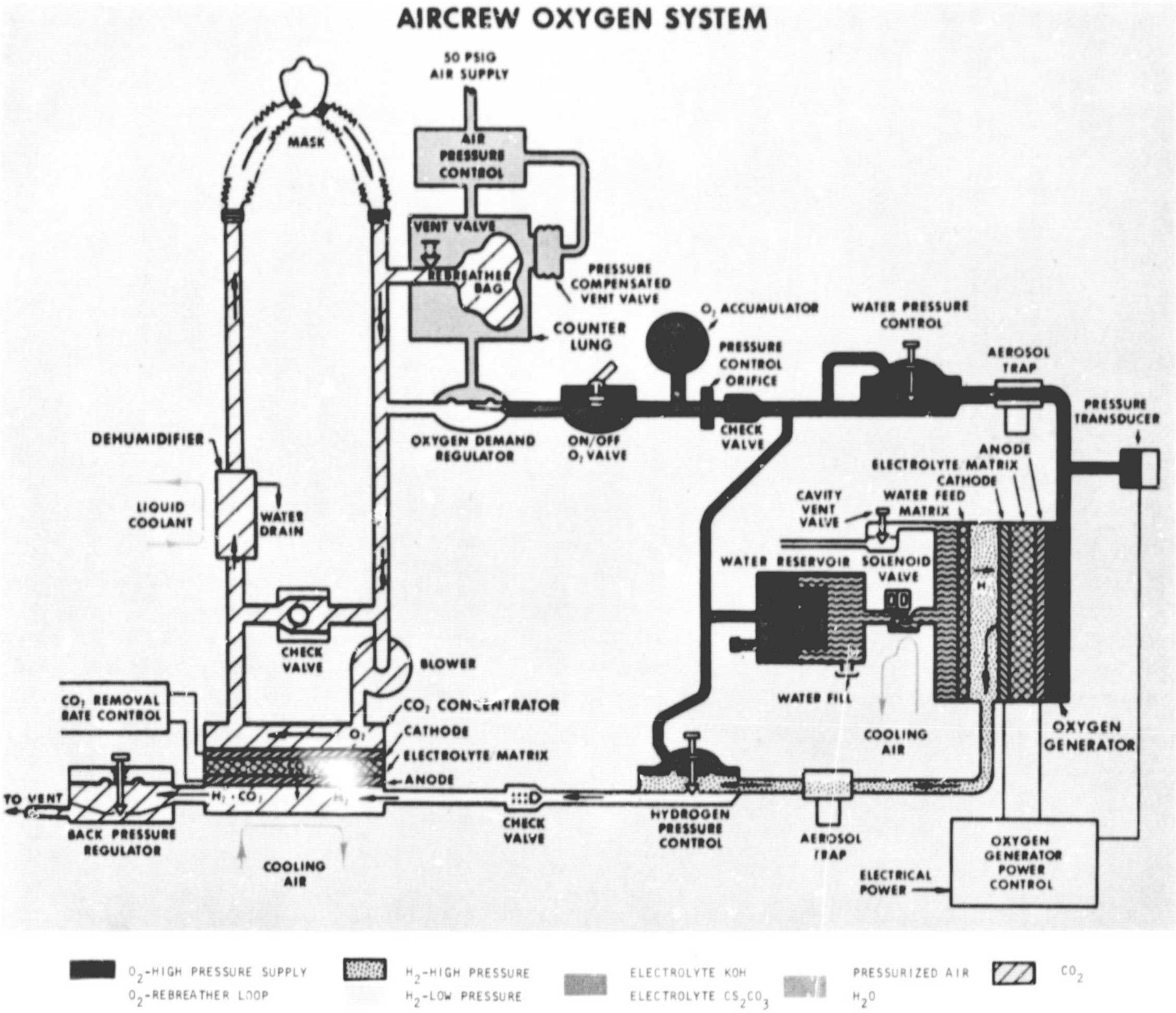

FIGURE 2 AIRCREW OXYGEN FLIGHT BREADBOARD SYSTEM SCHEMATIC

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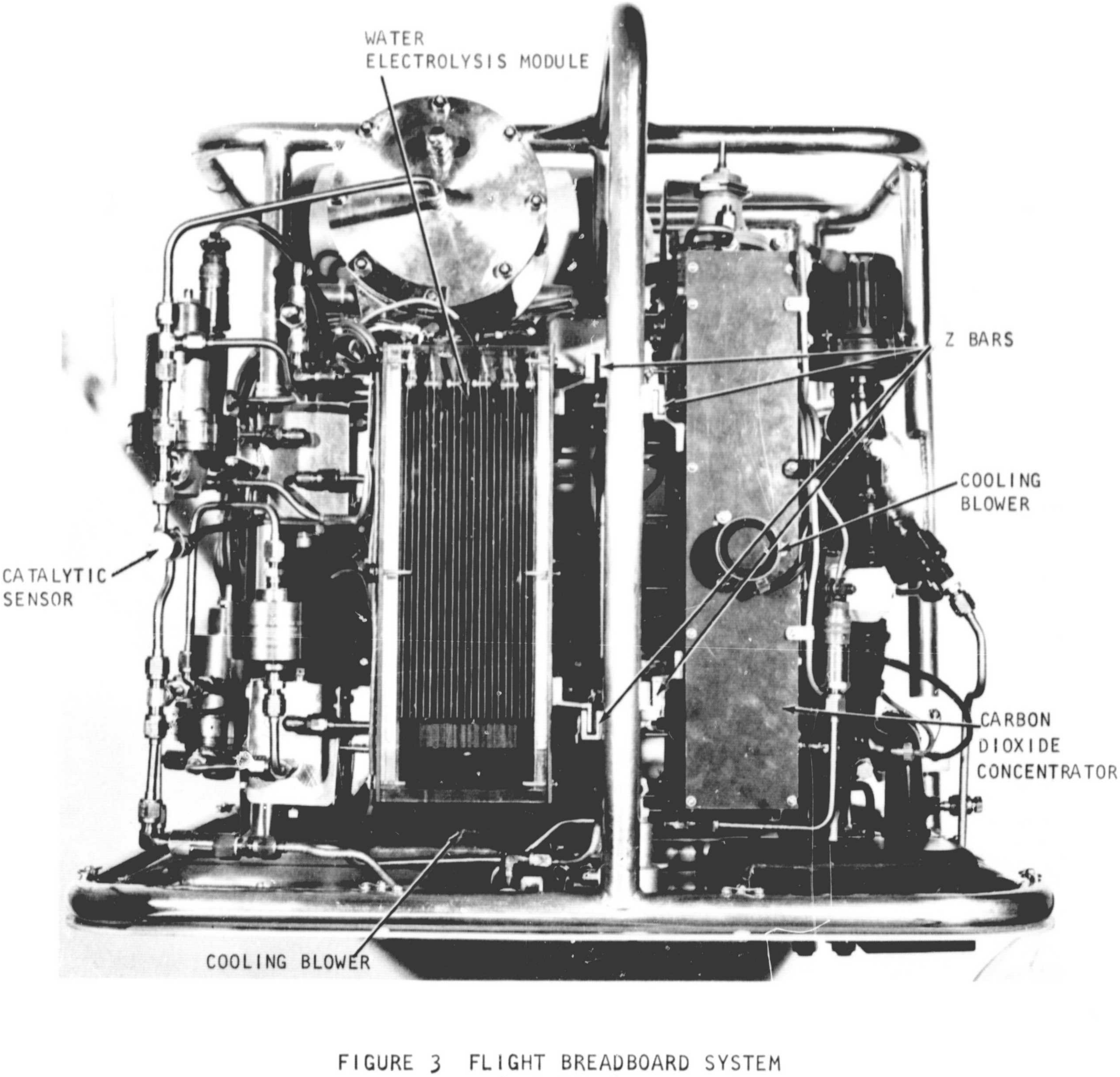

FIGURE 3 FLIGHT BREADBOARD SYSTEM
(TOP VIEW)

