LSI ER-265-7
CR-152073

TECHNOLOGY ADVANCEMENT OF THE STATIC FEED WATER ELECTROLYSIS PROCESS

(NASA-CR-152073) TECHNOLOGY ADVANCEMENT OF THE STATIC FEED WATER ELECTROLYSIS PROCESS Final Report (Life Systems, Inc., Cleveland, Ohio.) 89 p HC A05/MF A01 CSCL 06K N78-19772 Unclas G3/54 08860

FINAL REPORT

by

F.H. Schubert and R.A. Wynveen

November, 1977

Prepared Under Contract NAS2-8682

by

Life Systems, Inc.
Cleveland, OH 44122

for

AMES RESEARCH CENTER

National Aeronautics and Space Administration

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FOREWORD

This report was prepared by Life Systems, Inc. for the National Aeronautics and Space Administration (NASA) Ames Research Center in accordance with the requirements of Contract NAS2-8682, "Design, fabrication, testing, evaluation and data analysis of an Advanced Static Feed Water Electrolysis Module." The period of performance for the program was February 12, 1975 to November 20, 1977. The objective of the program was to advance the technology upon which the Static Feed Water Electrolysis Subsystem is based and to demonstrate the maturity of the hardware development for future multi-crew space missions.

All measurements and calculations contained in this report are expressed in SI (metric) units followed by conventional units in parentheses.

Mr. Franz H. Schubert was Program Manager. The personnel contributing to the program and their areas of responsibility are indicated below.

Personnel	Area(s) of Responsibility
Tim M. Hallick	Integrated subsystem testing and data reduction
Dennis B. Heppner, PhD	Four-person subsystem integration
Darlene A. Jones	Documentation
Eugene Koszenski	Electrode and matrix fabrication
Richard D. Marshall	One-person subsystem integration
J. David Powell	Control/Monitor Instrumentation design
Joe Schmidt	Electronics fabrication
Franz H. Schubert	Electrochemical and mechanical designs and system analyses
John W. Shumar	Product Assurance and advanced electrode and matrix development
Daniel C. Walter	Mechanical subsystem and component designs
Rick A. Wynveen, PhD	Systems Design and Contract Administration

The Contract's Technical Monitor was P. D. Quattrone, Chief, Advanced Life Support Project Office, NASA Ames Research Center, Moffett Field, CA.

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LIST OF ACRONYMS

ARS	Air Revitalization System
ARX-1	Air Revitalization System (one-person, experimental)
B-CRS	Bosch CO_2 Reduction Subsystem
BRS	Bosch Reduction Subsystem
C/M I	Control/Monitor Instrumentation
CRS	CO_2 Reduction Subsystem
DM	Dehumidifier Module
DVT	Design Verification Test
EC/LSS	Environmental Control/Life Support System
ESS	Electrical Signal Simulator
EDC	Electrochemical Depolarized CO_2 Concentrator
LBS-B/ORS-4(A)	Laboratory Breadboard System of a Bosch-based Oxygen Reclamation System at the four-man level using air cooling
LBS-S/ORS-1(L)	Laboratory Breadboard of a Sabatier-based Oxygen Reclamation System at the one-man level using liquid cooling
NSS	Nitrogen Supply Subsystem
OGS	Oxygen Generation Subsystem
ORS	Oxygen Reclamation System
RLSE	Regenerative Life Support Evaluation
S-CRS	Sabatier CO_2 Reduction Subsystem
SFWE	Static Feed Water Electrolysis
SFWEM	Static Feed Water Electrolysis Module
SFWES	Static Feed Water Electrolysis Subsystem
TSA	Test Support Accessories

SUMMARY

A program to advance the technology of oxygen- and hydrogen-generating subsystems based on water electrolysis has been successfully completed at Life Systems, Inc. Major emphasis was placed on static feed water electrolysis, a concept characterized by low power consumption and high intrinsic reliability. The program activities completed were a continuation of prior NASA and Contractor-funded research and development efforts.

The static feed-based Oxygen Generation Subsystem consists basically of three subassemblies: a combined water electrolysis and product gas dehumidifier module, a product gas pressure controller and a cyclicly filled water feed tank. The generation of oxygen and hydrogen occurs in a series of electrolysis cells forming an electrolysis module. The cells use an aqueous solution of potassium hydroxide retained in a porous asbestos matrix. Water feed into the individual cells and to the electrolysis sites is achieved statically, minimizing moving parts for increased subsystem reliability. Additional hydrogen and oxygen are generated during the process of electrochemically dehumidifying the process gases. The dehumidifier cells are similar in structure to the basic cells but use acidic electrolyte.

Development activities were completed at the subsystem as well as at the component level. An extensive test program including single cell, subsystem and integrated system testing was completed with the required Test Support Accessories designed, fabricated and assembled. Mini-Product Assurance activities were included throughout all phases of program activities. An extensive number of supporting technology studies was conducted to advance the technology base of the static feed water electrolysis process and to resolve past and present problems.

The subsystem level development activities included the completion of a preliminary design analysis for a three-person Oxygen Generation Subsystem and the design, fabrication and assembly of two Oxygen Generation Subsystems at the breadboard level; one, to support the integrated testing of a one-person capacity Oxygen Reclamation System, the other to support the testing of a four-person Oxygen Reclamation System. In the first integrated system the Oxygen Generation Subsystem was operated with an Electrochemical Depolarized Concentrator for carbon dioxide collection and a Sabatier Carbon Dioxide Reduction Subsystem for recovery of oxygen from the collected carbon dioxide. The four-person Oxygen Reclamation System was formed by integrating the Oxygen Generation Subsystem hardware with an Electrochemical Depolarized Carbon Dioxide Concentrator and a Bosch Carbon Dioxide Reduction Subsystem. A total of 30 days and 42 days of testing were accumulated supporting the one-person and four-person Oxygen Reclamation Systems, respectively.

A Three-Gas Pressure Controller was developed which uniquely satisfies the total and differential pressure control requirements of a Static Feed Water Electrolysis Subsystem. This single component combines the functions of three pressure regulators, one total pressure transducer, two differential pressure transducers and three regulator position indicators. By using motor-driven regulators the Three-Gas Pressure Controller can readily be adapted to closed-loop feedback control using microprocessor- or minicomputer-based Control/

Monitor Instrumentation. The Three-Gas Pressure Controller weighs only 3.64 kg (8.0 lb) and occupies a volume of 1.58 dm^3 (96 in^3).

Since the Oxygen Generation Subsystem consumes the most power of any of the subsystems forming a spacecraft Air Revitalization System, an extensive portion of the program's activities was directed towards reduction of this power requirement. High temperature and advanced catalyst single cell testing was completed to demonstrate subsystem power reduction through decreased electrolysis cell voltage levels. Increasing cell temperatures above the 355 K (180 F) level proved to be impractical due to the nonavailability of commercially-produced cell matrix fibers compatible with high temperatures and the difficulty of maintaining subsystem hardware at the elevated temperatures while simultaneously operating at low cell voltages. External heat sources were considered, but deemed impractical. A reduction in state-of-the-art cell voltage levels was achieved with a Contractor-developed catalyst for the oxygen evolving electrode. A total of 136 days of single cell operation were accumulated with representative cell voltage levels averaging 1.45 V at 161 mA/cm^2 (150 ASF) and 355 K (180 F) demonstrated.

It is concluded from the results reported herein that a Static Feed Water Electrolysis-based Oxygen Generation Subsystem is a viable solution for providing oxygen and hydrogen generation aboard manned spacecraft. Continued development of Oxygen Generation Subsystem related technology is recommended to further reduce power consumption and increase hardware reliability. Successful completion of this development will produce timely technology necessary to plan future advanced environmental control and life support system programs and experiments.

PROGRAM ACCOMPLISHMENTS

Key program accomplishments were:

- Decreased water electrolysis state-of-the-art power requirements by a substantial reduction in cell voltage levels - A voltage range of 1.45 to 1.50 V at 161 mA/cm^2 (150 ASF). (See Figure 1 and Table 1.)
- Completed a preliminary design analysis for a three-person Oxygen Generation Subsystem (OGS) - A package of 0.108 m^3 (3.8 ft^3) weighing only 54.6 kg (120 lb) was projected.
- Extensively tested OGS hardware as part of integrated Oxygen Reclamation Systems (ORS) - 720 h and 1000 h of testing obtained at the one- and four-person level, respectively.
- Developed a compact Three-Gas Pressure Controller uniquely satisfying the requirements of a Static Feed Water Electrolysis Subsystem (SFWES) - the functions of six separate peripheral components were combined into a single unit.
- Successfully completed nine studies expanding the technology base for Static Feed Water Electrolysis (SFWE) - no aerosol found, optimum operating pressure established, maximum depressurization rates

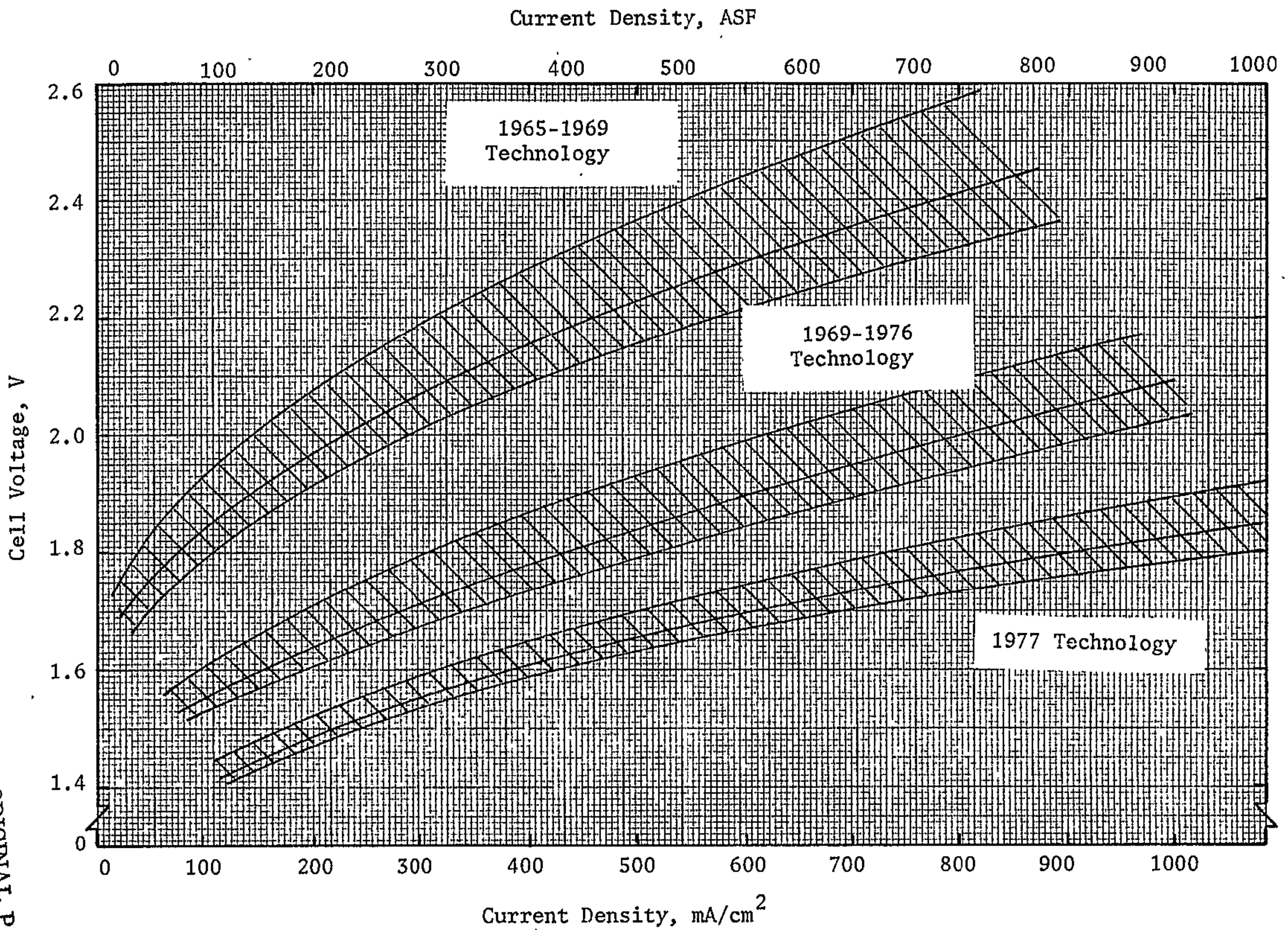


FIGURE 1 MAJOR ELECTRODE/CATALYST PERFORMANCE IMPROVEMENTS

TABLE 1 MAJOR ELECTRODE/CATALYST PERFORMANCE[a] IMPROVEMENTS

Period	Approximate Cell Voltage Ranges, V (at 160 mA/cm^2, 340 K (150 ASF, 153 F))
1965 - 1969	1.80 - 2.10
1969 - 1976	1.60 - 1.70
1977	1.45 - 1.50

(a) Range selected to allow for scale-up effects and lifetime of >40,000 hours.

determined, baseline operating temperature optimized, dehumidifier matrix fabrication demonstrated, "water-only" in feed compartment feasibility demonstrated, material compatibility questions resolved, power sharing scaled-up and increased power conversion efficiencies shown possible.

INTRODUCTION

Technology and equipment are needed to sustain man in space for extended time periods. An OGS is required to generate breathable oxygen (O_2) onboard a spacecraft. Presently considered techniques accomplish this through the electrolysis of water. The byproduct hydrogen (H_2) is used within the Air Revitalization System (ARS) of the spacecraft to recover O_2 from expired carbon dioxide (CO_2).[1,2] This recovery of the O_2 is accomplished by an Electrochemical Depolarized CO_2 Concentrator (EDC) integrated with either a Sabatier- or Bosch-based CO_2 reduction process.

Background

Past development efforts on water electrolysis subsystems and modules have included those that use the static water feed concept.[3-6] Subsystems using this concept have demonstrated an inherent simplicity and long operating life capability.[3-5] The SFWES has the most potential as the lowest power-consuming electrolysis subsystem due to its use of an alkaline electrolyte.[6] Various approaches to SFWES designs by different developers and results of extensive test programs have identified key subsystem improvements required. Problems inherent in the design of a SFWES, and of water electrolysis subsystems in general, have been eliminated as demonstrated by:

- elimination of water feed compartment degassing[4]
- elimination of condenser/separators which are characteristic of all other applicable water electrolysis subsystems[4] (especially significant for zero-gravity space application)
- elimination of aerosols in the product gas stream[7]

A reliable, low equivalent weight OGS based on the static feed concept with peripheral support hardware has been under development at Life Systems, Inc. (LSI) for the past several years. The currently-developed SFWES has demonstrated a capability of operating with current densities of 54 to 1080 mA/cm^2 (50 to 1000 ASF), pressures from ambient to 4140 kPa (600 psia) and internal temperatures from 323 to 372 K (120 to 210 F). The requirement of past SFWES' to vent the feed water cavity has been solved. A 90-day endurance run was successfully completed and two approaches to delivering dry product O_2 and H_2 gases to the spacecraft environment and other ARS subsystems were demonstrated.[4] One approach was gas expansion through a regulator; the second was an electrochemical Dehumidifier Module (DM) in the product gas lines.

(1,2) Numbers in parentheses are references found at the end of this report.

The objective of the present program was to continue to advance the technology of the SFWES with special emphasis on improving performance (lower cell voltages at higher current densities), customizing components inherently needed by the SFWES and reducing overall subsystem complexity in preparation for integration into a spacecraft's ARS.

Program Objectives

The overall objectives of the present program were:

1. Develop SFWES hardware for evaluation when integrated with other subsystems of an Environmental Control/Life Support System (EC/LSS).

2. Derive a static water feed-based OGS concept that can efficiently meet the O_2 generation requirements of future manned spacecraft.

3. Demonstrate reduction in OGS power requirements through improvements in cell hardware (electrodes, matrices and configurations) and other power consuming peripheral subsystem components.

4. Reduce subsystem complexity through the elimination of components and the development of customized components.

5. Derive "integration technology" by actual operation of an OGS with other subsystems of an ARS at one- through multi-person levels.

6. Enhance potential user acceptability by demonstrating SFWES hardware reliability and maturity through the elimination of past and suspected problems.

Program Organization

The program was organized into five tasks whose specific objectives were to:

1. Develop, fabricate and assemble SFWES hardware and concepts to support integrated ARS testing at the one- and four-person level.

2. Design, fabricate, assemble and functionally checkout the Test Support Accessories (TSA) required for the program's testing.

3. Establish, implement and maintain a mini-Product Assurance program throughout the contractual performance period to search out quality weaknesses and to define appropriate corrective measures.

4. Conduct an extensive test program at the single cell, subsystem and integrated system level to establish the quantitative effects of key engineering parameters.

5. Conduct supporting technology studies to support SFWES technology development.

The objectives of the program were met. The following sections present the results obtained.

SUBSYSTEM DEVELOPMENTS

The subsystem development activities performed consisted of two major thrusts. The first was conceptual in nature and resulted in the preliminary design of a three-person OGS based on the SFWE process. The second area of subsystem development addressed integration of OGS hardware into two central ARS laboratory breadboards, one employing a Sabatier-based, the other a Bosch-based CO_2 reduction process.

SFWES Process Descriptions

Detailed descriptions of the SFWE process, its theory of operation, specific hardware and performance have been discussed previously.[3-5,8,9] The following summarizes briefly the subsystem concept and the electrochemical processes.

Static Feed Water Electrolysis Subsystem Concept

A conceptual schematic of an OGS based on the SFWE concept is shown in Figure 2. The subsystem consists of three main parts: the combined SFWE and DM, the water feed tank and the product gas pressure controller. Oxygen and H_2 are generated in the electrolysis module from water supplied by the water feed tank. The product gases are dried to acceptable dew point levels in the DM. The water feed tank is cyclicly filled as required. The product gas pressure controller (1) maintains the absolute pressure of the subsystem, (2) maintains the pressure differentials required to establish and maintain fluid locations within the individual cells of the modules and (3) controls pressurization and depressurization of the subsystem during startups and shutdowns.

Electrochemical Processes

Two different electrochemical processes occur within the SFWES.

1. The production of O_2 and H_2 gases using an aqueous solution of a basic electrolyte (in the Static Feed Water Electrolysis Module (SFWEM)).

2. The electrochemical dehumidification of the product gases through the electrolysis of water vapor absorbed in an aqueous solution of an acidic electrolyte (in the DM).

Static Feed Water Electrolysis Cell. The reactions occurring at the cathode and anode of the SFWE cell with an alkaline electrolyte are:

Cathode

$$2H_2O + 2e^- = H_2 + 2OH^- \qquad (1)$$

Anode

$$2OH^- = H_2O + 1/2\ O_2 + 2e^- \qquad (2)$$

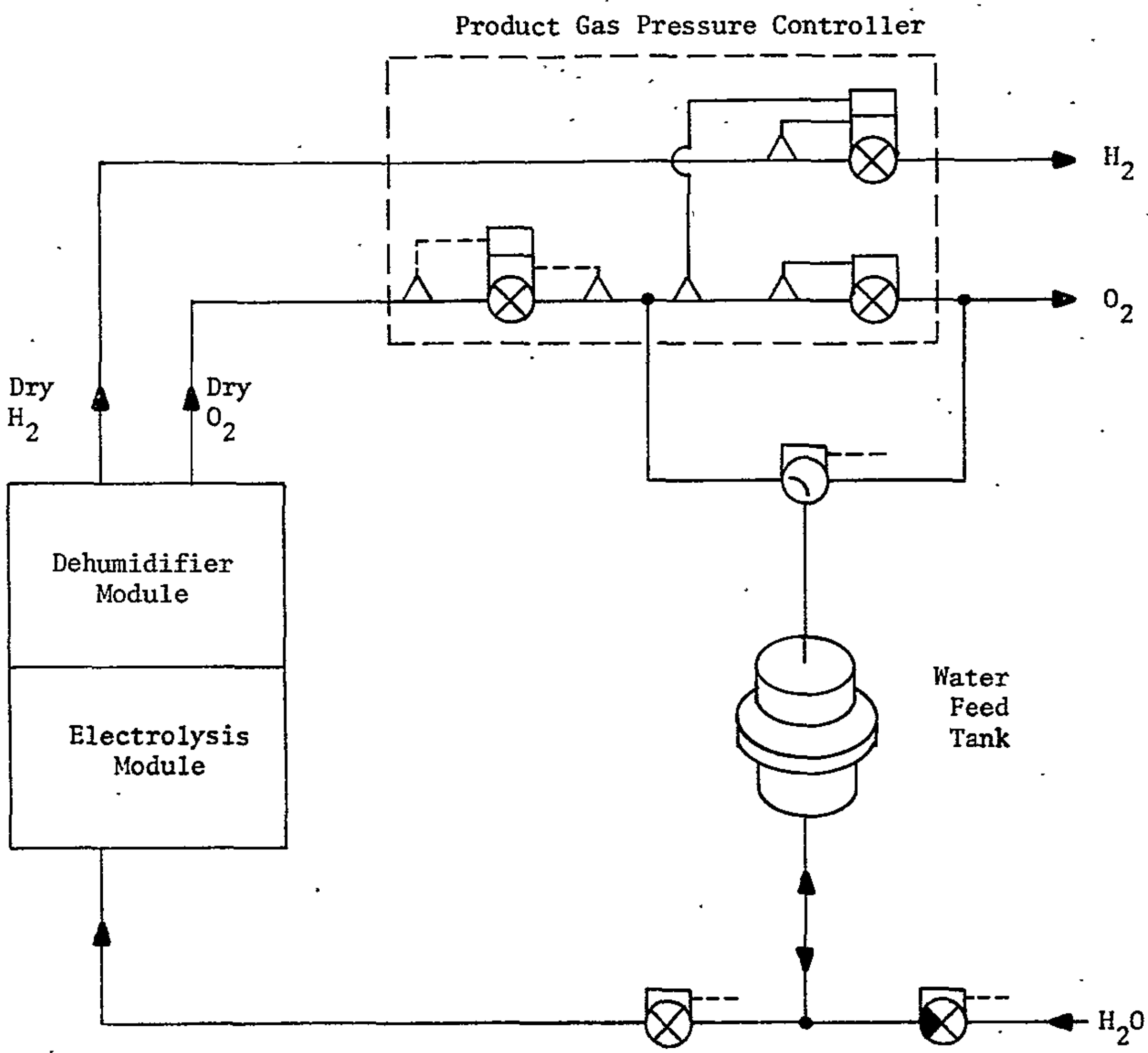


FIGURE 2 OXYGEN GENERATION SUBSYSTEM CONCEPT

resulting in the overall net reaction of:

$$\text{Electrical Energy} + H_2O = H_2 + 1/2\ O_2 + \text{Heat} \qquad (3)$$

The functional schematic of a SFWE cell is shown in Figure 3. Water vapor diffuses from the water feed matrix into the cell matrix due to a concentration gradient between the water feed cavity and the electrolyte in the cell matrix. Consumption of water from the water feed cavity results in its static replenishment from the external water feed tank.

Dehumidifier Cell. The reactions occurring at the anode and cathode of a dehumidifier cell having an acid electrolyte are:

Anode

$$H_2O = 1/2\ O_2 + 2H^+ + 2e^- \qquad (4)$$

Cathode

$$2H^+ + 2e^- = H_2 \qquad (5)$$

resulting in the overall net reaction of:

$$\text{Electrical Energy} + H_2O = H_2 + 1/2\ O_2 + \text{Heat} \qquad (6)$$

A functional schematic of the dehumidifier cell is shown in Figure 4. "Wet" O_2 and H_2 from the SFWE cells enters the dehumidifier cell where water vapor is absorbed and electrolyzed to form additional O_2 and H_2. Electrolysis of the absorbed water vapor results in a decrease in the dew point of the product gases, eliminating the need for external, zero gravity compatible condenser/separators.

Preliminary Design of a Three-Person Capacity OGS

A preliminary design of a three-person capacity OGS was completed. The three-person capacity was selected to take advantage of the guidelines, philosophies and specifications being established for a three-person capacity integrated Regenerative Life Support Evaluation (RLSE) experiment presently under consideration by NASA.[10]

Design Specifications

A set of specifications was prepared and used for the preliminary design. These specifications are presented in Table 2. In preparing Table 2 the specifications for the three-person RLSE were used as a guide.[11]

The subsystem was sized to deliver 4.20 kg/d (9.24 lb/d) of O_2. As shown in Table 2 this O_2 production rate provides for the metabolic needs of the crew, the requirements of the EDC used for CO_2 removal and that O_2 lost through cabin leakage. The requirements for the EDC were based on performance data available in literature.[1,2]

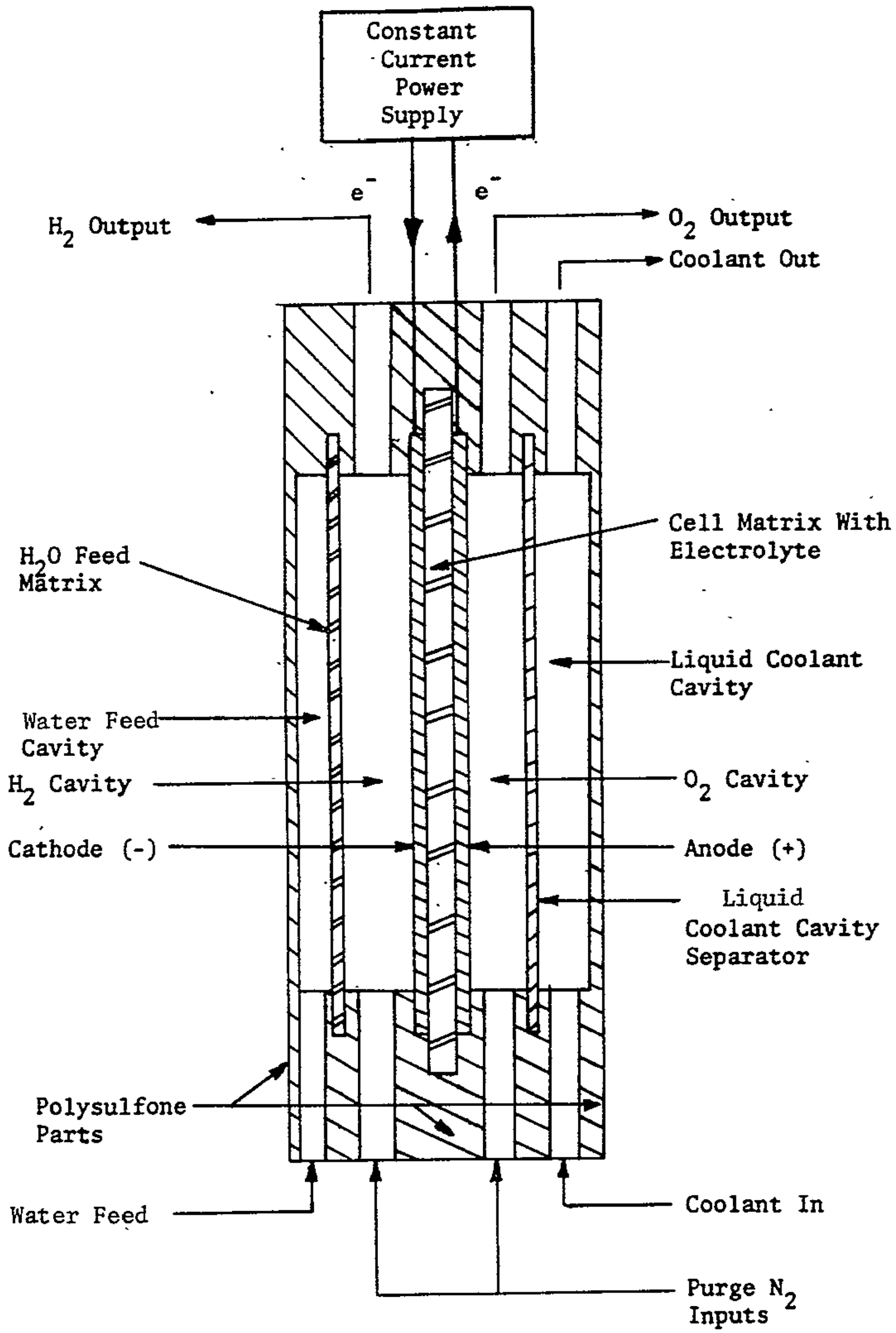


FIGURE 3 FUNCTIONAL SCHEMATIC OF A SFWE CELL

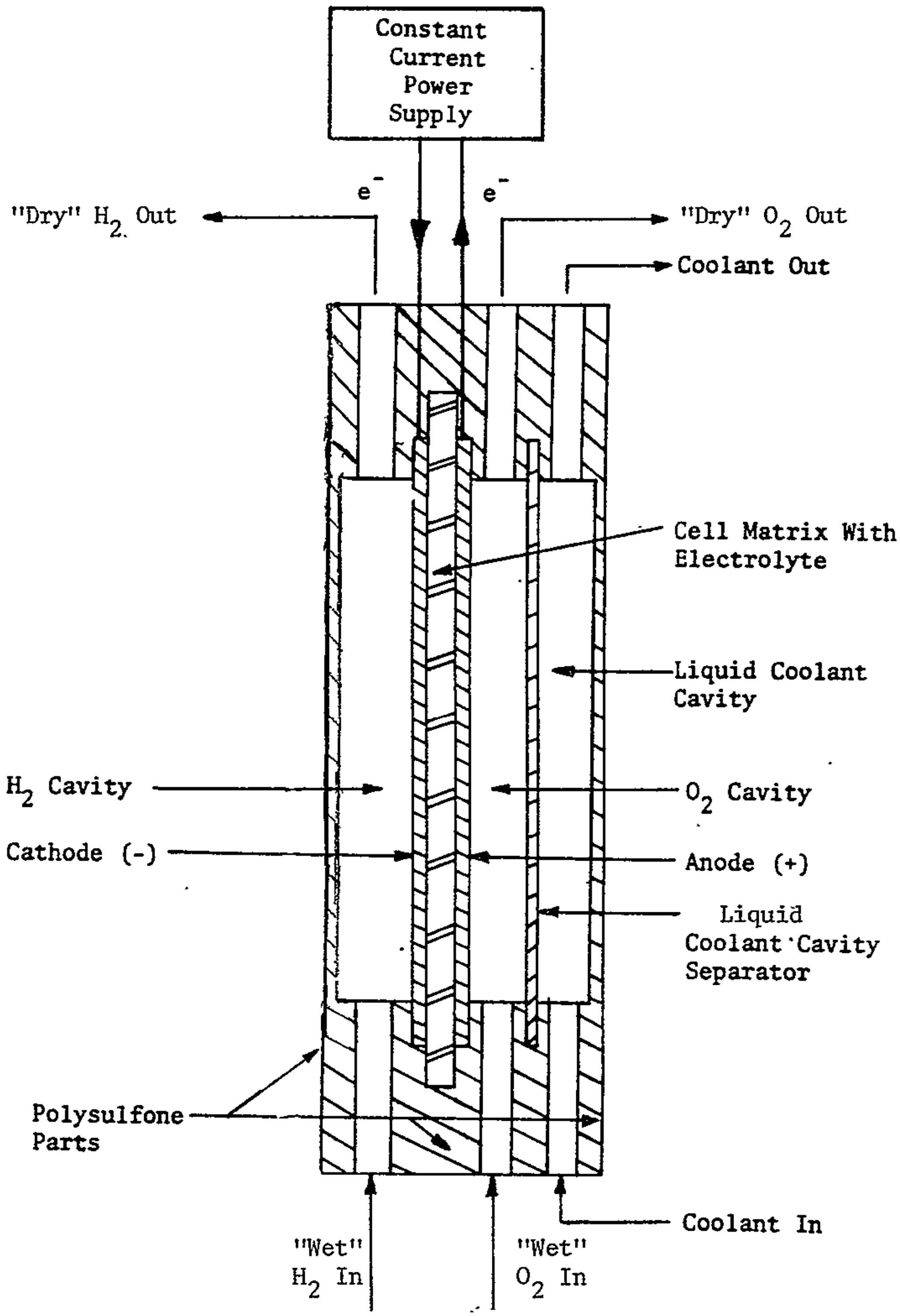


FIGURE 4 FUNCTIONAL SCHEMATIC OF A DEHUMIDIFIER CELL

TABLE 2 THREE-PERSON CAPACITY
SUBSYSTEM DESIGN SPECIFICATIONS

Number of Crew (Continuous)	3
O_2 Production Rate	
Metabolic Consumption (3 Persons), kg/d (lb/d)	2.51 (5.52)
EDC Consumption, kg/d (lb/d)	1.36 (3.00)
Cabin Leakage, kg/d (lb/d)	0.33 (0.72)
Total, kg/d (lb/d)	4.20 (9.24)
H_2 Production Rate, kg/d (lb/d)	0.52 (1.15)
Cabin Atmosphere	
Total Pressure, kPa (psia)	101 to 104 (14.7 to 15.2)
Temperature, K (F)	291 to 300 (65 to 80)
Dew Point Temperature, Min, K (F)	279 (42.5)
Relative Humidity, Max, %	70
O_2 Partial Pressure, kPa (psia)	21.0 to 22.6 (3.04 to 3.28)
Diluent	Air Constituents
Cooling Air (Ambient)	
Total Pressure, kPa (psia)	101 to 105 (14.7 to 15.2)
Temperature	Ambient
Water Supply	
Pressure, kPa (psia)	207 (30)
Temperature, K (F)	277 to 300 (40 to 80)
Purity	Deionized
Electrical Power, V	
DC	28
AC	115/200 (400 Hz, 3 Phase)
Purge Supply	
Type Gas	N_2
Pressure, kPa (psia)	862 (125)
Power Penalty, kg/W (lb/W)	0.269 (0.591)
Heat Rejection Penalty, kg/W (lb/W)	0.198 (0.436)
Packaging	Self-Contained
Gravity, g	0 to 1
Allowable Downtime, h	8 to 48
Duty Cycle	Continuous

Schematic and Operation

The schematic of the three-person capacity OGS is shown in Figure 5. Seventeen types of components were used in deriving the subsystem schematic. The types are indicated by numbers in Figure 5 with all components listed in Table 3. Table 3 also provides the number, individual weight, total weight, individual dimensions, total volume and power required for each of the components.

The design of the subsystem was based on the general concept shown in Figure 2. The two electrochemical modules are liquid-cooled with the waste heat rejected to cabin ambient via a liquid-air heat exchanger. The water feed tank is cyclicly refilled with water. Nitrogen (N_2) is used to repressurize the tank following an ambient pressure refill. The same N_2 interface is also used to supply the purge gases following a subsystem shutdown. Purge gas flow is regulated through orifices.

Packaging

To determine the overall size and configuration of the three-person capacity OGS a packaging layout was prepared. The resulting package had a height of 44.0 cm (17.3 in), a width of 60.0 cm (23.5 in), and a depth of 41.0 cm (16.3 in), for a total volume of only 0.11 m^3 (3.81 ft^3). Figure 6 presents the top, front and side view of the resulting package. The majority of the peripheral components are indicated and cross-referenced by number to Table 3.