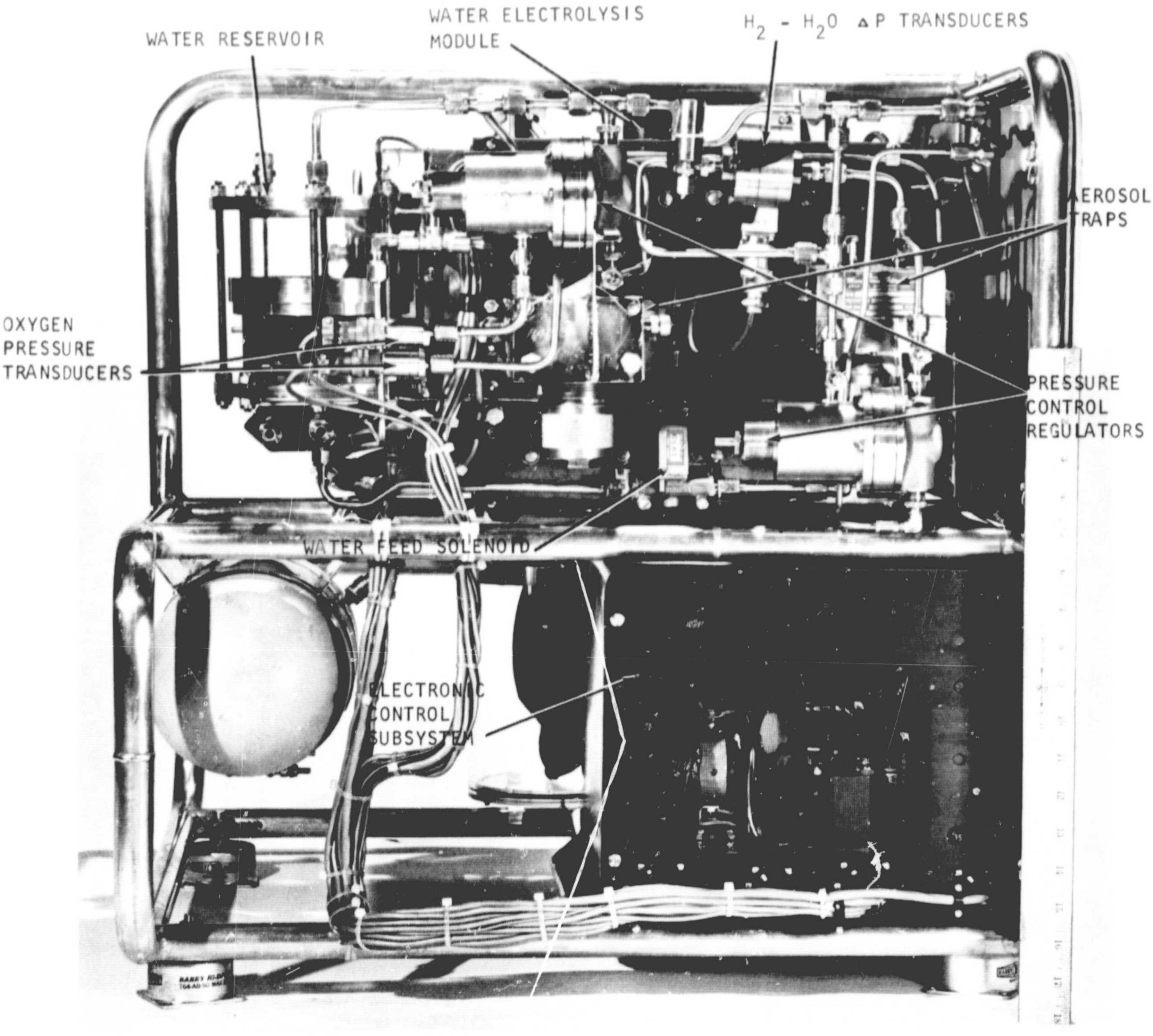

FIGURE 4 FLIGHT BREADBOARD SYSTEM
(LEFT SIDE VIEW)

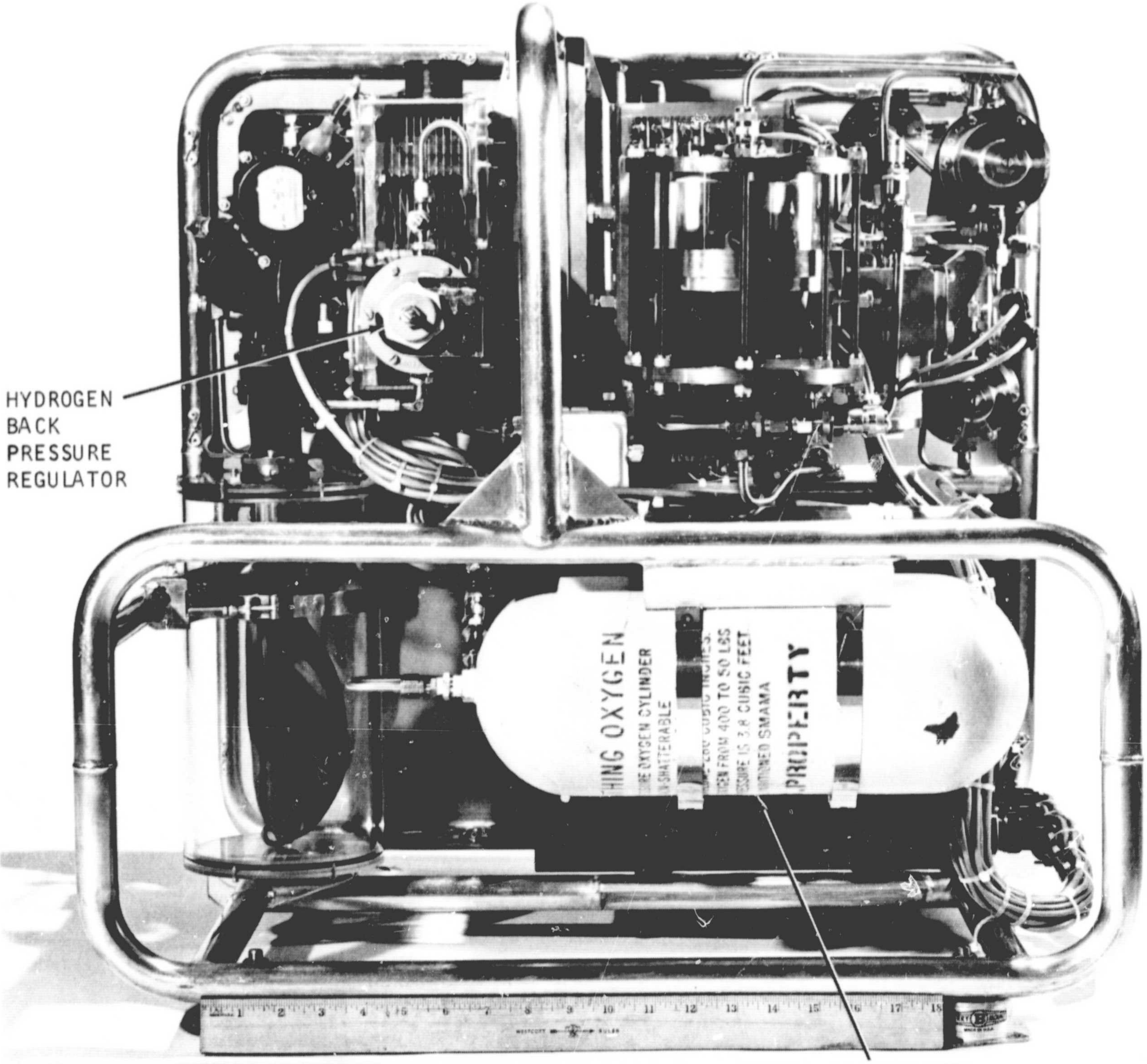

FIGURE 5 FLIGHT BREADBOARD SYSTEM
(REAR VIEW)