Subsystem Total Equivalent Weight

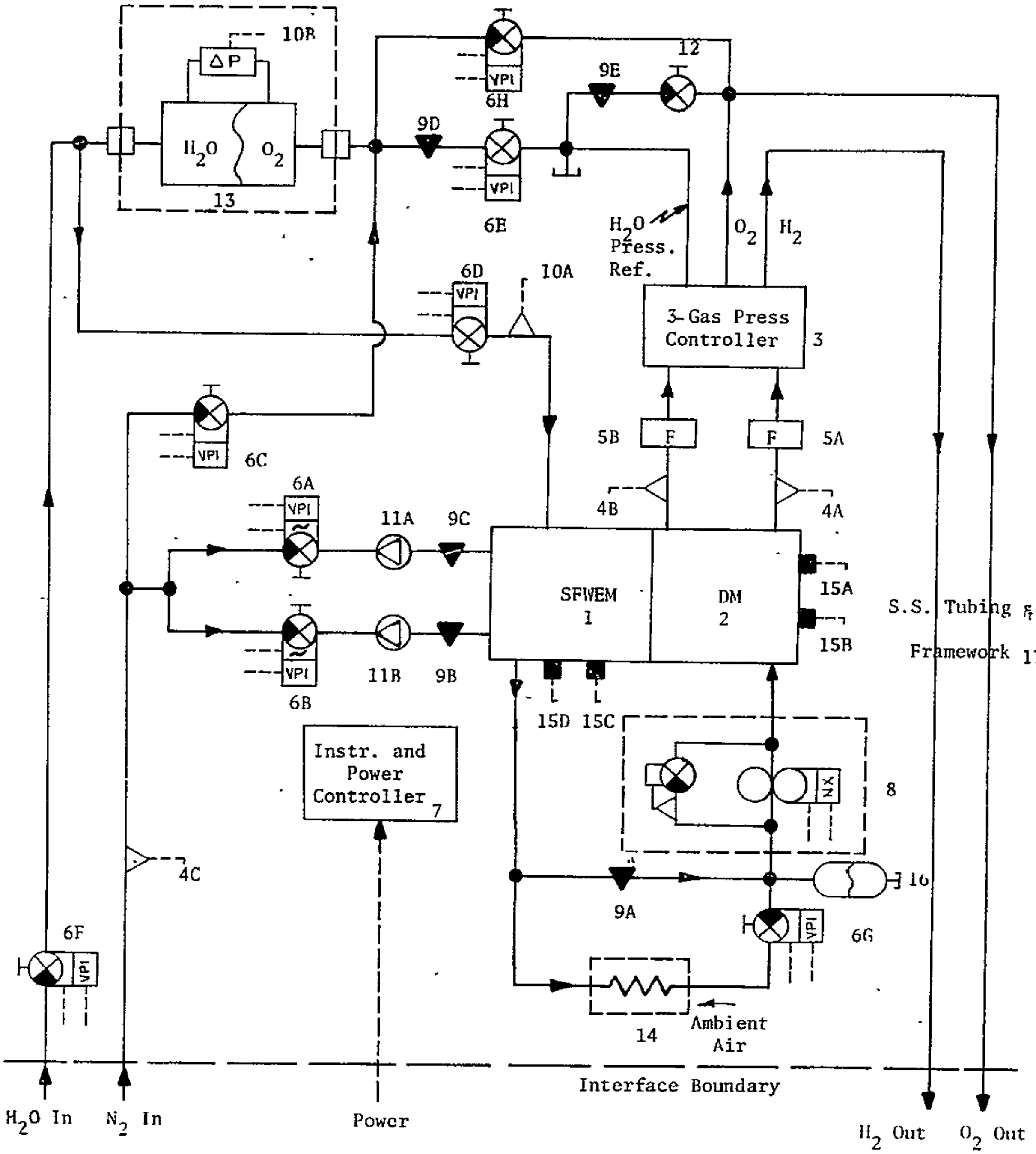
The total equivalent weight, without spares, of the three-person OGS was calculated. The results are presented in Table 4. As Table 4 indicates, two total equivalent weights were calculated; one based on 1976 technology and the other based on the technology level projected for 1980. The 1976 technology-based subsystem had a total equivalent weight of 383 kg (843 lb) with a 54.6 kg (120.3 lb) fixed hardware weight, while the 1980 technology would result in a total equivalent weight of 294 kg (647 lb) with a fixed hardware weight of 36.4 kg (80 lb). The analysis used the heat rejection and power penalties presented in Table 2.

Additional Analyses

As part of the preliminary design, a mass balance, definition of the subsystem interfaces, identification of the controlled and monitored parameters of the OGS as well as a reliability analysis were performed. The results of these activities are presented in Appendix 1.

Summary of Subsystem Characteristics

The major subsystem characteristics for three-person capacity OGS are presented in Table 5. The summary is based on the 1976 technology level.



Note: See Table 3 for component number relationship.

FIGURE 5 OGS SCHEMATIC

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TABLE 3 THREE-PERSON OGS (9.24 Lb O_2/Day)
COMPONENT LIST (1976 TECHNOLOGY)

OGS Part No.	Component	No. Req'd	Indiv. Wt., kg	Total Wt., kg	Indiv. Dimensions, cm	Total Volume, cm^3	Total Power, W
1	SFWEM	1	23.9	23.9	22.9 x 27.9 x 35.9	22,900	903
2	DM	1	6.6	6.6	22.9 x 27.9 x 13.2	8,430	12[a]
3	3-Gas Pressure Controller	1	3.6	3.6	7.0 x 12.7 x 17.8	1,580	2
4	Pressure Transducer (Gas)	3	0.1	0.3	2.5 x 2.5 x 2.5	49	1
5	Product Gas Filter	2	0.2	0.4	3.8 dia x 6.4	144	-
6	Solenoid Valves[b]	8	0.3	2.4	5.1 x 3.8 x 8.9	1,380	-
7	Power Controller	1	9.3	9.3	11.1 x 27.0 x 31.8	9,530	159[c]
8	Coolant Pump	1	0.3	0.3	3.5 dia x 13.0	125	12
9	Flow Restrictor	5	0.1	0.5	2.0 dia x 3.2	50	-
10	Pressure Transducer (Water)	2	0.1	0.2	2.5 x 2.5 x 2.5	33	1
11	Check Valves	2	0.1	0.2	2.4 dia x 5.7	25	-
12	Hand Valve	1	0.1	0.1	1.6 dia x 4.2	8	-
13	Water Storage Tank	1	1.2	1.2	12.1 dia x 10.2	1,170	-
14	Heat Exchanger	1	0.1	0.1	1.6 dia x 7.6	15	-
15	Temperature Probes	4	0.1	0.4	0.3 dia x 7.6	2	2
16	Accumulator	1	0.1	0.1	6.4 x 6.4 x 6.4	256	-
17	Frame (Aluminum) Tubing and Fittings (Stainless Steel)	AR[d]	5.0	5.0	- - -	-	-

Total Volume, m^3 (ft^3) : 0.057 (2.0)
Total Weight, kg (lb) : 54.6 (120)
Total Power, kW : 1.09

(a) When the DM is operating, the SFWEM power consumption is reduced by an amount equivalent to the DM's gas production.
(b) With valve position indicator, manual override, latched when normally energized, no steady-state power required, only actuation power.
(c) Assuming a state-of-the-art 85% conversion efficiency.
(d) As Required.

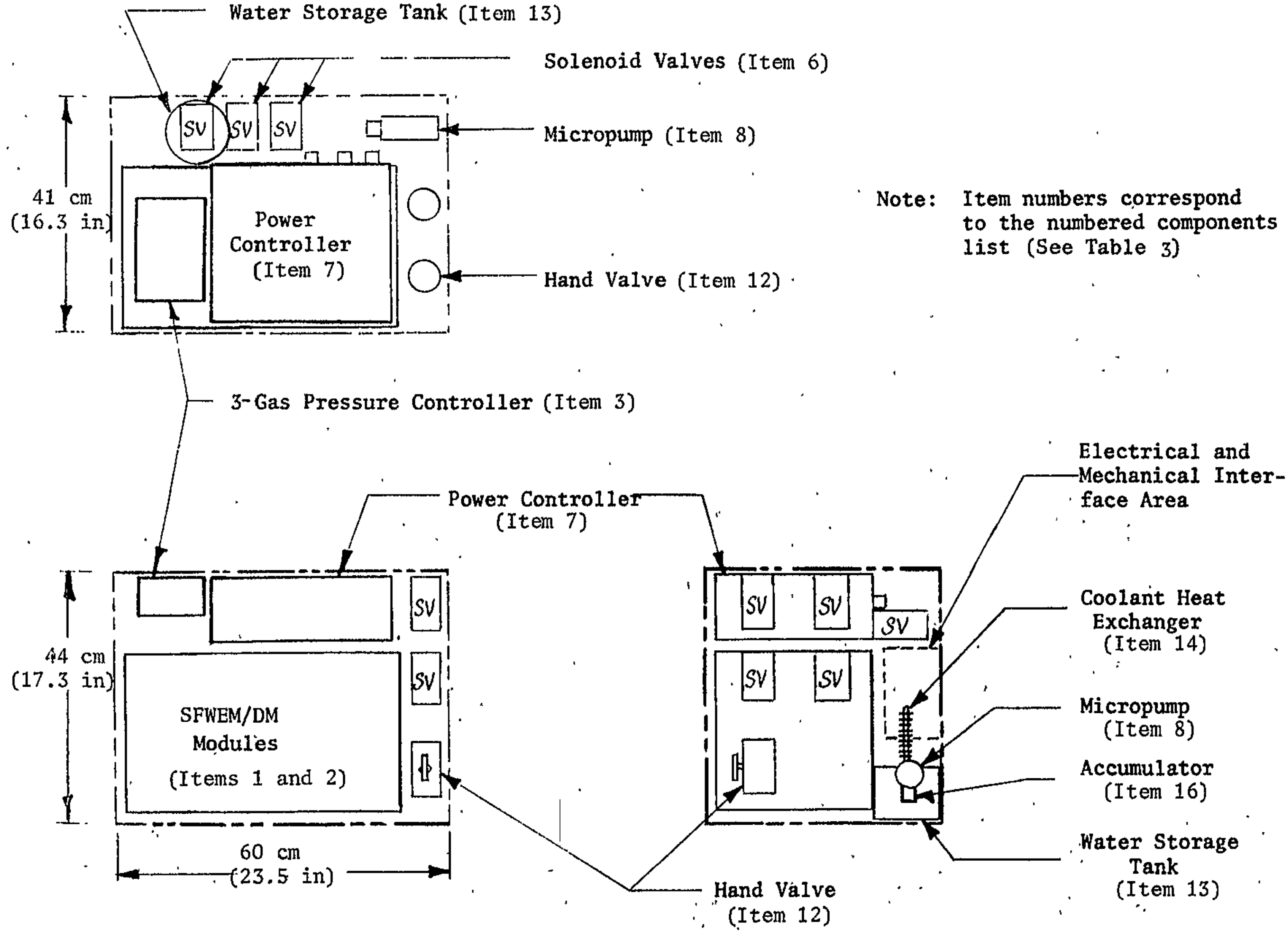

FIGURE 6 THREE-PERSON OGS PACKAGING

TABLE 4 THREE-PERSON OGS WEIGHT SUMMARY

Item	1976 Technology[a]	1980 Technology
SFWEM	23.9 (52.7)	17.2 (37.8)
DM	6.6 (14.5)	1.1 (2.4)
Power Controller	9.3 (20.5)	7.4 (16.3)
Fixed Hardware Weight of Peripherals	14.8 (32.6)	10.7 (23.5)
Subtotal Fixed Hardware Weight, kg (lb)	54.6 (120.3)	36.4 (80.0)
WES Heat Rejection Weight Penalty	7.5 (16.5)	0
WES Controller Heat Rejection Penalty	31.5 (69.3)[b]	6.2 (13.6)
WES Power Penalty	285.2 (627.4)[b]	249.7 (549.3)
DM Heat Rejection Weight Penalty	0.2 (0.4)	0
DM Controller Heat Rejection Penalty	0.3 (0.6)	0.05 (0.11)
DM Power Penalty	3.3 (7.3)	1.6 (3.62)
Subtotal Heat Rejection and Power Penalty Weight, kg (lb)	328 (722)	258 (567)
Total Equivalent Weight, kg (lb)	383 (843)	294 (647)

(a) For both metabolic and EDC O_2 requirements or 4.20 kg O_2/day (9.24 lb O_2/day).
(b) Includes 85% efficiency of present Power Controller.

TABLE 5 SUMMARY OF THREE-PERSON OGS CHARACTERISTICS

Crew Size	3
Total O_2 Generation Rate,[a] kg/d (lb/d)	4.20 (9.24)
Fixed Hardware Weight, kg (lb)	54.6 (120)
Total Equivalent Weight, kg (lb)	383 (843)
Overall Dimension, cm (in)	41 x 44 x 60 (16.3 x 17.3 x 23.5)
Total Volume, m^3 (ft^3)	0.11 (3.81)
Total Power Required, kW	1.09[b]

(a) Includes EDC and leakage requirements.
(b) Includes present 85% efficient Power Controller.

Subsystem Integrations

Part of the program's subsystem development activities included the design, fabrication and assembly of OGS hardware to allow integrated testing with other EC/LSS subsystems. This hardware was used to form part of two ORS's: (1) a one-person and (2) a four-person capacity ORS.

One-Person Laboratory Breadboard

Previously developed OGS hardware[4] was refurbished and modified for incorporation into a Laboratory Breadboard System, Sabatier-based O_2 Reclamation System, one-person capacity, liquid-cooled (LBS-S/ORS-1(L)). In addition to the OGS hardware the breadboard consisted of a liquid-cooled, one-person capacity EDC and a Sabatier-based CO_2 Reduction Subsystem (S-CRS).

Objectives. The overall objectives of the activities performed with the one-person laboratory breadboard were:

1. Demonstrate long-term, liquid-cooled OGS operation using the improved module components (current collectors, insulation plates, electrodes, frames and O-rings) developed as part of the technology advancement program.

2. Supply electrochemically generated H_2 to the EDC and S-CRS.

3. Define OGS operating control concepts to allow for integration with other ARS subsystems.

4. Expand integration technology for operating three subsystems as one ORS.

Integrated Test Benefits. Benefits of testing EC/LSS subsystems as part of an ORS or ARS are:

1. Verification of the integratability of a specific subsystem concept i.e., accumulation and generation of integration technology.

2. Reduction in TSA since other subsystems supply required fluid interfaces.

3. Elimination of commonality components.

4. Reduction in test program costs due to reduction in expendables as well as test operator time.

Block Diagram and Operation. Figure 7 is a block diagram of the one-man ORS. The philosophy of "one subsystem down, all down" was employed in the integration concept. A common N_2 purge was used for automatic purging of the H_2-carrying cavities, both at system startup and shutdown. Addition of excess H_2 between subsystems was incorporated to allow the simulation of operating the ORS with an N_2 Supply Subsystem (NSS) using decomposition of hydrazine (N_2H_4) to generate N_2 and H_2.

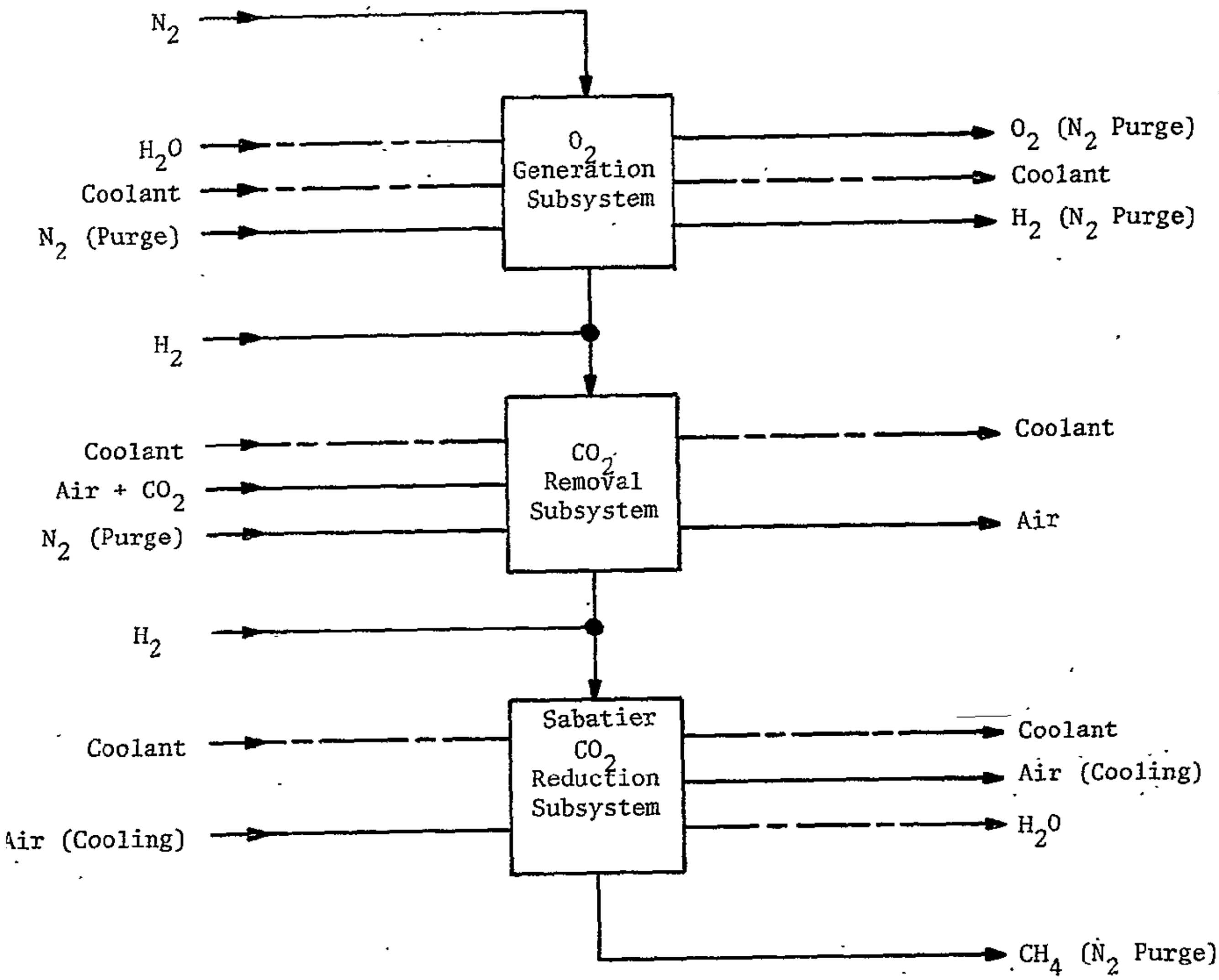

FIGURE 7 ONE-PERSON OXYGEN RECOVERY SYSTEM BLOCK DIAGRAM

System startup required sequentially starting the OGS followed by the EDC then followed by the S-CRS. Manual intervention was required by the operator to achieve system integration following individual subsystem startups. Shutdown was automatic, however, and did not require operator intervention. Also, in case any critical parameters exceeded pre-established tolerance limits, an automatic shutdown with N_2 purge was provided.

Hardware Description. The individual subsystems and their TSA are shown in Figure 8. Figures 9, 10 and 11 are photographs of the OGS, EDC and S-CRS reactor, respectively.

The one-person capacity OGS (Figure 9) had been modified and refurbished using previously developed hardware.[4] Cell hardware and operational improvements were incorporated prior to integration with the one-person ORS. The operational improvements were incorporated into the Control and Monitor Instrumentation (C/M I). Specific cell improvements developed as part of the present program and included into the 6-cell module prior to test initiation included:

1. High capacity current collectors.
2. New insulation plates with integral coolant passages.
3. Improved electrode configuration.
4. Injection molded frames with critical feed diameter passages.
5. Improved O-rings minimizing permanent compression set.

These improvements are discussed in more detail in a later section of this report.

Improvements incorporated into the C/M I included:

1. Modification of the water tank fill cycle.
2. Improved current controller stability.

The new water tank fill cycle eliminated self-repressurization of the water feed tank by using purge N_2 instead of module-generated O_2. Incorporation of this concept eliminated adverse pressure spikes between H_2 and O_2 cell compartments. Also, improved circuit designs increased the stability of the module current controller.

Four-Person Laboratory Breadboard

The OGS hardware used for the one-person laboratory breadboard testing was scaled-up and modified to allow it to be operated as part of a closed O_2 loop using an EDC for CO_2 collection, a Bosch CO_2 Reduction Subsystem (B-CRS) and a simulated crew space. The ORS was designated as a Laboratory Breadboard Bosch-based O_2 Reclamation System, four-person, air-cooled (LBS-B/ORS-4(A)).

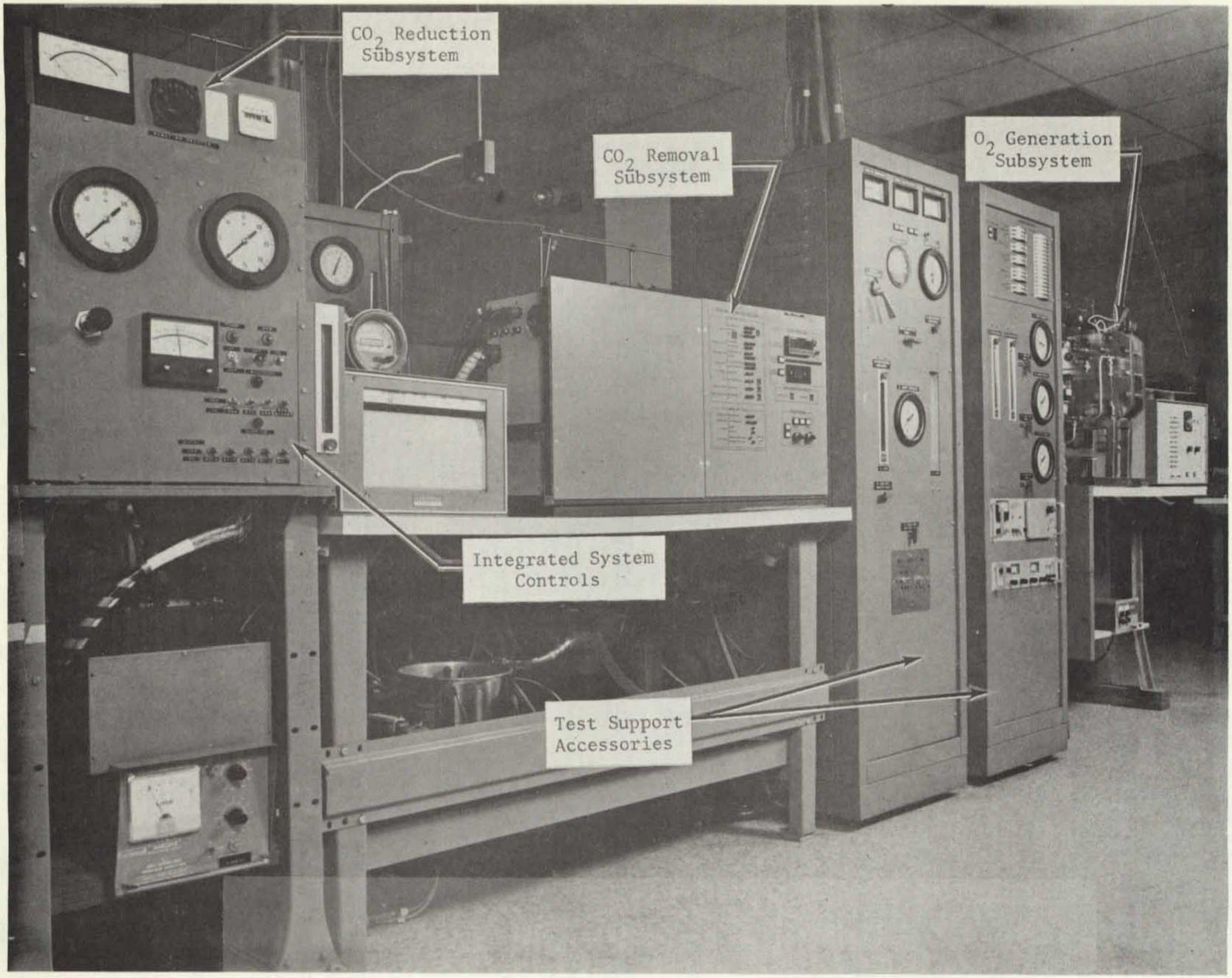

FIGURE 8 ONE-PERSON LABORATORY SYSTEM TEST FACILITY

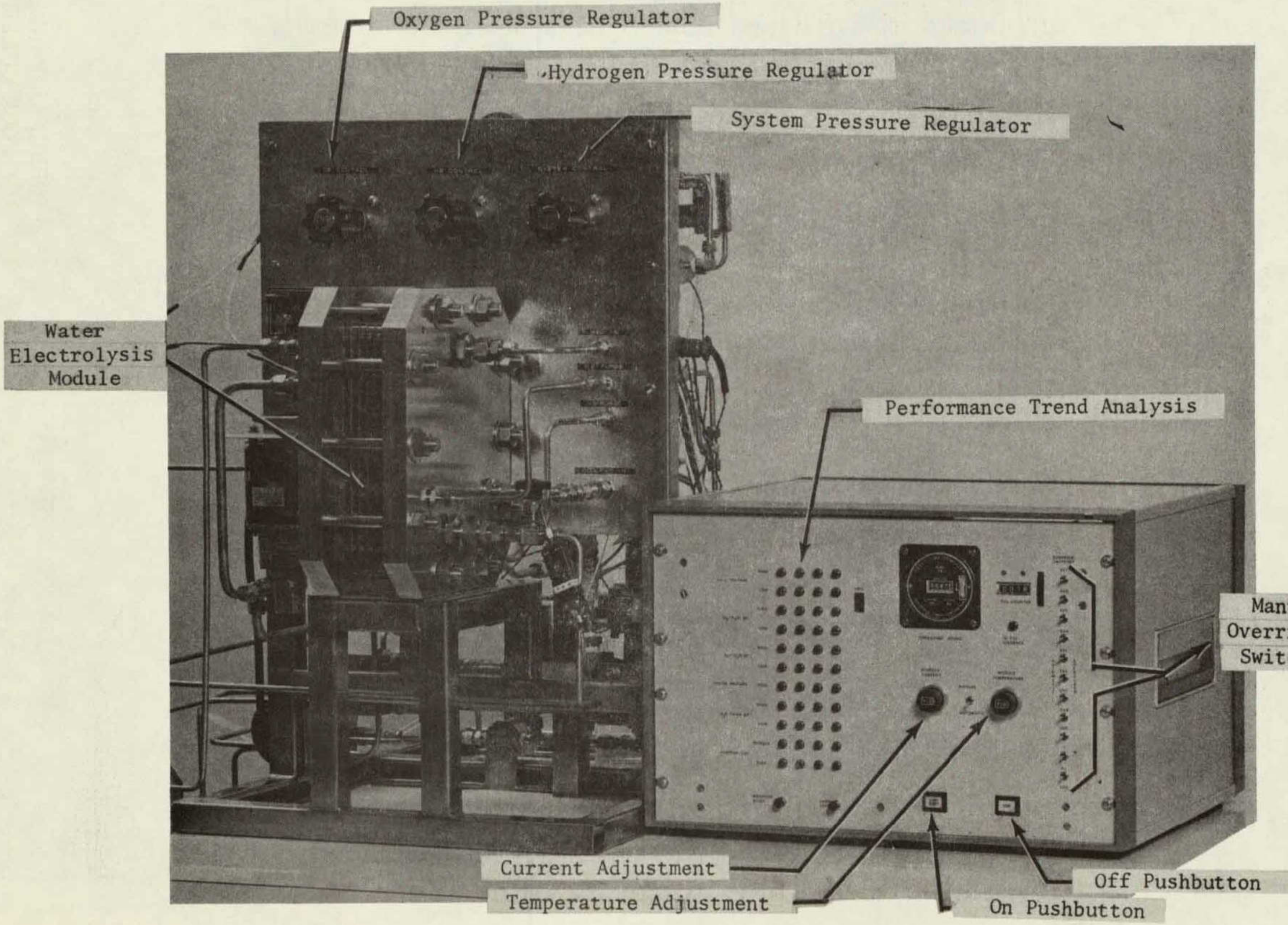

FIGURE 9 ONE-PERSON OGS

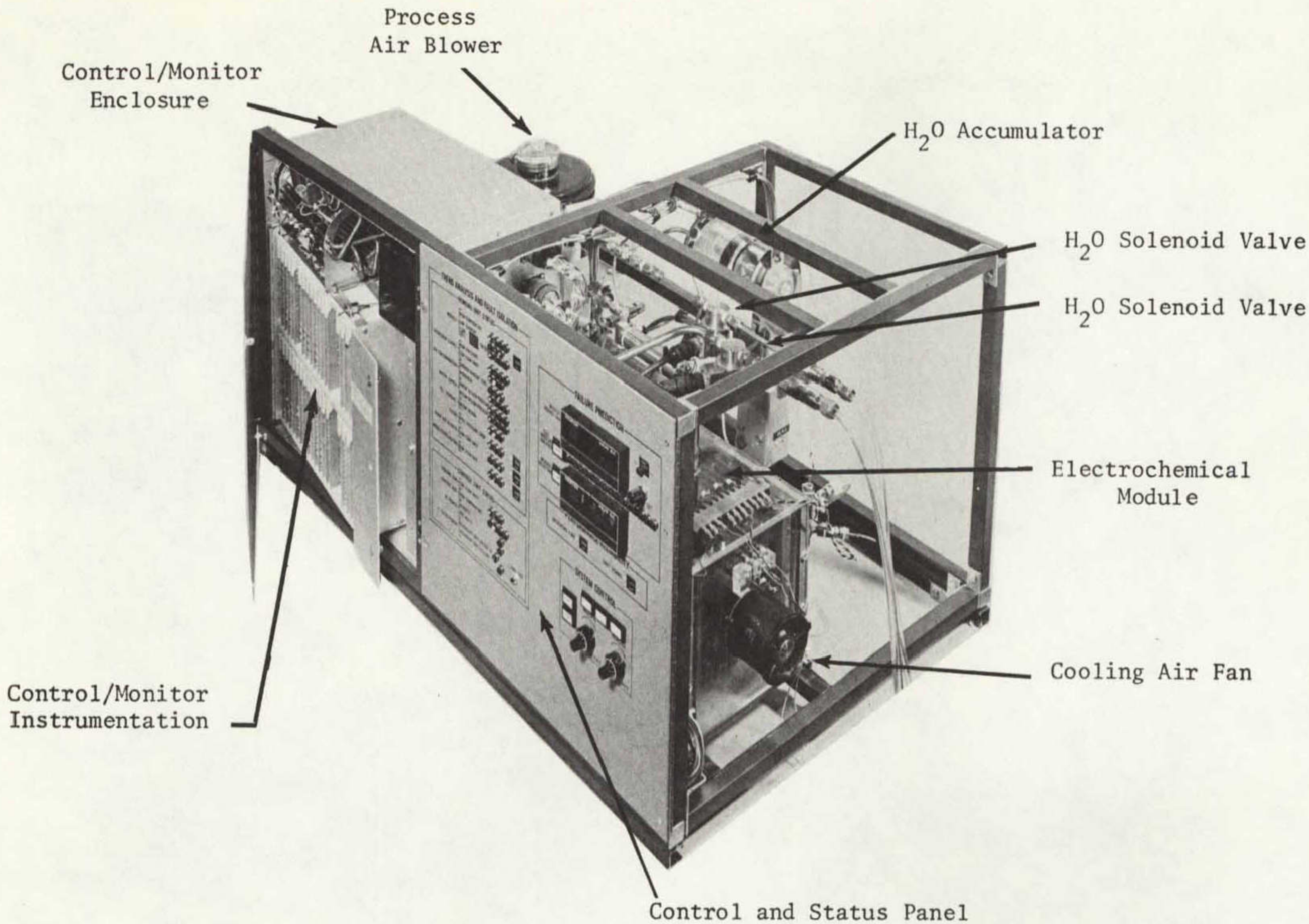

FIGURE 10 ONE-PERSON ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR

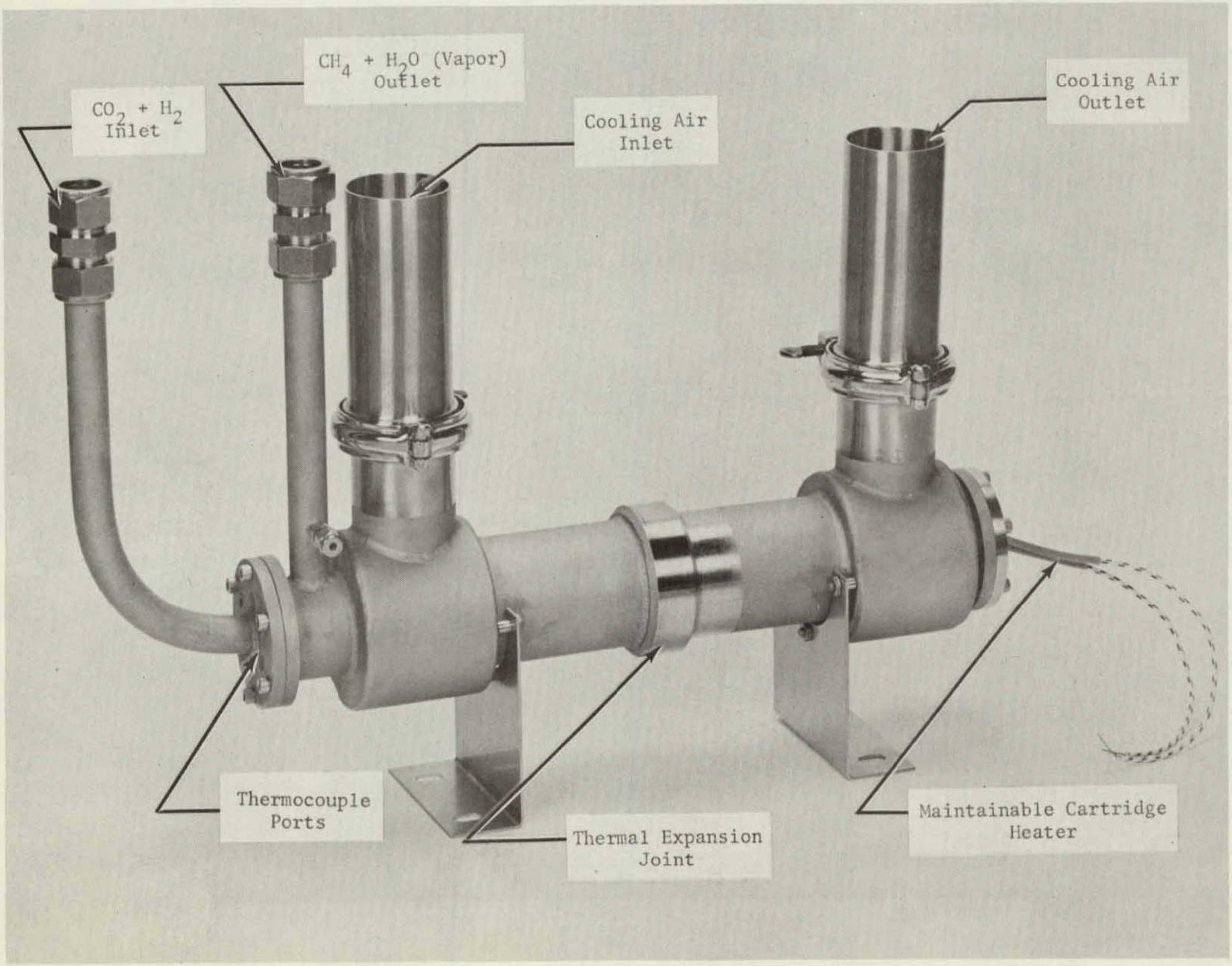

FIGURE 11 ONE- TO THREE-PERSON SABATIER REACTOR

Objectives. The overall objectives of the activities provided to the four-person laboratory breadboard were:

1. Demonstrate scale-up capability of the SFWEM by increasing the number of cells from 6 to 12.

2. Supply electrochemically regenerated H_2 to the B-CRS and electrochemically generated O_2 and H_2 to the EDC.

3. Verify the control concept derived for operation of an ORS using a SFWES, an EDC and a B-CRS.[12]

Integrated Test Benefits. The benefits achieved by testing the multi-person OGS as part of an ORS are similar to those derived with the one-person laboratory breadboard but using NASA's alternate CO_2 reduction process. Also, performing the integration at the multi-person level results in increased confidence in the processes selected.

Block Diagram and Operation. A block diagram of the four-person, closed O_2 loop integrated system is shown in Figure 12. As shown the OGS supplies O_2 to the crew space for metabolic consumption, spacecraft leakage and EDC requirements. The byproduct H_2 is sent to the EDC where it is premixed with the CO_2 removed from the cabin atmosphere prior to being sent to the B-CRS where it is converted to water and solid carbon. The water produced by the B-CRS is returned to the OGS. The byproduct water of the electrochemical CO_2 removal process is returned to the cabin as water vapor for condensing and eventual use in the OGS. A more detailed description of the four-person ORS has been presented elsewhere.[12]

Hardware Description. The OGS hardware used for the one-person laboratory breadboard (see Figure 9) was scaled-up and modified to allow integration with the four-person ORS. First, the module parts necessary to increase the SFWEM from 6 to 12-cells were fabricated and assembled. Then the mechanical subsystem was replumbed to accept the larger module and to allow interfacing with the other subsystems of the four-person ORS.

To accommodate the larger capacity SFWEM, the C/M I of the OGS was modified to allow handling the larger current requirements. Also, to retain individual cell monitoring for automatic subsystem protection the cell scanning circuits were increased to handle the 12 cells.

A detailed schematic of the OGS used for the four-person testing, a block diagram showing the three major subsystems and associated TSA, as well as baseline system flow conditions are presented in Appendix 2.

The EDC and the B-CRS hardware that was integrated with the OGS to form the four-man capacity ORS is shown in Figures 13 and 14, respectively. Each of these two subsystems is pictured with its associated TSA.