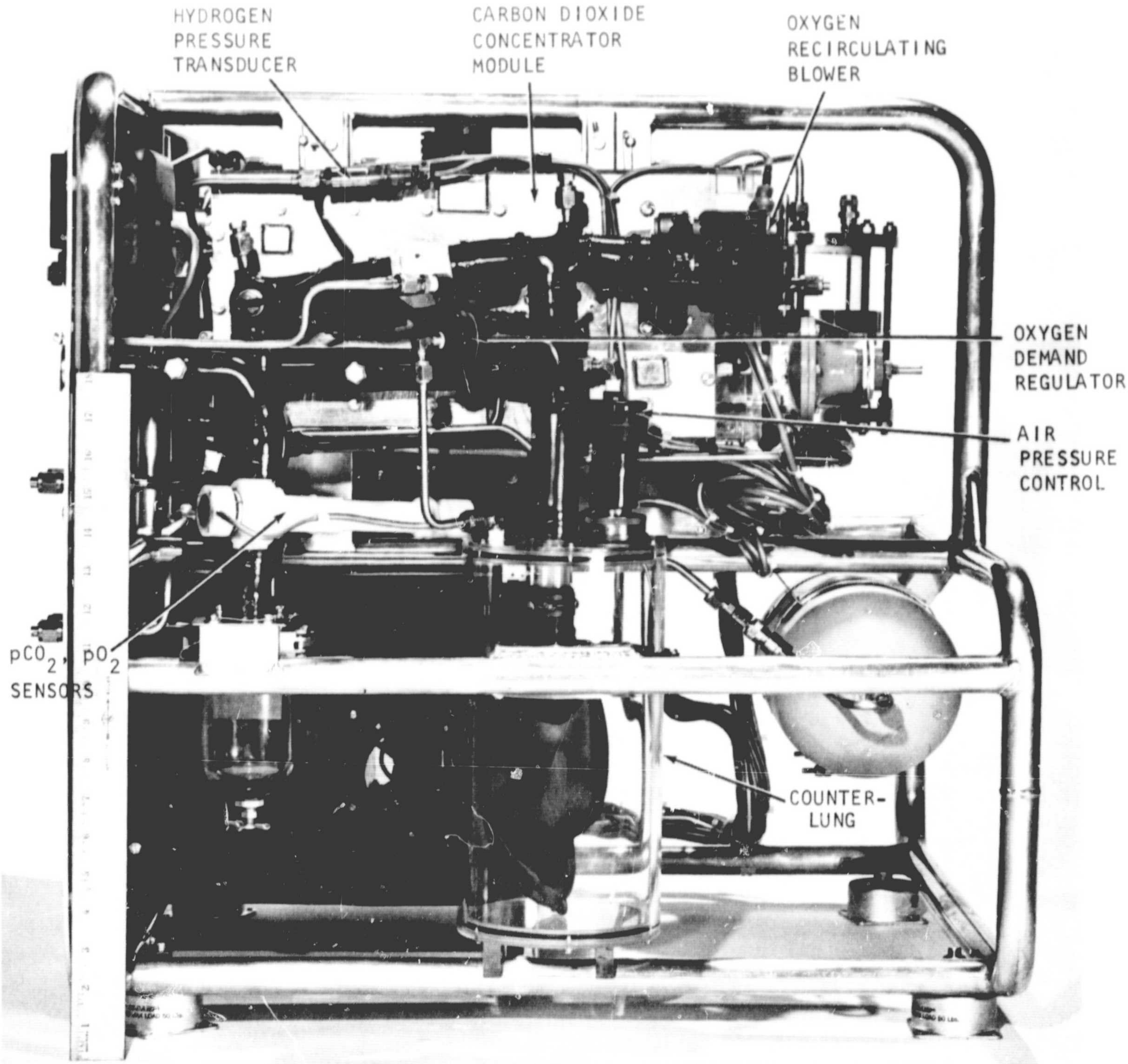

FIGURE 6 FLIGHT BREADBOARD SYSTEM
(RIGHT SIDE VIEW)

through the fins, thus providing cooling as required to maintain the set point temperature.

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 pre-set 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 retain the excess moisture and any aerosol generated. Check valves prevent backflow of gas 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.

Carbon Dioxide Concentrator Subsystem (CDCS). - The Carbon Dioxide Concentrator Subsystem (CDCS) is composed of the carbon dioxide concentrator module, oxygen circulating loop including a blower and check valve, 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 cooling system incorporates a temperature controller which operates an air blower when the concentrator reaches a set temperature.

Rebreather Subsystem (RS). - The Rebreather Subsystem (RS) 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°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.

Electrical Control Subsystem (ECS). - The Electrical Control Subsystem (ECS) 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 pre-set 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 pre-set 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.

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.

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.

Auxiliary Equipment

Breathing Simulator. - The breathing simulator, Figure 7, simulates the pilot's inputs to the system. A breathing machine simulates respiration and has adjustable tidal volume, inspiration/respiration ratio and breathing rate. A vacuum

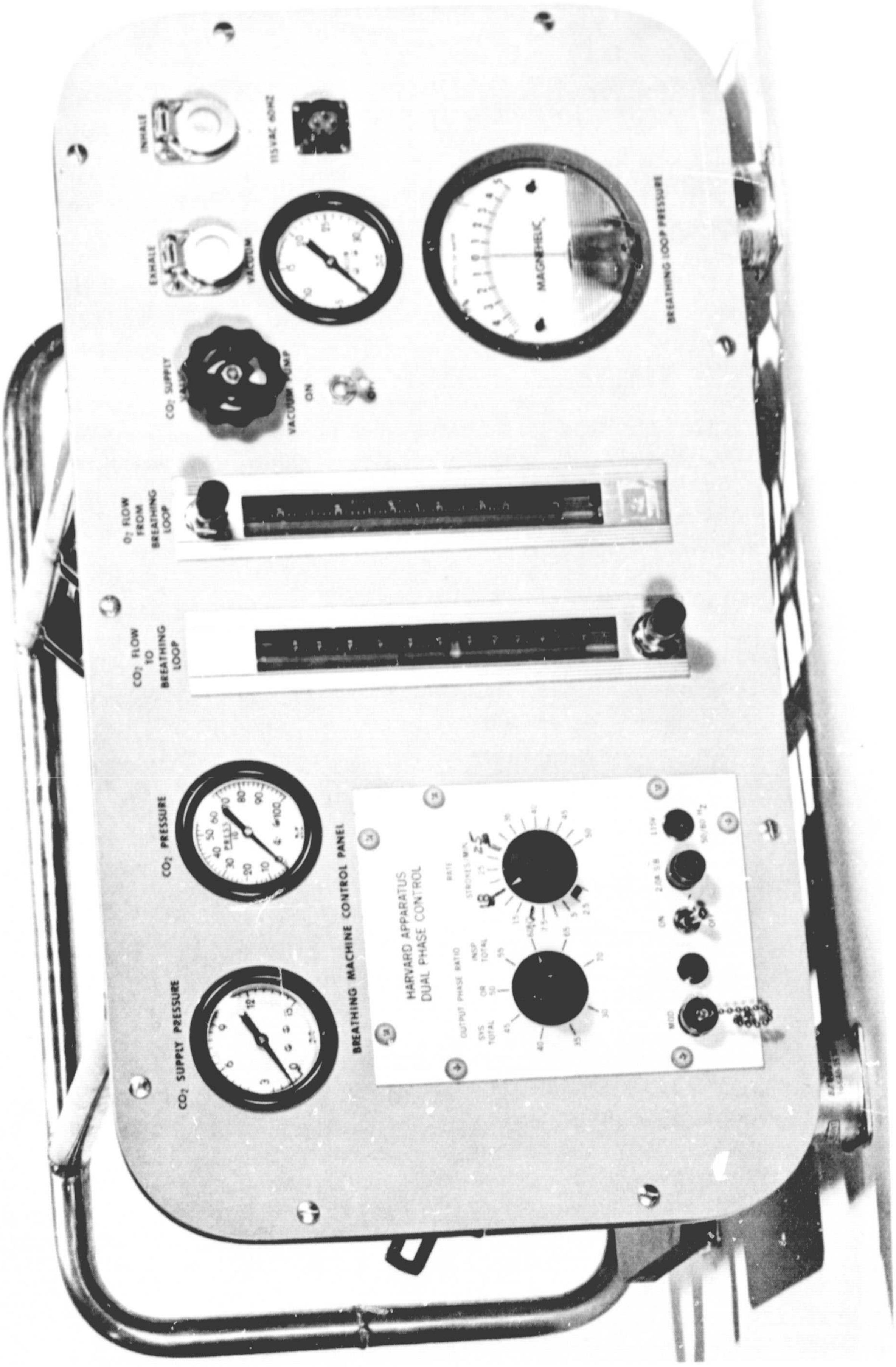

FIGURE 7 BREATHING SIMULATOR

pump removes 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. A rack capable of holding five 500 ml gas sample bottles is mounted on the rear of the package. A manifold and valving necessary for obtaining rebreather loop gas samples are provided.

<u>Aircraft Resources Adapter</u>. - The FBS requires 50 psig air at 3 CFM and liquid coolant. These services are provided by the aircraft resources adapter, Figure 8. 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° to 100°F. The air supply consists of a compressor, accumulator, pressure relief valve and pressure regulator. The compressor and accumulator are operated to provide 75 psig air to the regulator. This pressure is then dropped to 50 psig by the pressure regulator for use in the counter-lung.

<u>Flight Instrumentation Package</u>. - The Flight Instrumentation Package contains all the readouts, meters, indicators and controls to operate and monitor the operation of the FBS. The system condition readouts consists of thirty-nine (39) meters.

A running time meter is used to indicate total operating hours. Eight (8) system condition 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 FBS can be operated and monitored from this Flight Instrumentation Package. Figure 9 is a photograph of the Flight Instrumentation Package.