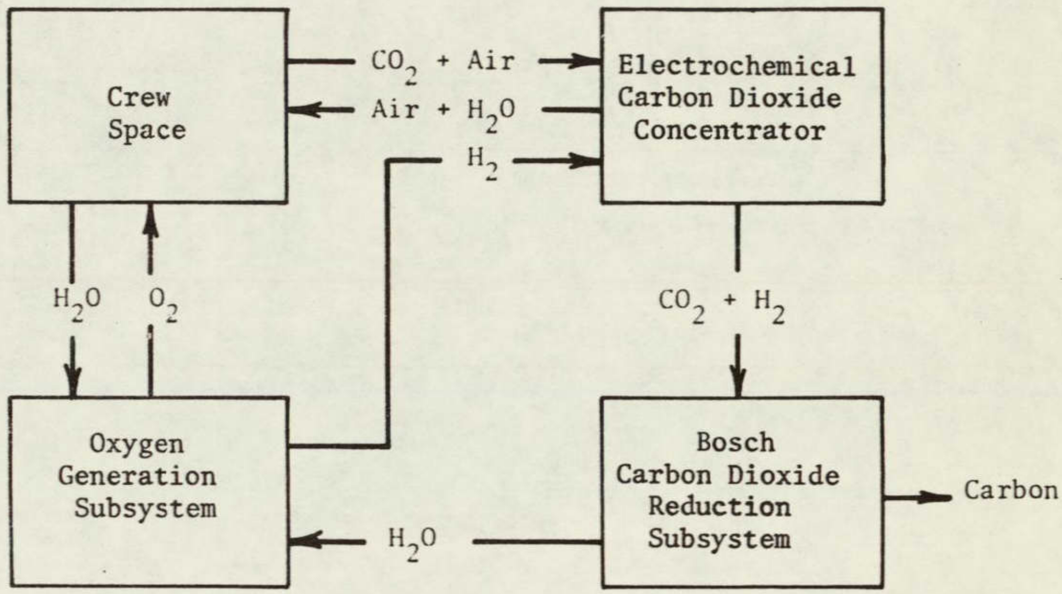

FIGURE 12 CLOSED OXYGEN LOOP WITH INTEGRATED EDC/B-CRS/OGS

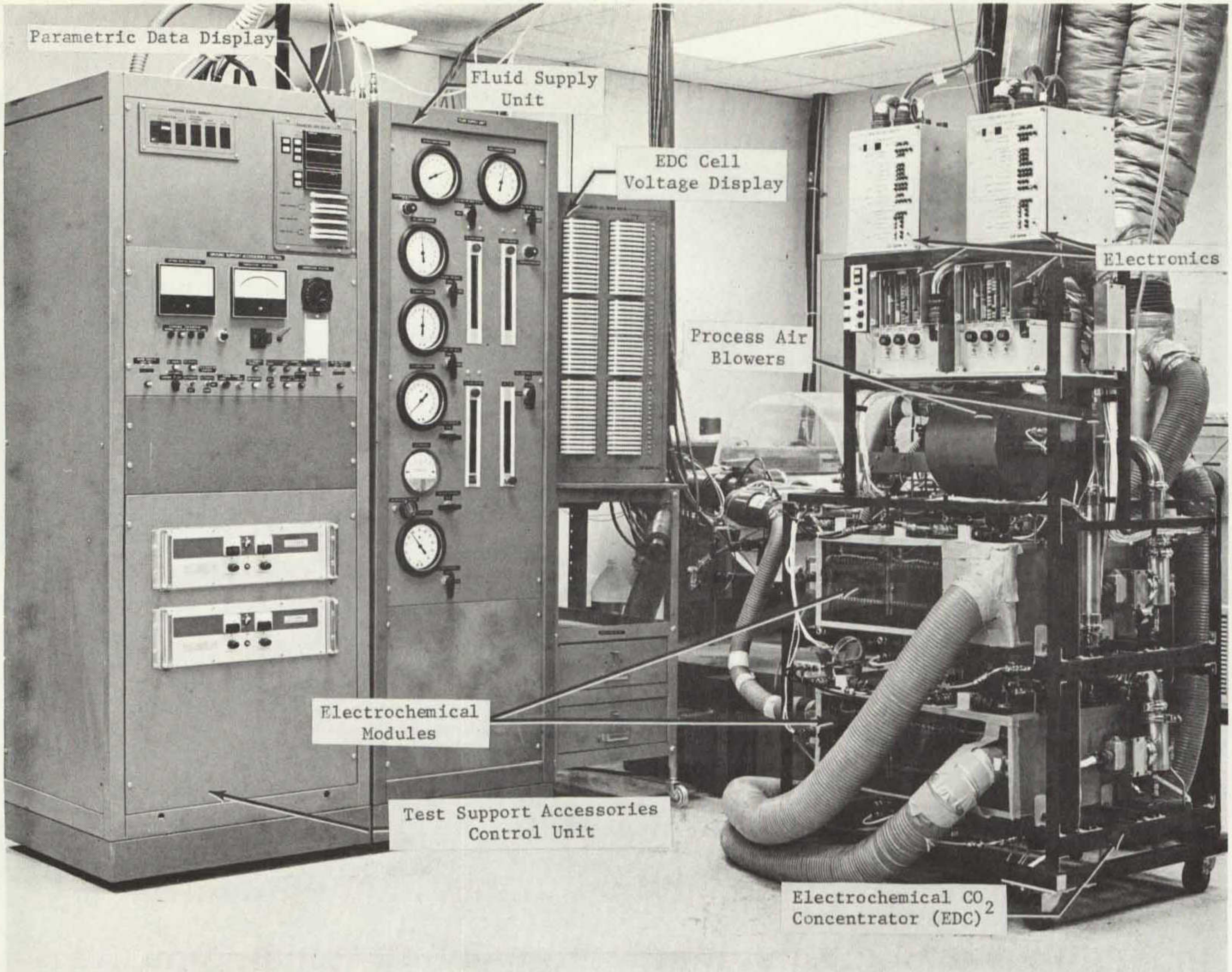

FIGURE 13 ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR WITH ASSOCIATED TSA

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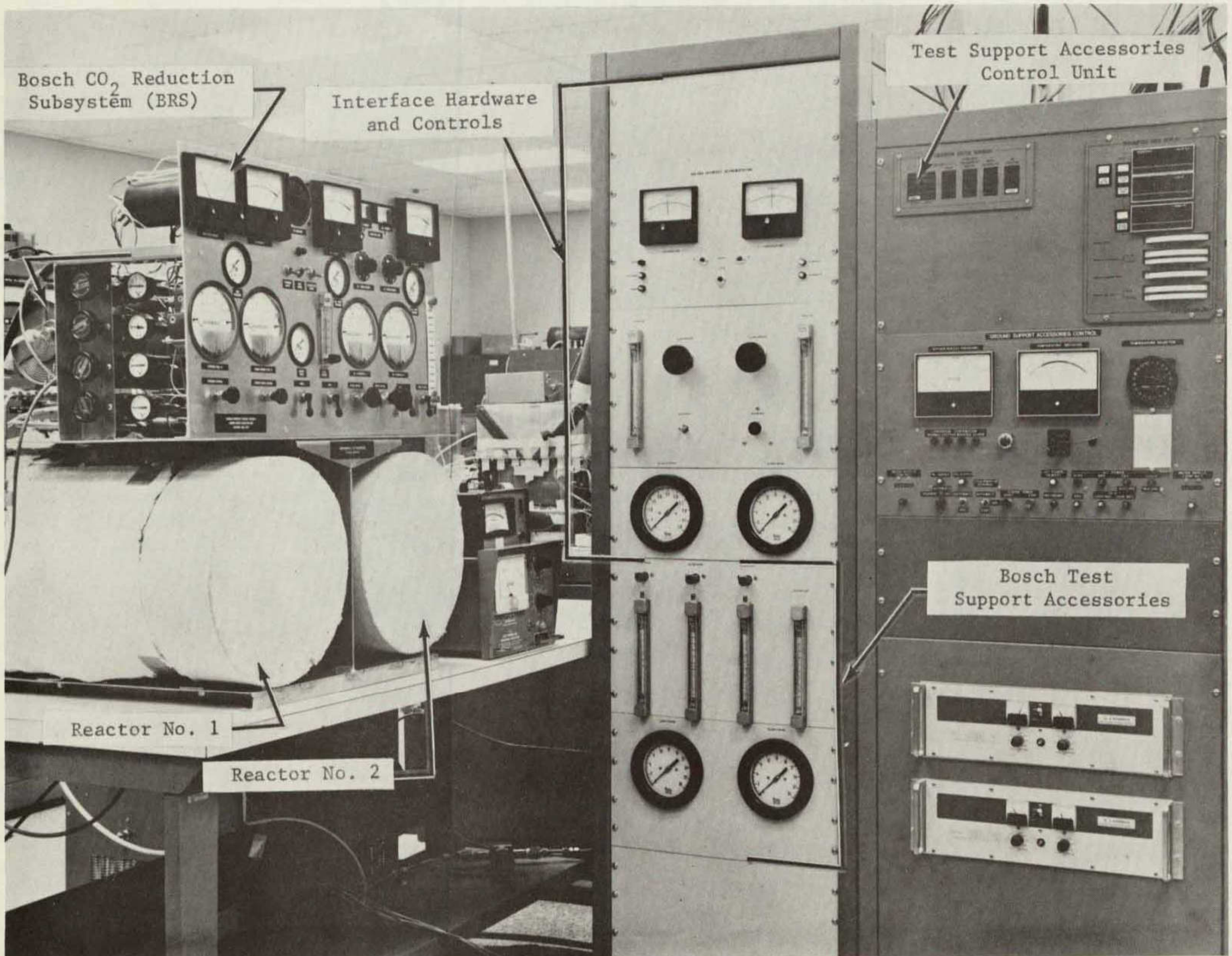

FIGURE 14 BOSCH CO_2 REDUCTION SUBSYSTEM WITH ASSOCIATED TSA

COMPONENT DEVELOPMENTS

The component development activities were concentrated on the electrochemical module and selected peripheral subsystem components.

Electrochemical Module Hardware

Hardware improvements were incorporated at the cell and module level. A one-person combined static feed/dehumidifier module incorporating the improvements was designed, assembled and checked out.

Cell Level Hardware

Five areas requiring improvement had been identified:[4]

1. Dimensions of the water feed passages.
2. Location and shape of the anode current collector tabs.
3. Material hardness of the anode current collector
4. Flatness of injection molded cell frames.
5. Permanent set in the redundant O-ring seals.

Table 6 presents, in summary form, the hardware area/concept needing improvement, the impact on cell operation and a brief description of the implemented improvement for each of the five areas addressed.

Water Feed Passages. The dimensions of the water feed passages of the previously tested cell design[4] were too large to prevent gas entrapment due to sporadic gas bubbles. The resulting entrapment could cause maldistribution or discontinuities in the water feed to individual cells. The critical diameter for water at the projected operating conditions of the SFWEM was calculated, implemented at a single-cell level and verified through testing.

Current Collector Tab Location. Post-test analyses of previously operated cells[4] had indicated that current maldistributions existed between adjacent cells. Through mapping (current flow versus voltage drop) the problem was traced to the current connection made previously in one corner of the anode current collector. A new current collector design was completed which placed the current collection tab in the center of the leading edge of the collector. Voltage drop versus current flow mapping tests showed that current maldistribution problems had been eliminated.

Current Collector Material Selection. The original nickel (Ni) current collectors deformed under high pressure due to the low yield strength of the raw material. The resulting deformation caused internal leaks in the SFWEM. The material specification for the Ni current collectors was changed from using fully annealed Ni to hard Ni sheet. Calculations showed that the new hard Ni would prevent deformation at pressures in excess of those projected for the SFWEM.

Cell Frame Warpage. The original SFWEM cells showed signs of warpage following injection molding and cool-down. Initially, each individual cell frame was annealed in a hot-air oven.[4] As part of this program, the injection mold

TABLE 6 SFWE CELL HARDWARE IMPROVEMENTS

	Hardware Area/Concept Needing Improvement	Impact on Cell Operation	Improvement Description
1.	Water Feed Passages	Stagnant gas bubbles could accumulate and block water feed.	Made water feed passage dimensions less than critical dimension for water to eliminate gas entrapment.
2.	Anode Current Collector Tab Location and Shape	Small tabs located in corner caused current maldistributions and localized heat up.	Increased tab size and relocated in center. Configuration used generous radii.
3.	Anode Current Collector Material Hardness	Low yield strength nickel (raw material) deformed into cooling channels causing leaks.	Selected high strength nickel instead of fully annealed nickel.
4.	Injection Molded Cell Frame	Frames warped after molding process causing leaks.	Reworked mold to incorporate coring (more uniform cross section of frame) and researched literature[13] to establish preferred injection molding conditions.
5.	Internal to External Redundant O-Ring Seal	Excessive permanent set caused loss of redundant seal.	Designed special O-ring mold and used preferred compound.

was redesigned to minimize large changes in cell cross sectional thickness. The more even cross sections were achieved through the use of mold coring. Also, a literature search suggested that warpage improvements are possible if the molding conditions are optimized.[13]

Modifications to the injection mold were completed and improved molding conditions specified. Parts required under the program were successfully molded using the new techniques and mold. The frames were flat and could be used without the annealing process.

O-Ring Compression Set. The design of the SFWEM includes double O-ring sealing around all H_2 carrying cavities for increased reliability. To keep the overall size of the cell to a minimum, non-standard O-rings supplied by different vendors had been selected. One of the O-rings (providing a redundant seal between the internal cavities and the environment) showed excessive permanent set following extensive testing.[4] The remaining O-rings supplied by one specific vendor were satisfactory but were unavailable in the precise size required.

A special mold was designed and fabricated and the one vendor's proven compound was used to manufacture new O-rings. The new O-rings successfully sealed the cells and subsequent disassemblies showed minimal permanent set.

Module Level Hardware

Improvements at the module level were incorporated in two areas: (1) the module insulation plates and (2) the water feed manifold sizing.

Improved Insulation Plate. A new improved insulation plate with integral liquid-cooling compartment was designed, fabricated and tested. The cooling channel was added to the insulation plate to provide a thermal environment for the top end cell similar to that of any other cell within the module. Normally, a cell will receive its cooling from an adjacent cell frame which forms the cooling cavity. Without the special insulation plate, the top end cell did not receive a similar environment.

Water Feed Manifold. Entrapment of sporadic gas bubbles similar to that possible in the individual cell water feed passages is also possible within the module water feed manifold. Using similar calculations, a manifold insert was sized, installed in a 12-cell module and used successfully to verify uniform water feed distribution.

One-Person Combined Static Feed/Dehumidifier Module

A one-person capacity module was designed, fabricated and assembled. The combined module was designed to supply the combined function of generating O_2 for metabolic, cabin leakage and EDC needs as well as producing product gases at a sufficiently low dew point so that condenser/separators are not required. Based on a total O_2 requirement of 1.4 kg/d (3.08 lb/d) and operating at a current density of 209 mA/cm^2 (195 ASF), a 12-cell SFWEM resulted. A 3-cell DM was needed to provide the moisture removal function for the product gases. The module was developed for eventual use in an OGS that will form a portion of a one-man experimental Air Revitalization System (ARX-1) breadboard. The new module employed all of the cell and module level hardware improvements discussed above.

To facilitate packaging the two modules as well as minimizing interconnecting plumbing the two modules were designed to allow endplate-to-endplate assembly. Figure 15 is a photograph of the combined module assembly. The modules were designed with the flexibility to operate separately as well as individually. Figure 16 is a photograph showing the two modules separated. The interconnecting fluid ports are provided with O-ring seals to a-low endplate-to-endlplate assembly, but are also equipped with threaded parts for direct plumbing connections.

Peripheral Components

Peripheral components performing two specific functions within an OGS were evaluated for improvements: (1) maintaining and controlling fluid pressures within the subsystem and (2) circulating liquid coolant for temperature control through the internal cavities of the electrochemical modules.

Pressure Controllers

Within the SFWES the feed water, the product O_2 and the product H_2 pressure levels must be controled. The control concept is such that the O_2 presssure is maintained above the H_2 pressure and the H_2 pressure is maintained above the water feed pressure. In the past, off-the-shelf pressure regulators had proven inadequate in performing this function successfully.

To alleviate the problem a near- and long-term solution approach was adopted. For the near-term, which included all testing under the present program, the best available off-the-shelf pressure regulators were evaluated and modified to meet the requirements. For the long-term solution a special component called a Three-Gas Pressure Controller was designed, fabricated and assembled for eventual use in the OGS to be tested as part of the ARX-1.

Requirements. The pressure controller(s) for the SFWES must meet the following fluidic requirements:

1. Pressure differential control capability to 3.4 kPa (0.5 psid) over a pressure range from ambient to 2760 kPa (400 psia).

2. Total pressure control capability for both the low density H_2 and higher density O_2 from zero flow to the flow levels required by a six-person OGS.

3. Materials compatibility with a basic (pH >10) environment.

In addition to the fluidic requirements the pressure controller(s) must have the capability to increase the pressure levels of the three fluids from ambient to operating levels at a predetermined rate(s). Similarly, during a subsystem shutdown the controller(s) must decrease all pressures at a rate sufficiently low to prevent sudden and sporadic dissolution of dissolved gases. At too