<u>Flight Data Acquisition Unit</u>. - The data recorder is shown in Figure 10. This machine puts four tracks of analog information on 1/4" 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. Also, a voice track is used for running commentary during the test.

The signals from the FBS are fed to the tape recorder through an amplifier box which converts the signals from the FBS to the 5 volt level required by the tape recorder on the multiplex channels.

<u>Ground Power Conversion Unit</u>. - Because the FBS was designed to operate on aircraft power, it requires 28 volts DC and 115V, 400 Hz AC power. For this reason a ground power conversion unit was assembled using standard components. With this unit, the FBS can be operated anywhere in which there is 115V 60 cycles available.

The ground power conversion unit consists of a 50 amp, 28 volt DC power supply and a 200Va, 115 volt, [illegible] 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 11 is a photograph of this assembly.

FIGURE 8 AIRCRAFT RESOURCES ADAPTER

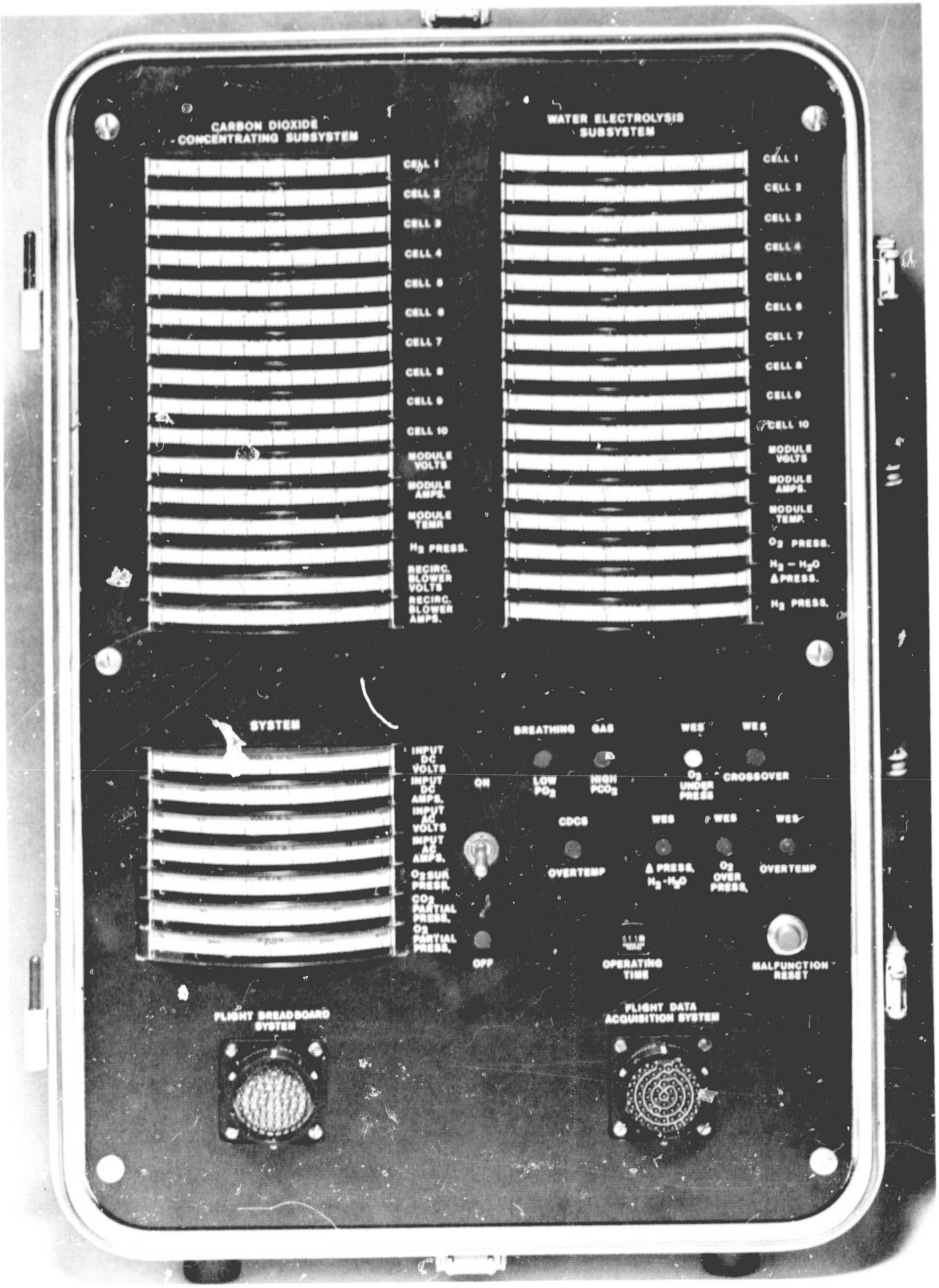

FIGURE 9 FLIGHT INSTRUMENTATION PACKAGE

FIGURE 10 FLIGHT DATA ACQUISITION UNIT

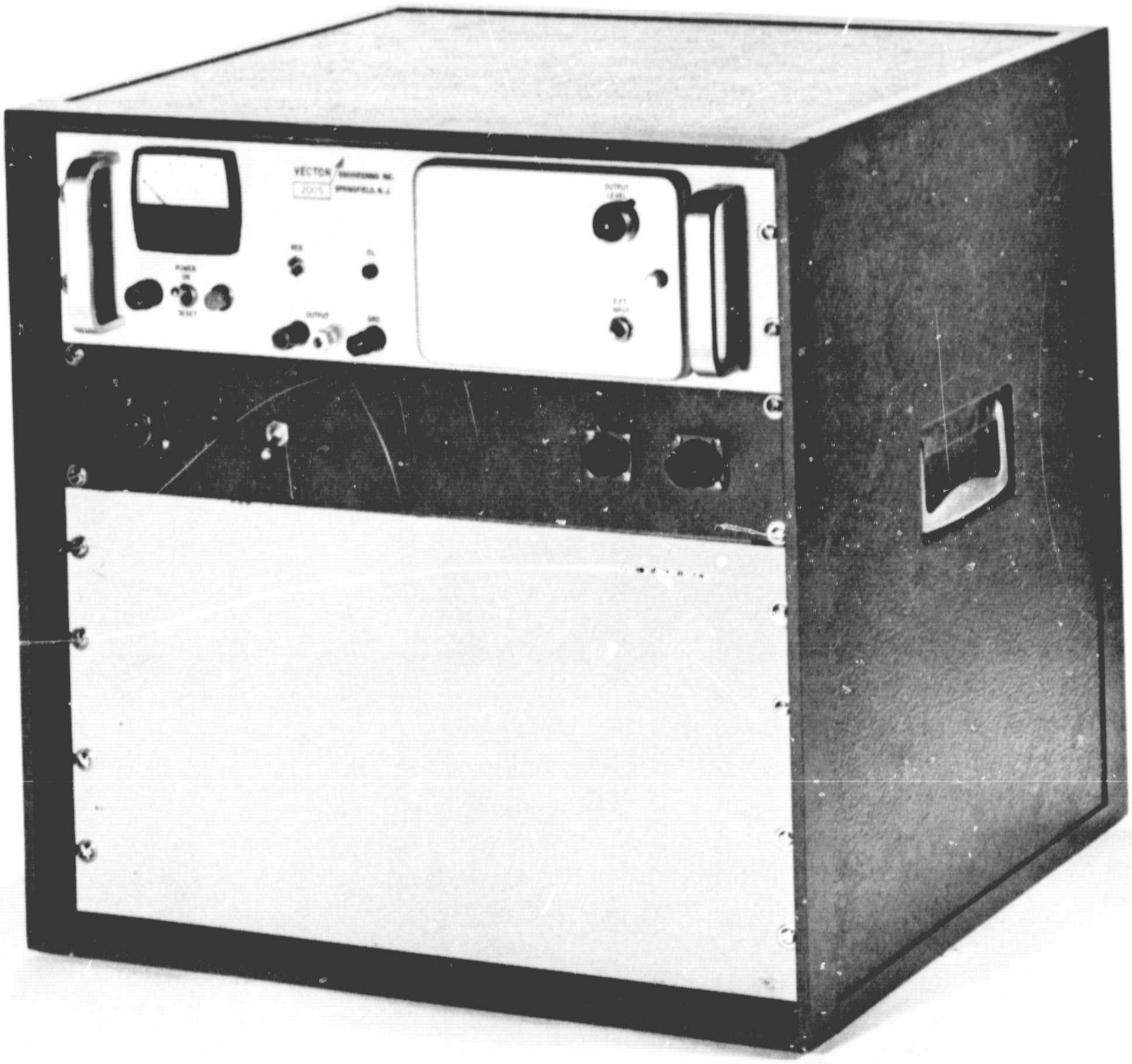

FIGURE 11 GROUND POWER CONVERSION UNIT

System Spare Parts . - To support the flight test program of the FBS, 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.