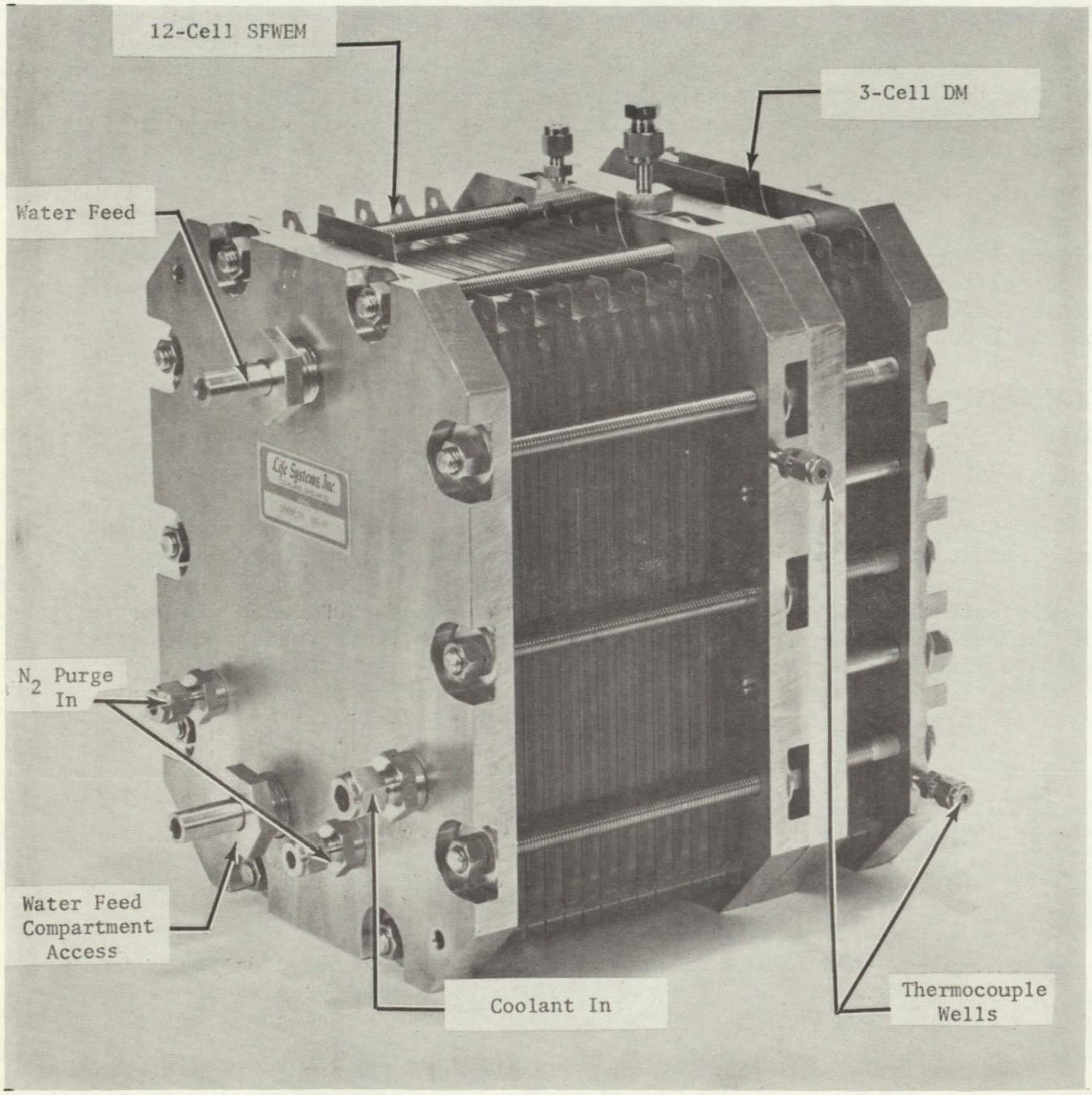

FIGURE 15 STATIC FEED/DEHUMIDIFIER MODULES - COMBINED ASSEMBLY

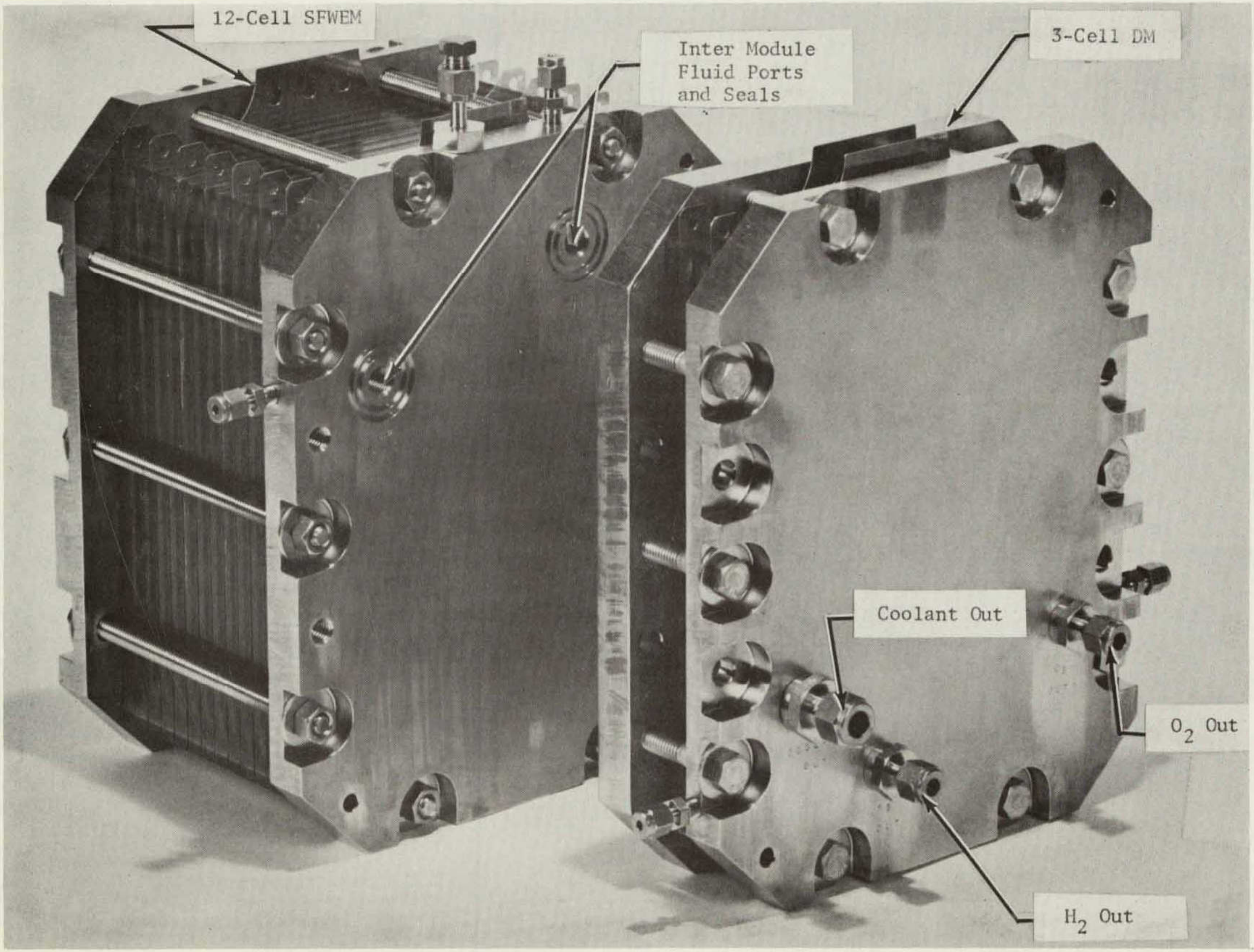

FIGURE 16 STATIC FEED/DEHUMIDIFIER MODULES - SEPARATED

rapid a depressurization rate undesirable shifts of fluids within individual cells can occur.[4]

Modification of Off-the-Shelf Hardware. To meet the near-term requirements of the program testing (support for the one-person and four-person laboratory breadboards), off-the-shelf regulators were identified that required only minor modifications to meet the fluidic requirements outlined above. Three regulators were purchased for the pressure control scheme schematically demonstrated in Figure 2.

The regulators were tested as received, modified and used successfully to complete the program testing. The concept, however, still required manual intervention by the operator during startups and shutdowns to control pressure levels at desired rates and within desired differentials.

Three-Gas Pressure Controller. To meet the unique fluidic and pressure control requirements of the SFWES, a Three-Gas Pressure Controller was designed, fabricated, assembled and checked out. The Three-Gas Pressure Controller combined, in one single assembly, the sensors and actuators necessary to control and monitor fluid pressure levels and differentials. These functions were achieved by incorporating three motor-driven regulators, one total pressure level sensor, two differential pressure sensors and three feedback position indicators in the unit. The assembled Three-Gas Pressure Controller is shown in Figure 17 while Figure 18 is a photograph showing the parts of the controller.

Although weight and volume optimization were not a primary consideration, the Three-Gas Pressure Controller weighed only 3.64 kg (8.0 lb) and occupied a volume of 1.58 dm^3 (96.3 in^3). Its overall dimensions were 17.8 x 12.7 x 7.1 cm (7.0 x 5.0 x 2.8 in). To achieve this small volume, miniaturized sensing elements were used for the total pressure transducer (called out in Figure 17) and the differential pressure transducer shown in Figure 19.

To perform the fluidic pressure control function within the SFWES the Three-Gas Pressure Controller requires five fluid interfaces. Four of these interfaces are used for H_2 and O_2 inlets and H_2 and O_2 outlets while the fifth interface provides the pressure reference to the water feed tank (see OGS concept presented in Figure 2). All fluid interconnections are manifolded internally and sealed with O-rings.

The electrical interface to the Three-Gas Pressure Controller is made via a standard connector. Sensor signals are sent to and actuator drive signals are received from the subsystem C/M I. With these features the Three-Gas Pressure Controller is ideally suited for a closed-loop control concept using microprocessor or minicomputer-based C/M I.

Appendix 3 contains a detailed component specification for the Three-Gas Pressure Controller. An extensive test program of the controller is scheduled as part of follow-on work to the present program. The Three-Gas Pressure Controller is scheduled to be installed into a one-person OGS forming part of the laboratory breadboard ARX-1.

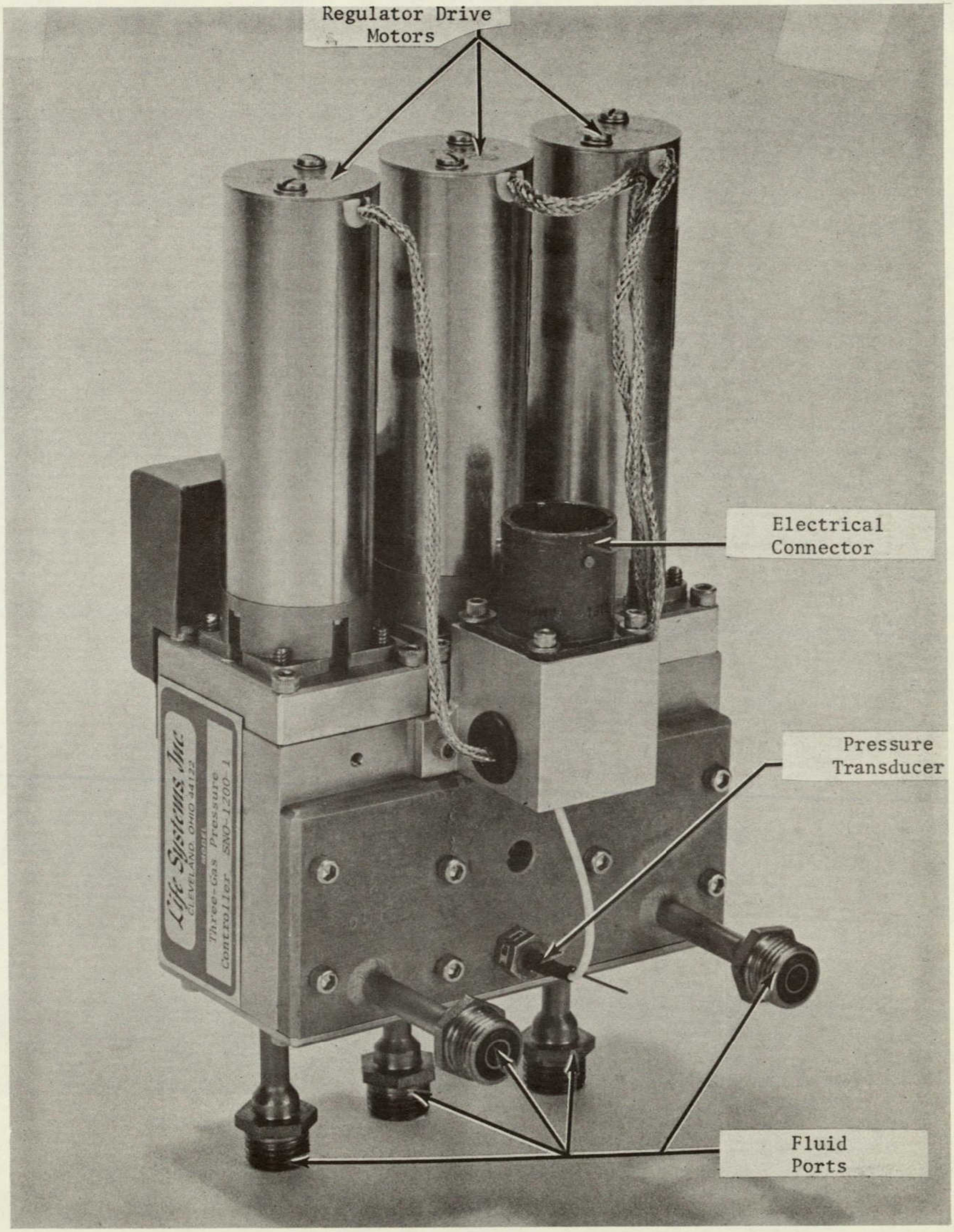

FIGURE 17 THREE-GAS PRESSURE CONTROLLER

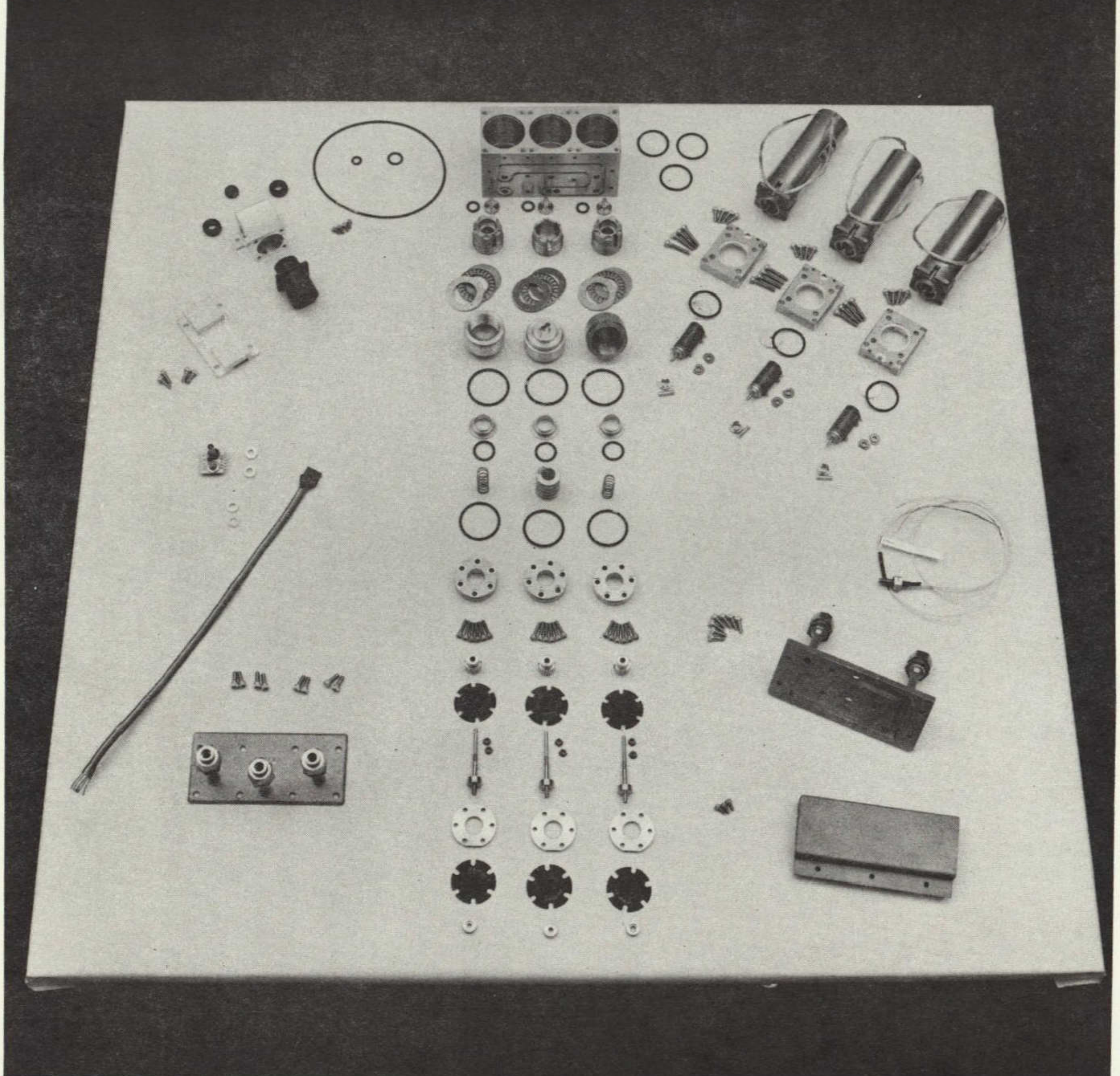

FIGURE 18 THREE-GAS PRESSURE CONTROLLER PARTS

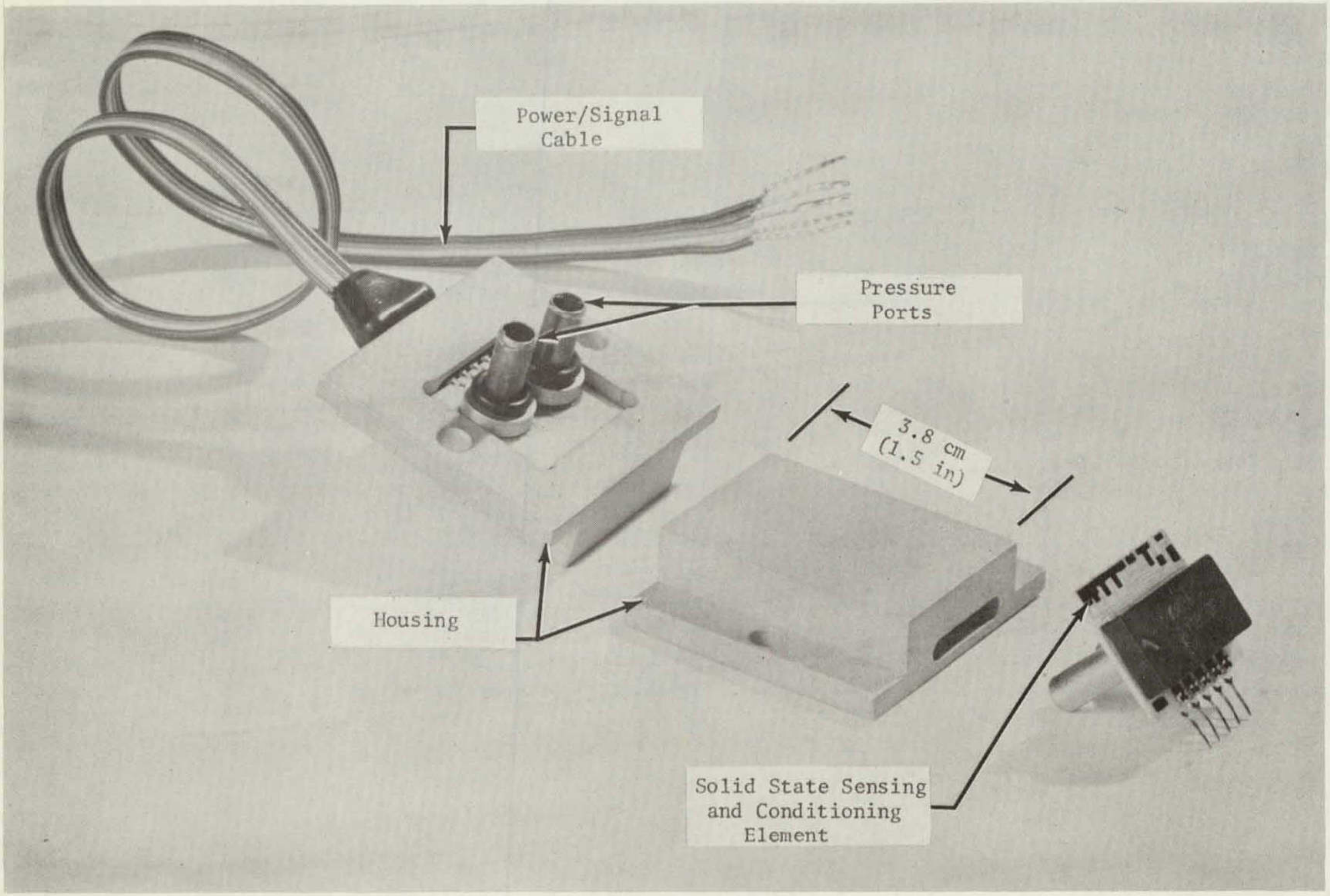

FIGURE 19 MINIATURE DIFFERENTIAL PRESSURE TRANSDUCER

Coolant Pump

An off-the-shelf, gear-type coolant pump had been selected previously for use within the SFWES. This style pump had been selected based on its pressure versus flow characteristics. During past test programs[4] it was noted that periodically internal and external leaks occurred at the pump head.

The coolant pump was disassembled and inspected. The gasketing and pump housing cover were determined to be insufficient for the operating conditions of the SFWES. The pump was modified and tested for an excess of 1,000 hours. No leaks were observed.

TEST SUPPORT ACCESSORIES

Test Support Accessories were designed and fabricated to support single-cell and integrated laboratory breadboard testing.

Single-Cell Test Stand

A low pressure test stand was designed and built to provide a test bed for single-cell work. A schematic of this test stand is shown in Figure 20. The primary purpose of the test stand was to allow for comparative evaluation of high performance electrodes and matrices. Since neither evaluation requires high pressure operation a low pressure approach was selected to conserve program funds.

Laboratory Breadboard TSA

The TSA for the one-person laboratory breadboard and the four-person laboratory breadboard was similar in function and configuration. The primary difference resulted from an upgrading in the capacity when going from the one- to the four-person ORS. Both sets of TSA provided the OGS with electrical power and system level control, process water, and N_2 purge and reference pressure.

Electrical Power and Control

The electrical requirements for the OGS were 24 to 32 VDC for the electrolysis function and 115 VAC, 60 Hz for the C/M I function. The DC power was unregulated and supplied by the TSA to the C/M I enclosure. Intersystem control signals, originating from the OGS, simulated crew space or the other two subsystems of the ORS were controlled by an Electrical Signal Simulator (ESS).

Process Water

The TSA supplied pressurized deionized process water to the interface of the OGS. The TSA consisted of a holding tank and a circulating pump. Deionized water from a laboratory source was controlled to maintain a constant level in the tank. The pump would continually circulate feed water past the OGS interface to simulate a spacecraft pressurized water system. The function of the holding tank was to allow the process water to equilibrate with ambient pressure since tap water supply pressure is normally in excess of 414 kPa (60 psia). At that pressure dissolved gases exist in excess of those experienced in a

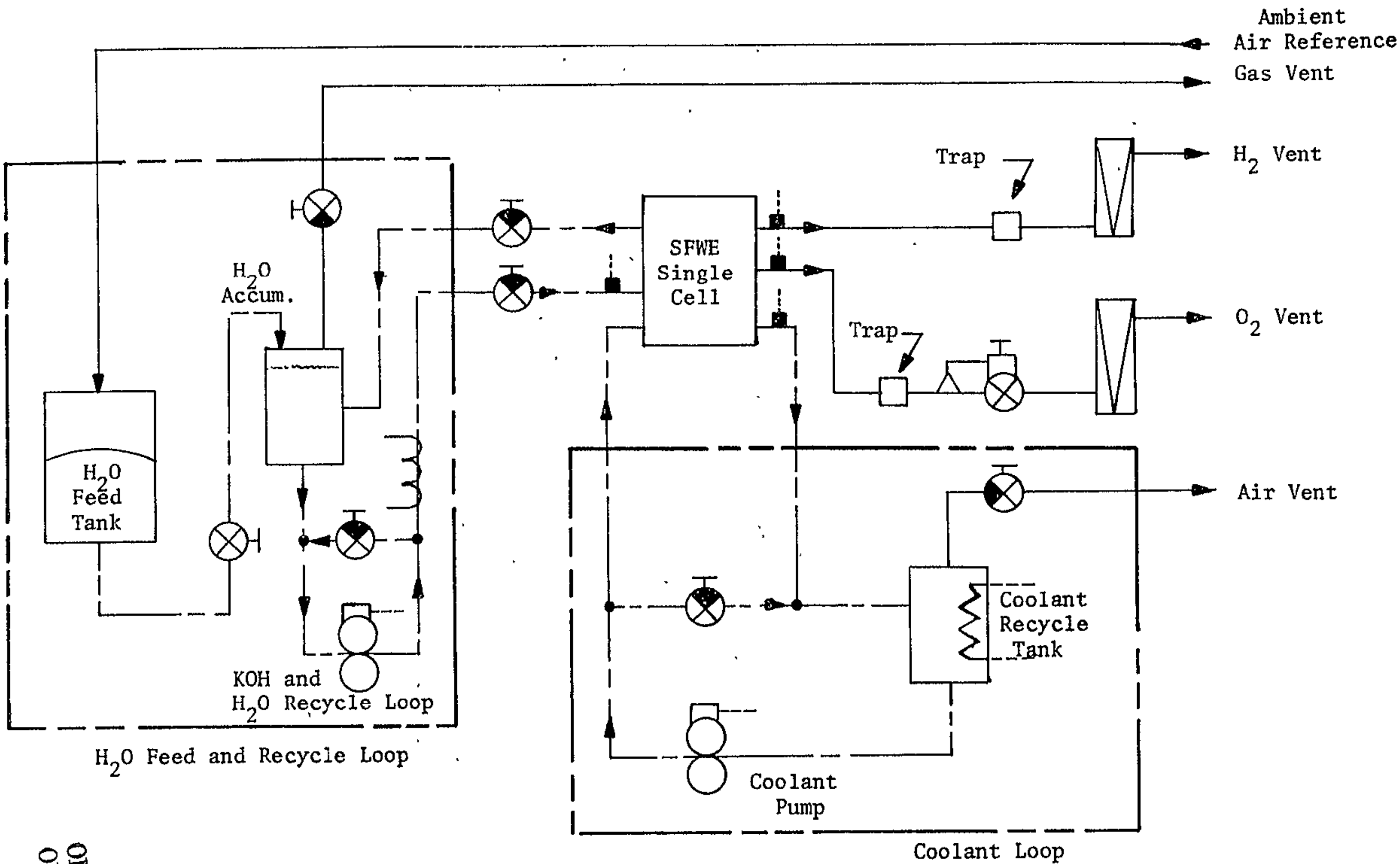

FIGURE 20. SINGLE CELL TEST STAND SCHEMATIC

spacecraft feed water supply. High levels of dissolved gases would require higher OGS operating pressures to eliminate gas accumulation in the feed compartments.

Nitrogen Purge and Reference Pressure

The TSA supplied N_2 for safety purging of the O_2 and H_2 compartments and lines following a subsystem shutdown.

The N_2 supplied by the TSA was regulated to a level equal to that of the system pressure. This reference pressure served as a gas source for subsystem shutdowns not requiring depressurizations. The N_2 pressure source also added the capability of the OGS to operate in a standby mode; i.e., not producing O_2 and H_2, but maintaining the subsystem at temperature and pressure.

MINI-PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance including design, purchasing, fabrication and testing.

Quality Assurance

Quality Assurance activities were included during the design studies, interface requirement definitions and during inspection of fabricated and purchased parts. The objective was to search out quality weaknesses and provide appropriate corrective action. Also, a quality assurance effort was involved in the preparation of the final report with the objective of identifying and resolving deficiencies that could affect the quality of future equipment.

Reliability

Reliability personnel participated in the program to insure (1) proper calibration of test equipment and TSA instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. A survey of the subsystem and TSA design was performed to determine the calibration requirements for testing.. Appropriate components were calibrated during assembly and after installation.

A test procedure was followed to insure that all critical parameters were properly monitored and that the testing conformed to the program's quality assurance and safety procedures. All major testing required that a test plan be completed and reviewed.

Safety

A safety program was initiated to assure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted of identifying possible adverse subsystem characteristics, reviewing designs and design changes for potential safety hazards, reviewing NASA Alerts for safety information and incorporating the equipment's protective features.

Materials Control

A mini-materials control program was initiated to provide assurance that the OGS will not preclude the efficient application of a more detailed subsystem materials control program during subsequent developments. As a goal materials of construction were selected to comply with projected spacecraft material specifications.

Configuration Control

A mini-configuration management program was established, implemented and maintained. This program provided for documentation concerning interface requirements for the OGS as applicable for the laboratory breadboard testing. The program was implemented with a primary goal to provide assurance that the efficient application of a more detailed configuration management program can be applied during subsequent development of the OGS hardware.

PROGRAM TESTING

The overall objectives of the test program were to (1) demonstrate the reduction in OGS power needs by testing advanced electrodes at the single-cell level and (2) advance integrated system technology by supporting test programs of two laboratory breadboard ORSs.

Single-Cell Tests

The OGS consumes the largest amount of power compared to the other subsystems of a spacecraft's ARS. The major portion of this power goes directly to the electrolysis module where water is broken down electrochemically into O_2 and H_2. Past efforts have been directed toward decreasing the cell voltage required for a SFWE cell.[3-5,8,14] These efforts were continued under the present program. Two areas of reducing cell voltage were addressed, (1) increase in cell operating temperatures and (2) use of improved catalyst for the O_2-evolving electrode (anode).

High Temperature Testing

Water electrolysis cell voltage is a strong function of operating temperature. As the temperature increases, the power required for the cell to produce the product O_2 and H_2 gases is reduced. For actual hardware this temperature dependence is generally in the order of a 4.3 mV decrease/K (2.4 mV decrease/F) rise in temperature over a temperature range of 295 to 354 K (72 to 178 F).

The upper temperature limit for baseline SFWE cells has been 355 to 366 K (180 to 200 F) with the cell matrix material (chrysotile asbestos) being the limiting material. Previous work[4] and activities conducted under the supporting technology studies of the present program (presented below) have identified an alternate cell matrix material good for long-term operation to temperatures of 394 K (250 F). This material is potassium titanate (PKT).

A single-cell using the PKT matrix was assembled and its performance characterized at an operating temperature of 366 K (200 F). The cell exhibited good performance as indicated in the cell voltage versus current density plot presented in Figure 21. Two such performance curves were obtained, one immediately after startup of the single-cell and one after 48 hours of operation.

An initially-scheduled 30-day endurance test with the high temperature single-cell was terminated after four days of operation due to two factors: (1) the supplier for PKT fibers notified its users that the PKT material would no longer be commercially-produced and (2) a Contractor-developed high performance anode (WAB-6) exhibited extremely low cell voltages at operating temperatures compatible with chrysotile asbestos. A lower operating temperature is more desirable and practical since high temperature operation of a SFWEM is questionable due to the low waste heat available to maintain the high hardware temperatures. It was concluded that raising cell operating temperatures through an external heat source (e.g., waste heat from another subsystem) would complicate OGS/ARS integration and would not be compatible with low system hardware weights.

As a result, the 26 days remaining from the scheduled 30 days of high temperature single-cell testing was added to a 30-day test scheduled with the Contractor's advanced anode.

Advanced Catalyst Tests

Under a past NASA Ames Research Center sponsored program an advanced catalyst and substrate combination had been derived that exhibited low cell voltages over large ranges in current density.[4] While the absolute performance of this combination was excellent its long-term operating capability was not. The present program activities continued the evaluation of low power consuming electrolysis cell electrodes by testing a Contractor-developed anode (designated WAB-6).

The program requirements called for testing the advanced anode at a single-cell level for a period of 30 days with an additional 26 days of testing to be added based on the time remaining from the high temperature testing. During endurance testing, cell voltage versus current densities spans were scheduled periodically.

These contractual requirements were exceeded by (1) testing the initial advanced anode (WAB-6-1) for a total of 76 days or an excess of 20 days, (2) constructing a second advanced anode (WAB-6-2) and testing it for a total of 30 days at a current density of 161 mA/cm^2 (150 ASF), and (3) testing the WAB-6-2 anode for an additional 30 days at a current density of 323 mA/cm^2 (300 ASF). The second advanced anode (WAB-6-2) was constructed to verify repeatability of the advanced electrode manufacturing process.

The advanced anode test results are shown in Figures 22 through 24. Figure 22 shows 35 days of initial operation of the WAB-6-1 electrode followed by 41 days of final testing of the same electrode. The current density for the testing was varied periodically as indicated in Figure 22, while the operating temperature was maintained between 350 and 360 K (171 to 189 F).

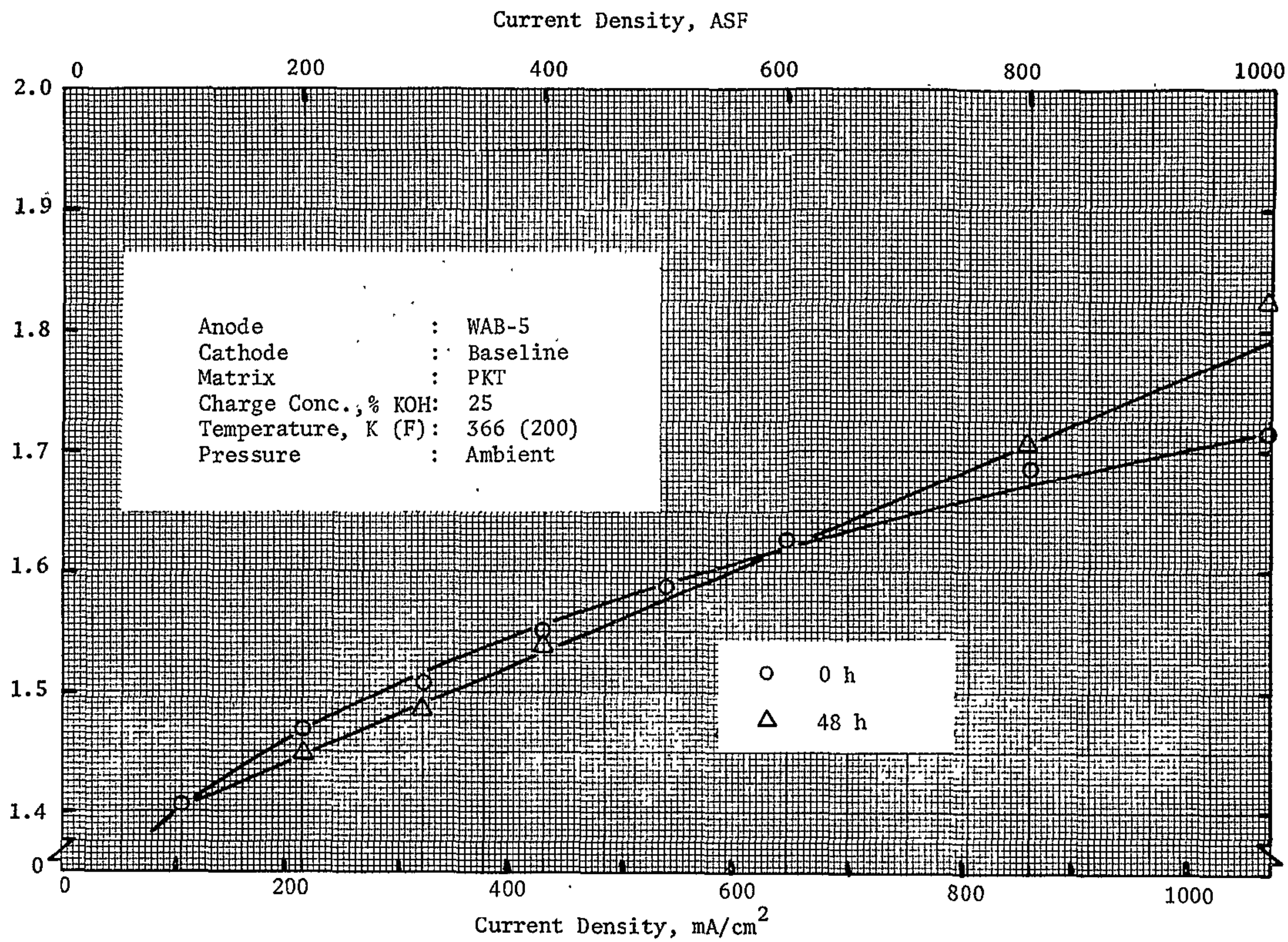

FIGURE 21 SINGLE CELL HIGH TEMPERATURE PERFORMANCE

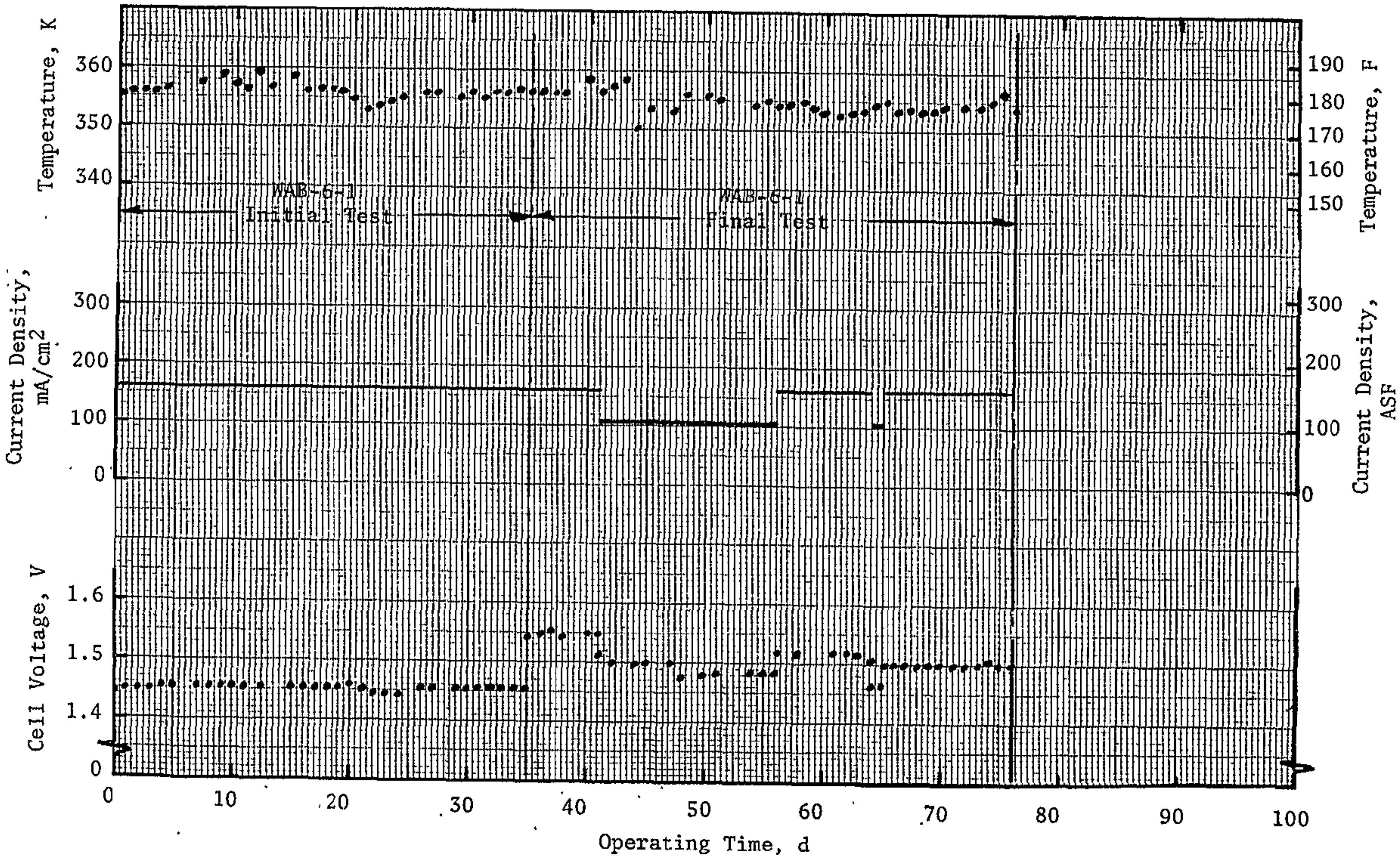

FIGURE 22 ADVANCED CATALYST SINGLE CELL ENDURANCE TEST (WAB-6-1)