TEST PLAN AND PROCEDURES

The complete Flight Test Program is summarized in Table I, 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 780 cc. 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 I

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 FBS 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 12 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 9, 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 are used to mount equipment in the aircraft. The breadboard system and the breathing simulator were mounted in one rack shown in Figure 13 while the resources adapter, the instrumentation package and the tape recorder were mounted in the second rack shown in Figure 14. 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.

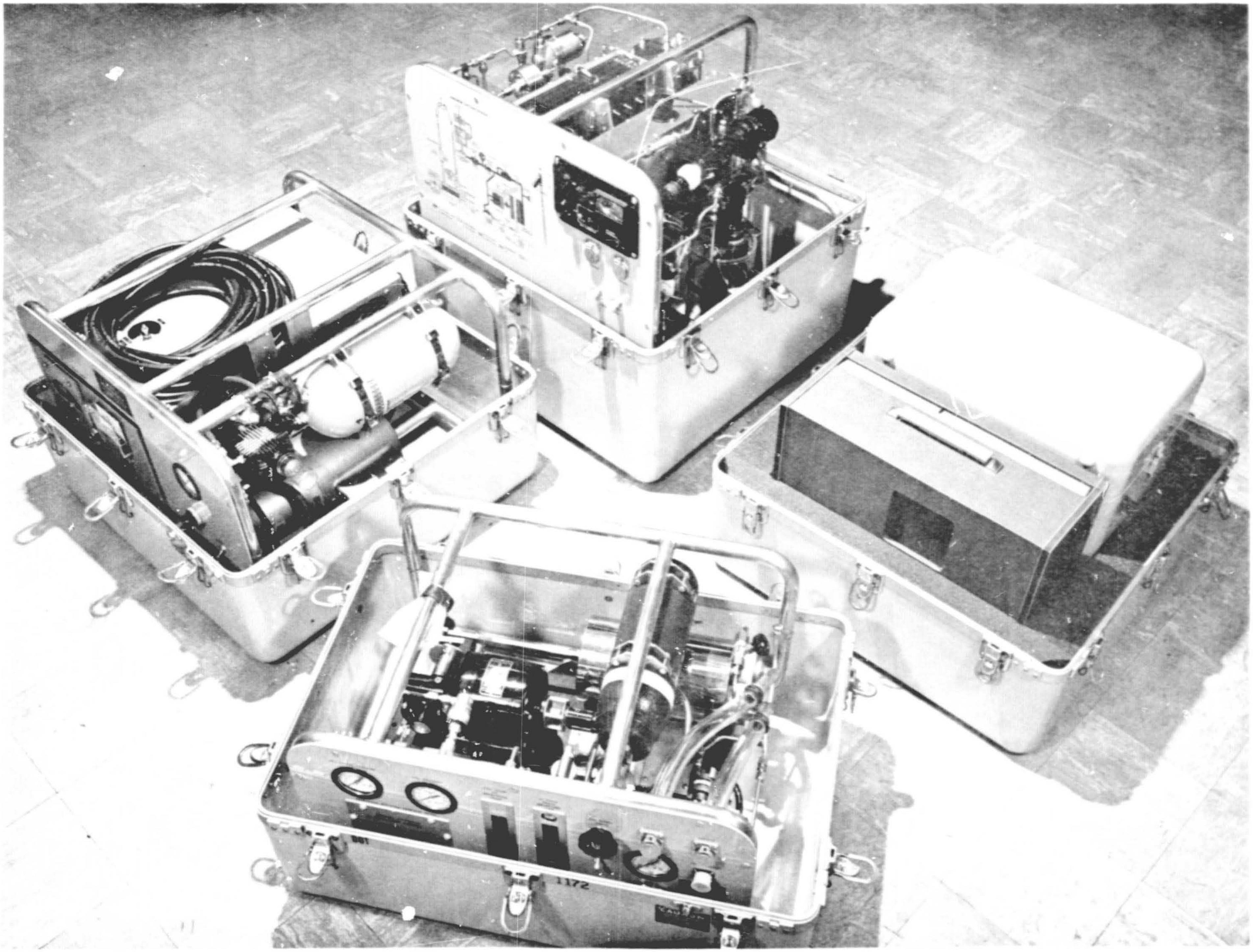

FIGURE 12 FLIGHT BREADBOARD SYSTEM AND AUXILIARY EQUIPMENT IN SHIPPING CONTAINERS

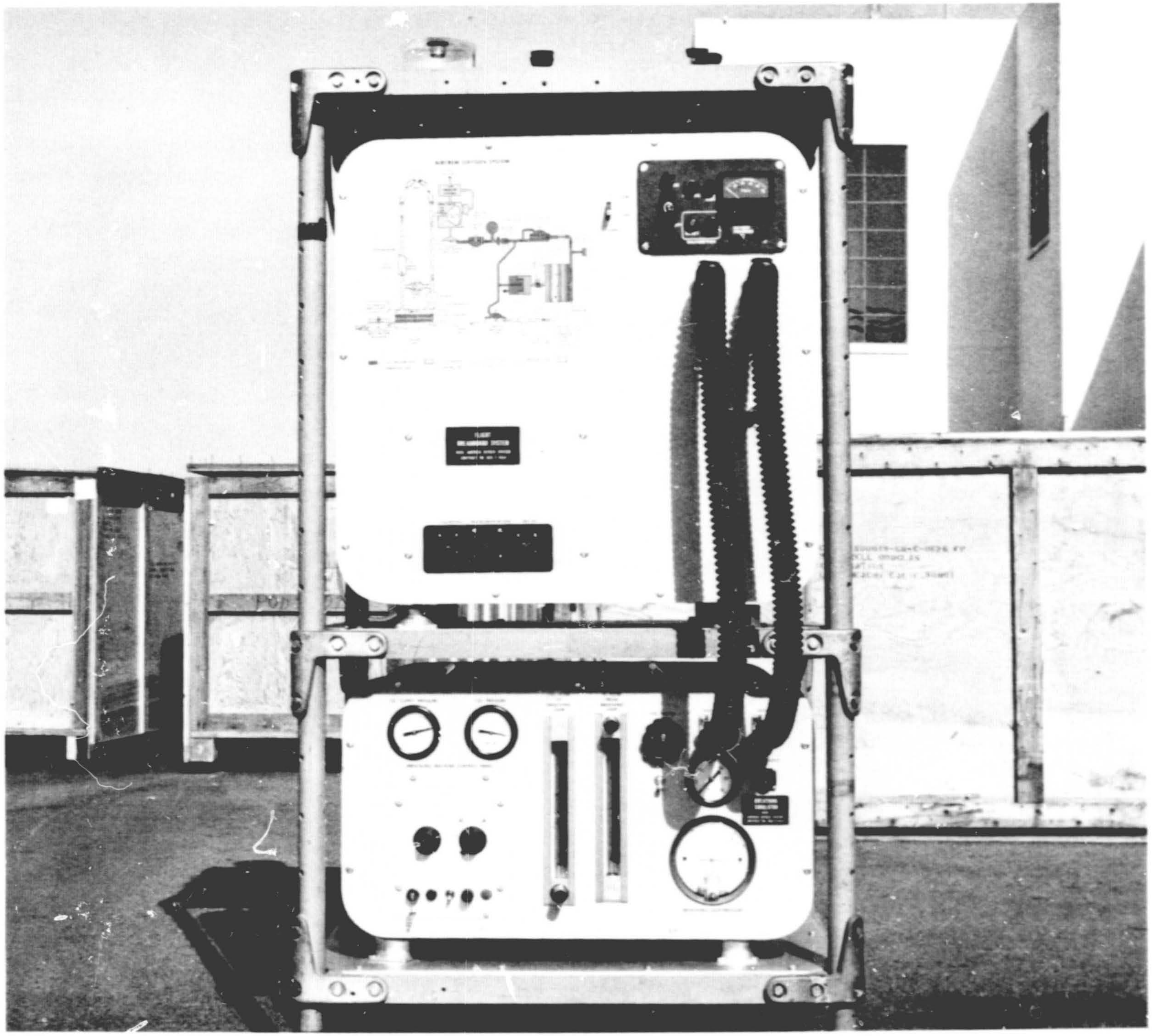

FIGURE 13 FLIGHT BREADBOARD SYSTEM AND BREATHING SIMULATOR MOUNTED IN AIRCRAFT RACK

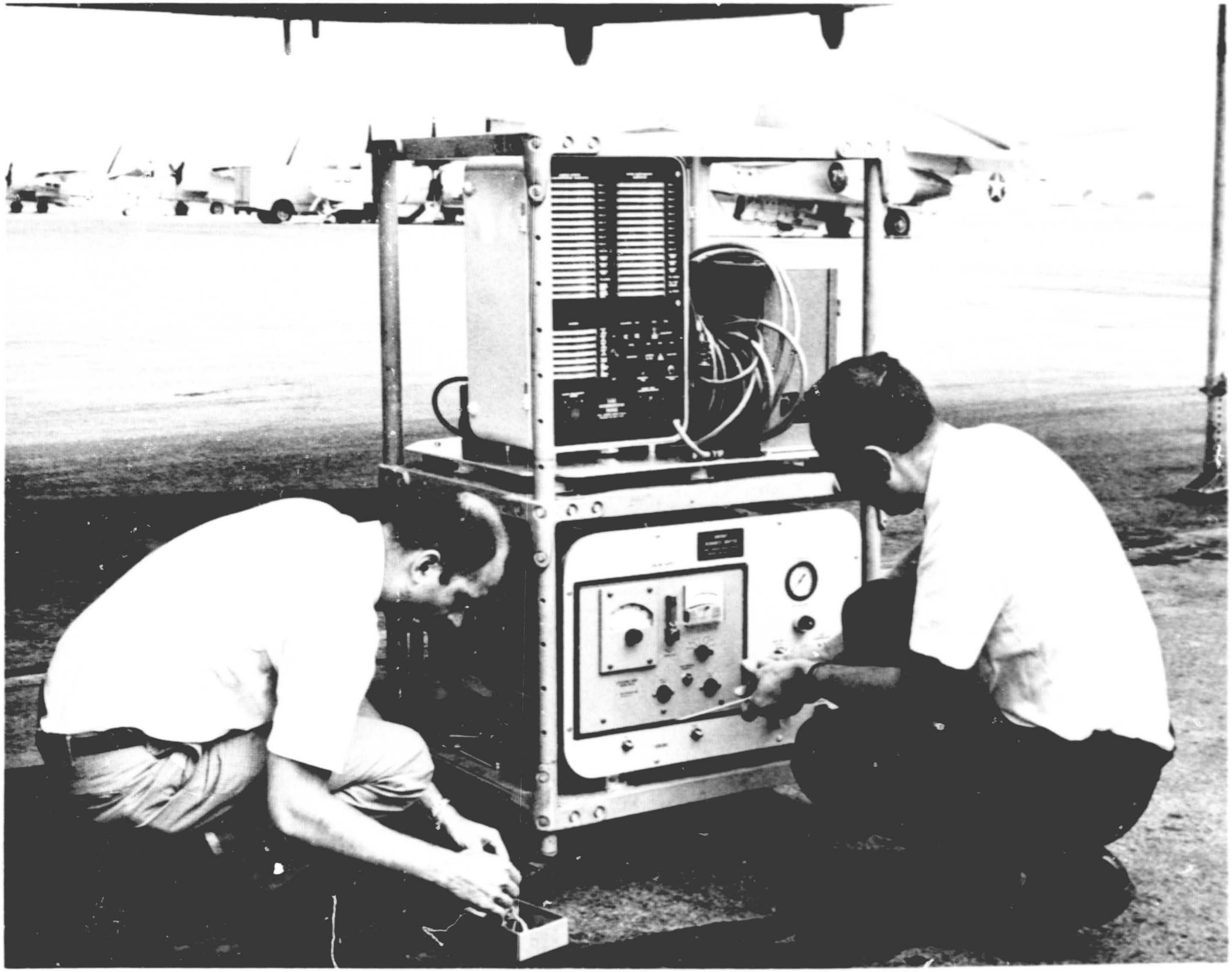

FIGURE 14 INSTALLATION OF INSTRUMENTATION AND AIRCRAFT RESOURCES ADAPTER IN AIRCRAFT RACK

The racks containing the FBS and auxiliary equipment were installed in the aircraft on July 15. Figure 15 shows the racks being lifted into the aircraft. Figure 16 is a view towards the rear of the aircraft showing the racks installed. Figure 17 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. 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 is caused by stray electrical currents flowing through the electrolyte to ground in the system frame. The result of the gas generation is the gradual accumulation of gas in the water feed cavities which then decreases 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 FBS 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 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

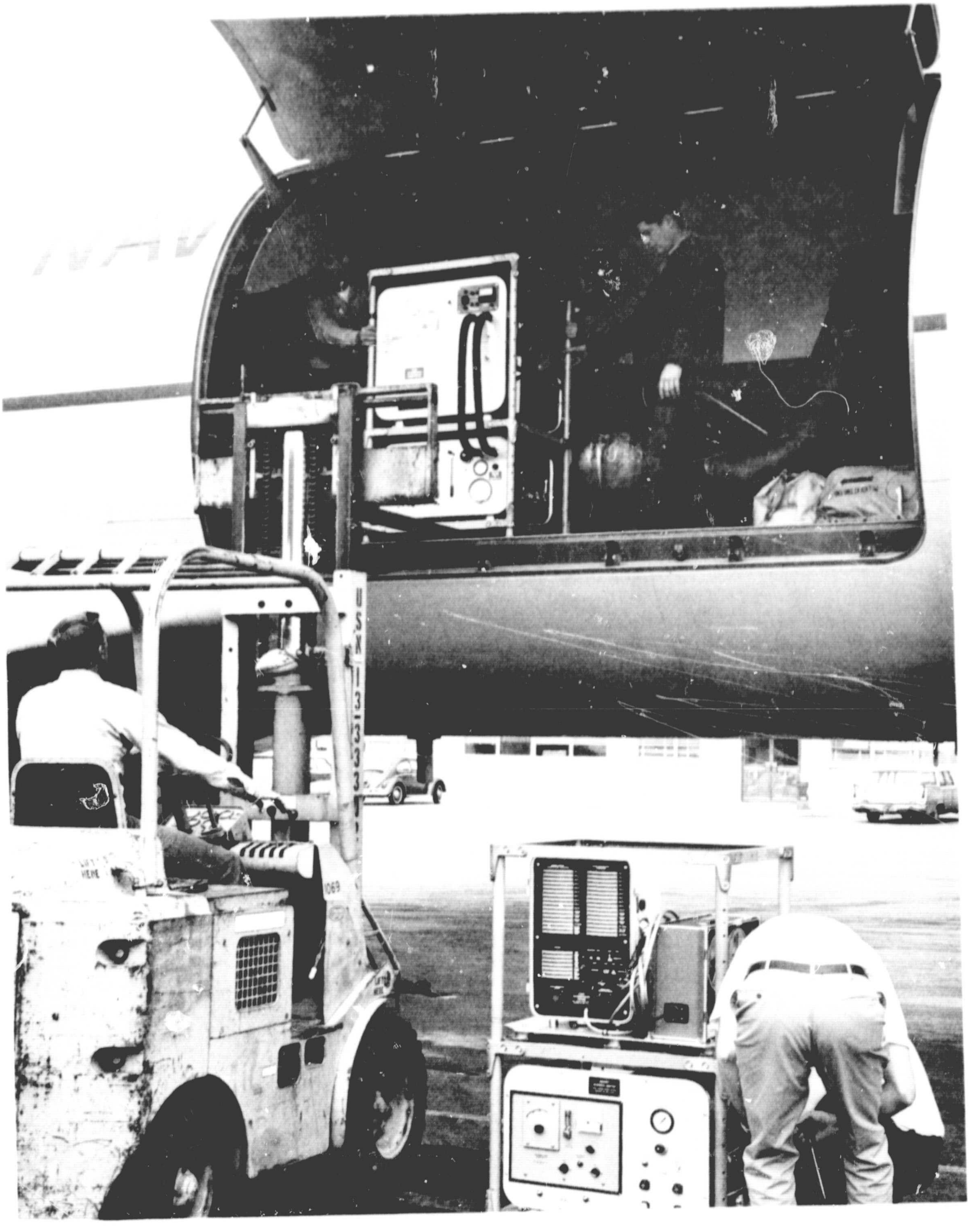

FIGURE 15 LOADING EQUIPMENT INTO C-131 AIRCRAFT

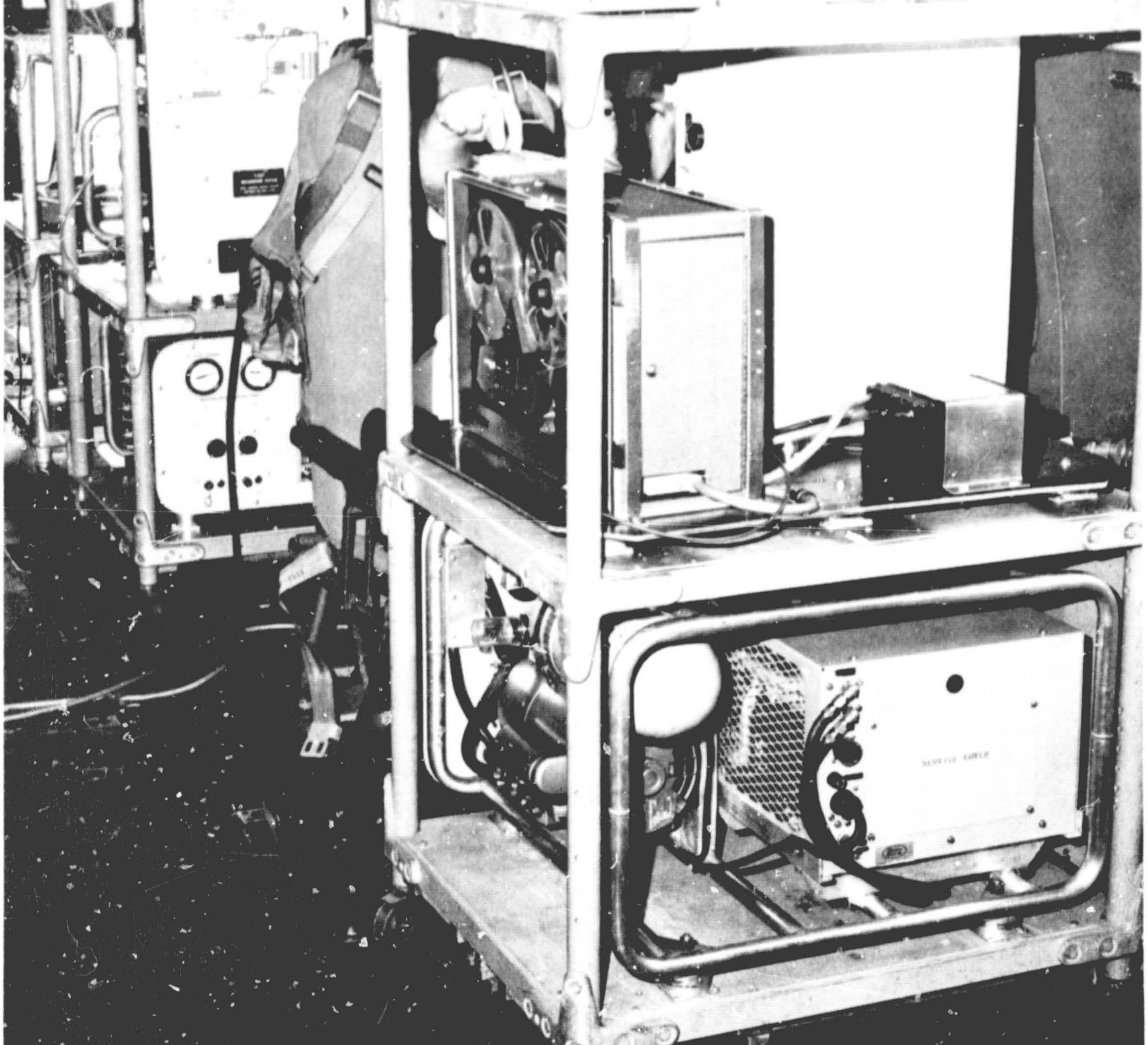

FIGURE 16 AFT VIEW OF EQUIPMENT INSTALLATION IN AIRCRAFT

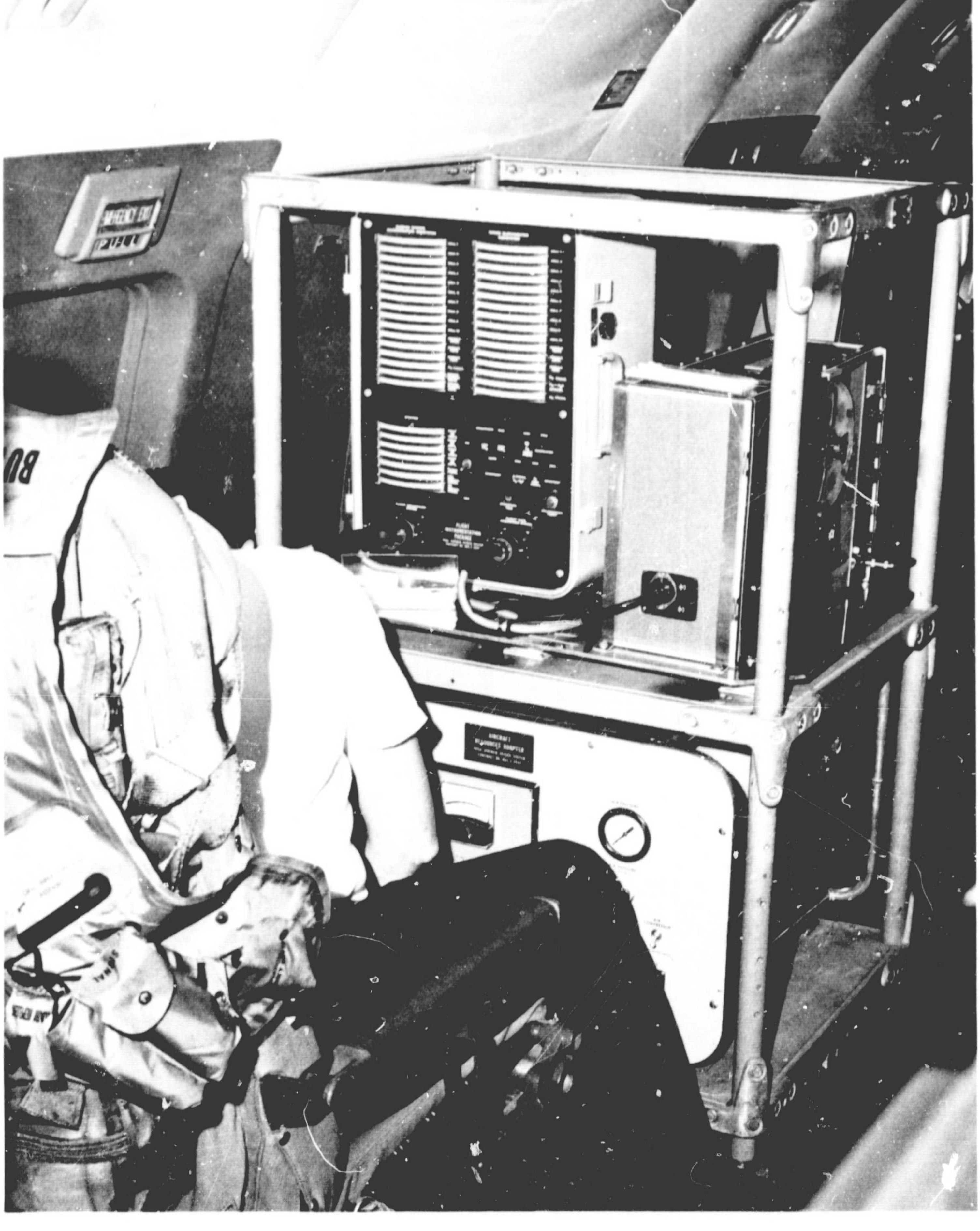

FIGURE 17 FORE VIEW OF EQUIPMENT INSTALLATION IN AIRCRAFT

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, requires 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 is 0.010 inch thick. It is 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 FBS 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 FBS 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 II through V. The data and performance of the FBS 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 indicates 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 is evident in the post-flight tests. This is 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-powered 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 II through V. 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 VI 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 VII.

The samples in Table VII 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 II

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. - °F	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. - °F	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. - °F		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 III

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 IV

FLIGHT BREADBOARD SYSTEM DATA - FLIGHT TESTS

					INSTALLED IN C-131 - 7/15/69			FLIGHT TEST #1		FLIGHT TEST #2			FLIGHT TEST #3				FLIGHT TEST #4					FLIGHT TEST #5		
Date		7/11	7/11	7/11	7/15	7/17	7/17	7/17	7/17	7/13	7/18	7/18	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.		4	4	4	6	6	8	2	2	4	5	6	9	9	10	11	14	14	14	16	17	-	18	-
Operating Time - Hours		69.6	70.7	71.9	75.7	76.9	77.9	79.0	80	81.6	82.5	83.4	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	22.4	24.8	21.6	17.8	20.1	18	19	19.6	21.3	21.3	23.4	20.1	21	21	21.2	20.4	20.4	21	21.5	21.3	20.6	23.2	21.6
	Module Amps	21	21	11	14	14.5	23	18	19	17.5	19	25.5	22.5	22.5	18	18	19	19	19	19	17	17	23.5	16
	Module Temp - ^oF	149	149	149	98	123	131.5	134	149	126	149	150	115	134	149	149	111	107	132	149	149	139	149	149
	O_2 Press - psia	75	75	77.5	77	75	73	74	73.5	74	73.5	71	73	73	74	74	74	74	74	74	74	74	65	74
	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	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	74.5	74.5	77	76	77	74	75.5	75	75.5	75	72	74	74	75	75	-	75.5	75.5	75.5	75.5	76	66.5	74
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	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	7	7	7.9	7.2	7.2	7.2	7.2	7	7	7	7.2	7	7	7	7.2	7	7	7	7	7	7	7
	Module Temp - ^oF	109	109	109	105	109	109	109	109	109	110	113	102	109	109	109	102	100	109	109	109	109	105	109
	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	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	90	90	90	90	84	80	83	82	84	82	84	82	81	81	81	82	82	82	82	10	80	80	81
	Blower Current - ma	182	185	176	210	195	195	187	178	170	175	173	185	182	180	180	185	180	180	174	35	177	178	178
System	Input DC Volts	26	28.5	30	27.5	27	26.5	27.4	27.2	27.4	26.9	26.5	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	23.5	24	12	16	18	25	20	21	20	21	26.2	26	26	20	20	22	19	20	21	18	18	26	16.5
	Input AC Volts	118	117	117	118	114	112	109	109	110	109	109	110	110	110	109	110	110	110	110	109	108	108	108
	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	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	73	72	75.5	72	73	71	72	71	72.5	72	70	69	73	72	72	70	71	71	71	71	71	62	72
	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	[illegible]	340	585	560	350	340	310	320	200	200	200	200	200	220	220	269
Coolant Temp - ^oF		67	53	63	75	67	68	69	65	66	65	91	66	65	57	65	65	65	67	66	67	66	66	65
O_2 Bleed - SLPM		.57	.57	.17	.40	.41	.70	.54	.57	.57	.57	.57	.57	.57	.37	.37	.57	.17**	.26**	.36**	.36**	.36**	.65**	.36**
CO_2 Flow - SLPM		.49	.49	.49	.49	.49	.49	.47	.48	.4[illegible]	.48	.50	.50	.49	.49	.49	.49	.49	.63	.49	.49	.49	.45	.49
Breathing Rate - Cycles/min		18	18	18	18	18	18	18	18	18	[illegible]	25	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	420	900	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	-[illegible]	-2/2	-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		GROUND						7300	7300	7500	GROUND		8000	8000	8000	5300	CLIMB	8400	8400	8400	8400	5200	5200	5200
Ambient Temperature		-	-	-	85	85	90	98	100	90	100	105	82	84	97	104	78	75	90	95	95	82	95	105
Gas Samples	H_2	-	10	-	-	-	-	-	11	12	-	-	-	13	-	-	14	-	-	-	-	-	-	-
	O_2	-	16	-	-	-	-	-	17A	18	19	20	-	21	22	23	24	-	-	-	-	-	-	-
	Rebreather	-	26	-	-	-	-	-	27	28	29	30	-	31	32	33	34	-	35	36	37	-	38	-

*Partial pressure instrumentation erratic

**Bleed set low to offset regulator leak

TABLE V

FLIGHT BREADBOARD SYSTEM TESTS - POST-FLIGHT

		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 - °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 - °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 - °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

TABLE VI

GAS SAMPLE COMPOSITIONS

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 VII

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		

Normal procedure in collecting the oxygen and hydrogen samples results in gas samples with a nominal 20 percent argon content. The data in Table VII 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 VII. 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 co-operation 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.

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.

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 simplicity 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 start-up, install one gas sample bottle at each sample tap: H_2, O_2, and rebreather lines. Have breathing machine set for 780 cc 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 FBS instruction manual for system start-up.

3. After start-up, use normal O_2 bleed rate of 570 cc/minute and CO_2 flow rate of 480 cc/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 480 cc/minute. Set O_2 bleed rate at 430 cc/minute and hold for 30 minutes.

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

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

9. Change O_2 bleed rate to 570 cc/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 480 cc/minute and O_2 bleed rate at 570 cc/minute. Operate for four (4) hours at these steady conditions. At three (3) hours after start-up, 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, 3 cylinders on the O_2 tap and 3 cylinders on the rebreather tap.

13. Start system. Set O_2 bleed rate for 570 cc/minute and CO_2 flow rate at 480 cc/minute. Turn on breathing machine adjusted to 18 breaths/minute (780 cc 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 start-up. Shut system down.

17. Remove gas sample cylinders and install a cylinder on the H_2 tap, 3 cylinders on the O_2 tap and 3 cylinders on the rebreather tap.

18. Start system. Set O_2 bleed rate for 570 cc/minute and CO_2 flow rate at 480 cc/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 420 cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480 cc/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 900 cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480 cc/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 780 cc. Restart breathing machineat 18 breaths/minute. Restart CO_2 flow rate at 480 cc/minute. Operate until four (4) hours have been accumulated since start-up. Shut down system.

22. Remove gas sample cylinders. Install a cylinder on the H_2 tap, one cylinder on the O_2 tap, and 5 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 570 cc/minute and CO_2 flow rate at 480 cc/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 620 cc/minute and hold for one (1) hour. Take a rebreather gas sample.

25. Return CO_2 flow rate to 480 cc/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 710 cc/minute and hold for 30 minutes. Take a rebreather gas sample.

28. Return O_2 bleed rate to 570 cc/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 start-up. Shut system down.

30. Repeat Steps 1 through 29.

31. Laboratory testing is completed.

II. PRE-FLIGHT GROUND CHECKOUT AT PT. MUGU

1. Assemble and interconnect FBS with auxiliaries and ground power conversion unit. Prior to start-up install one gas sample bottle at each sample tap: H_2, O_2 and rebreather lines. Have breathing machine set for 780 cc tidal volume, 18 breaths/minute and 40% inspiration ratio. The water coolant temperature should be adjusted to 65°F.

2. Follow operating instructions in FBS instruction manual for system start-up.

3. After start-up, use normal O_2 bleed rate of 570 cc/minute and CO_2 flow rate of 480 cc/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 FBS and accessories in aircraft and connect system to aircraft power. Start system. Maintain CO_2 flow rate of 480 cc/minute. Set O_2 bleed rate at 430 cc/minute and hold for 30 minutes.

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

8. Change O_2 bleed rate to 710 cc/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 480 cc/minute and O_2 bleed rate at 570 cc/minute. Set breathing machine for 780 cc tidal volume, 18 breaths/minute and 40% inspiration ratio. Operate system for four (4) hours at these steady conditions. At three (3) hours after start-up, 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, 3 cylinders on the O_2 tap, and 3 cylinders on the rebreather tap.

4. Flight Test 2: Start system, set O_2 bleed rate for 570 cc/minute and CO_2 flow rate at 480 cc/minute, set breathing machine for 780 cc tidal volume (18 breaths/minute and 40% 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/minutes 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 start-up. Shut system down.

8. Remove gas sample cylinders and install a cylinder on the H_2 tap, 3 cylinders on the O_2 tap and 3 cylinders on the rebreather tap.

9. Flight test 3: Start system. Set O_2 bleed rate for 570 cc/minute and CO_2 flow rate at 480 cc/minute, set breathing machine for 780 cc tidal volume (18 breaths/minute and 40% 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 420 cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480 cc/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 900 cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480 cc/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 780 cc. Restart breathing machine at 18 breaths/minute. Restart CO_2 flow rate at 480 cc/minute. Operate until four (4) hours have been accumulated since start-up. Shut down system.

13. Remove gas sample cylinders. Install a cylinder on the H_2 tap, one cylinder on the O_2 tap, and 5 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 570 cc/minute and CO_2 flow rate at 480 cc/minute, set breathing machine for 780 cc tidal volume (18 breaths/minute and 40% 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 620 cc/minute and hold for one (1) hour. Take a rebreather gas sample.

16. Return CO_2 flow rate to 480 cc/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 710 cc/minute and hold for 30 minutes. Take a rebreather gas sample.

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

20. Remove gas sample cylinders. Remove FBS 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 FBS.

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.