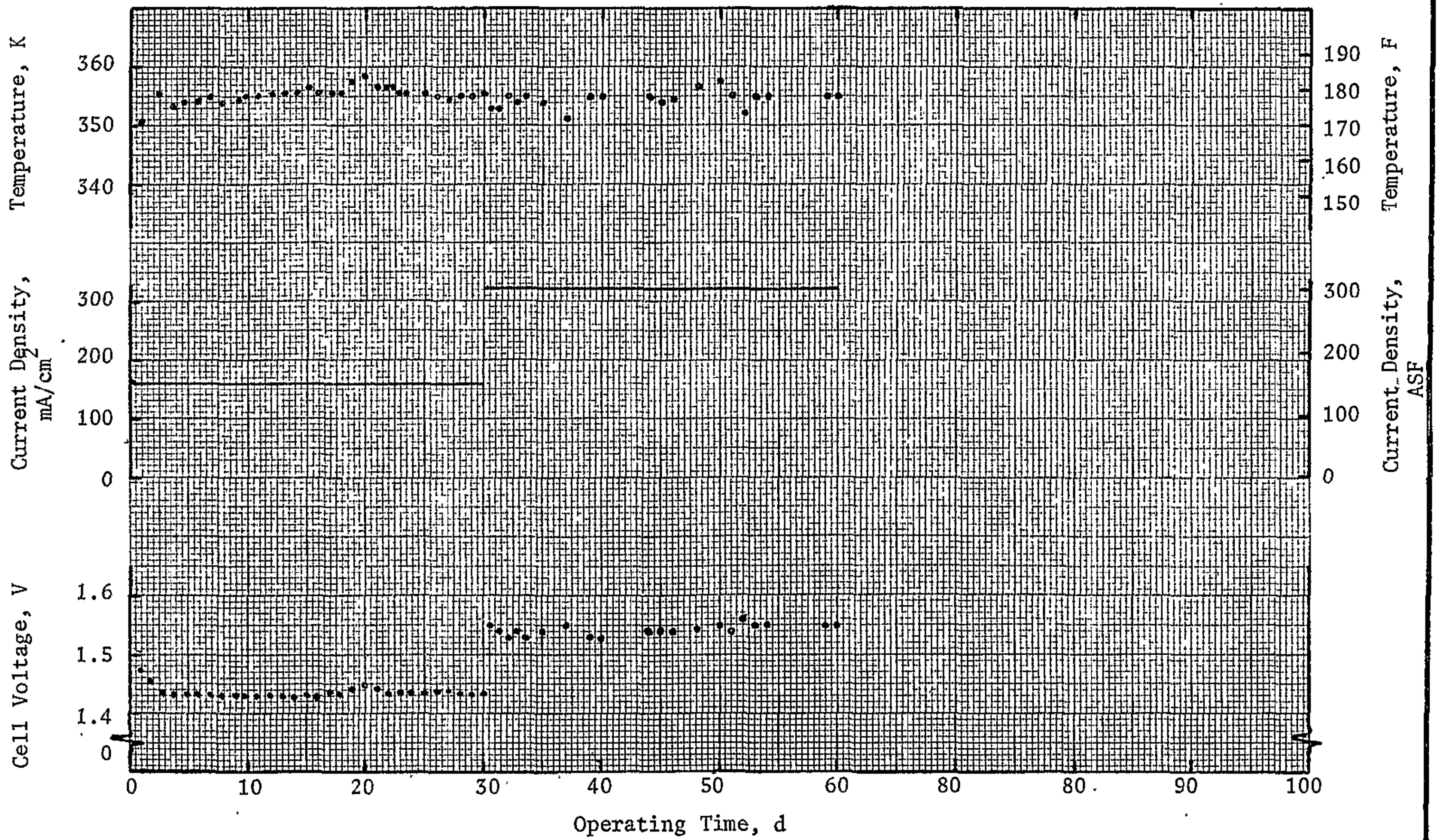

FIGURE 23 ADVANCED CATALYST SINGLE CELL ENDURANCE TEST (WAB-6-2)

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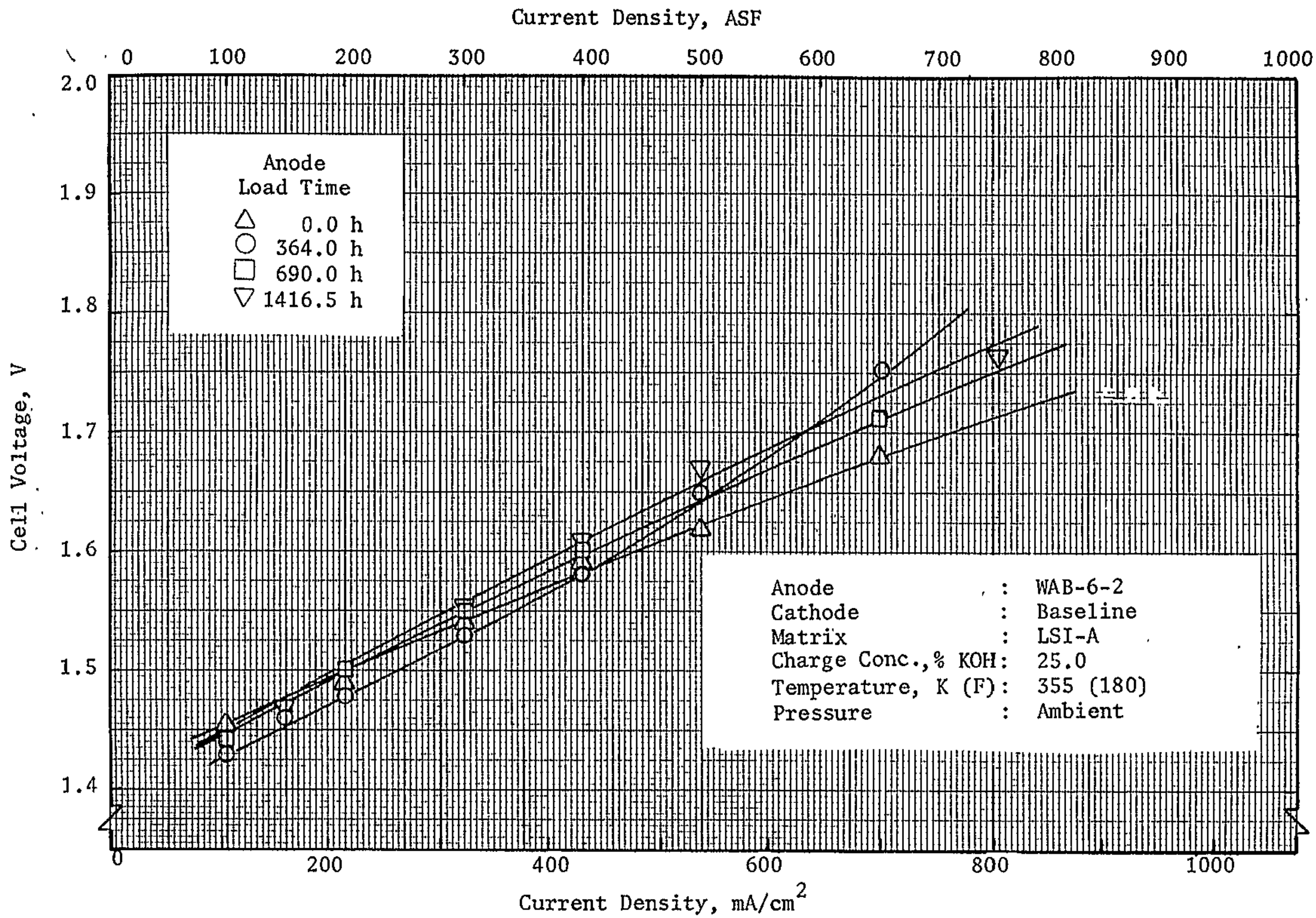

FIGURE 24 ADVANCED CATALYST PERFORMANCE VERSUS CURRENT DENSITY (WAB-6-2)

To verify the reproducibility of the advanced electrode manufacturing process a second anode (WAB-6-2) was fabricated and tested. The WAB-6-2 electrode was tested for 30 days at a current density of 161 mA/cm^2 (150 ASF) for direct comparison with the WAB-6-1 electrode. To verify the capability of the advanced anode to operate also at stable voltage levels over an extended period of time at elevated current densities, the WAB-6-2 electrode was tested for 30 days at a current density of 323 mA/cm^2 (300 ASF). The 60 days of total testing are shown in Figure 23. The cell voltage averaged 1.43 and 1.55 V at 161 mA/cm^2 (150 ASF) and 323 mA/cm^2 (300 ASF), respectively, at an average operating temperature of 355 K (180 F).

The current density spans performed at four different operating times with the WAB-6-2 electrode are presented in Figure 24. Besides the excellent absolute voltage levels shown in Figure 23, the cell experienced only a voltage change from 1.475 to 1.495 V at 200 mA/cm^2 (189 ASF) over an operating time from 0 to 1,416 hours (0 to 59 days).

Integrated System Tests

Two integrated system tests were performed: a one-person level test and a four-person level test.

One-Person Laboratory Breadboard

A one-person capacity OGS was integrated with an EDC and a S-CRS to form the LBS-S/ORS-1(L) and was tested for a 30-day period. The OGS hardware used was that shown in Figure 9.

Prior to test initiation baseline operating conditions for the integrated system were established. These conditions are listed in Table 7. The conditions selected for the 6-cell SFWEM were those that would generate a metabolic O_2 requirement for one person (0.84 kg/d (1.84 lb/d) of O_2). The endurance test was performed maintaining the baseline conditions at constant values.

The performance of the one-person OGS for the 30 days of testing is shown in Figure 25. The average of the 6-cell voltages, the current density, the representative module temperature and the overall system operating pressure are plotted in Figure 25 as a function of the 30 days of operation. Of special interest is the level and constant average cell voltage of 1.7 V at a current density of 209 mA/cm^2 (194 ASF). The 6-cell module employed previously developed anodes (WAB-5) since manufacture of the lower voltage WAB-6 anodes was not part of the present program. The average module temperature of 340 K (153 F) and pressure of 1000 kPa (145 psia) were compatible with projected OGS operation. These conditions were sufficient to prevent liberation of dissolved gases within the water feed compartments.

Four-Person Laboratory Breadboard

The one-person capacity OGS was scaled-up to support the four-person ORS testing conducted as part of NASA Marshall Space Flight Center Contract NAS8-30891.[12] The scaled-up OGS was integrated with an EDC and a B-CRS to form the LBS-B/ORS-4(A). The testing consisted of a familiarization test, an

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TABLE 7 BASELINE OPERATING CONDITIONS FOR THE LBS-S/ORS-1(L)

Process Air Inlet	
pCO_2, Pa (mm Hg)	400 (3.0)
Air Flow Rate, dm^3/min (scfm)	227 (8.0)
Dew Point Temperature, K (F)	286 to 289 (56 to 60)
Dry Bulb Temperature, K (F)	291 to 294 (65 to 70)
Relative Humidity, %	61 to 84
EDC Module	
Number of Cells	5
Current, A	13.7
Current Density, mA/cm^2 (ASF)	30.1 (28)
Temperature, K (F)	296 to 298 (73 to 77)
Pressure, kPa (psia)	101 (14.7)
Cell Voltage, V	0.3
CO_2 Removal Efficiency, %	74
Power Generated, W	20.6
Heat Generated, W	65.1
Water Electrolysis Module	
Number of Cells	6
Cell Current, A	19.4
Cell Current Density, mA/cm^2 (ASF)	208.8 (194)
Temperature, K (F)	333 to 339 (140 to 150)
Pressure, kPa (psia)	965 (140)
Cell Voltage, V	1.60
Power Required, W	186.2
Heat Generated, W	14.0
Sabatier Reactor	
Temperature, K (F)	644 (700)
Pressure, kPa (psia)	108 (15.7)
CO_2 Reduction Efficiency, %	68
H_2 Conversion Efficiency, %	96

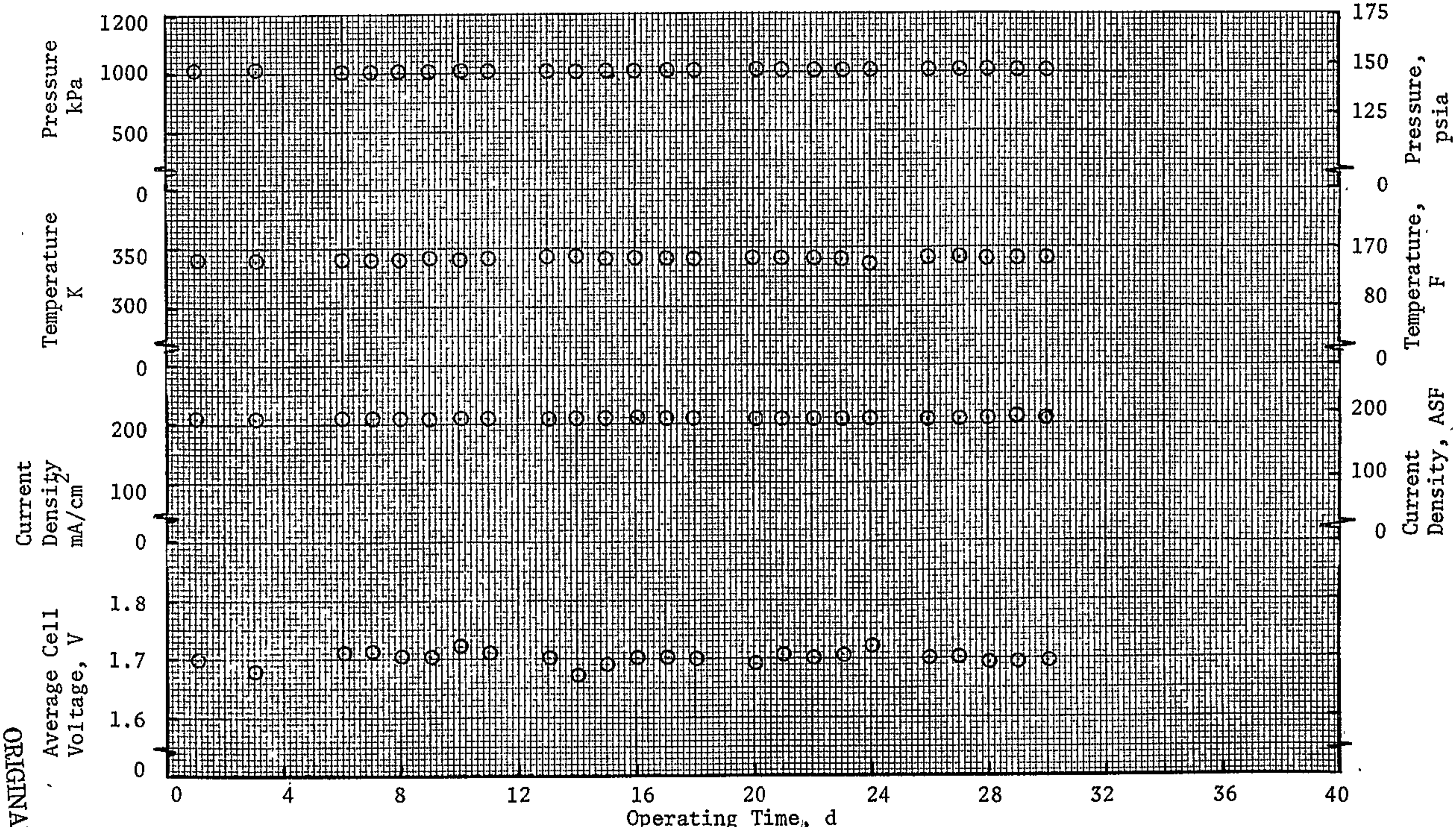

FIGURE 25 OGS PERFORMANCE DURING 30-DAY ENDURANCE TEST AS A PART OF ONE-PERSON LABORATORY BREADBOARD (WAB-5 ANODES)

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integrated shakedown test, an integrated Design Verification Test (DVT) and endurance testing. A goal of 30 days of endurance testing had been established.

Prior to test initiation the baseline operating conditions and characteristics for the OGS were established. These conditions are listed in Table 8. A net mass balance for the four-person laboratory breadboard is shown in Table 9.

The performance of the OGS for the four-person laboratory breadboard testing is shown in Figure 26. As indicated, a total of 1,000 h (42 d) of test time was accumulated. The breakdown of the test time was 2.5, 1.5, 6.0 and 32.0 days of testing for the familiarization, integrated shakedown, integrated DVT and endurance testing, respectively.

The average cell voltage, current density and module operating temperature are plotted as a function of time in Figure 26. The remaining pertinent operating conditions and characteristics are also indicated in Figure 26. At these conditions the average performance of the 12-cell SFWEM using WAB-5 anodes was 1.58 V/cell at a current density of 108 mA/cm^2 (100 ASF) and 1.62 V/cell at a current density of 161 mA/cm^2 (150 ASF).

Completion of the 42 days of testing demonstrated the success of the scaled-up activities. Primary areas of concern had been the capability to distribute feed water successfully to all 12 cells. The smaller dimensions for the water feed passages of the individual cells and the main water feed manifold of the module proved sufficient.

SUPPORTING TECHNOLOGY STUDIES

A variety of supporting studies was completed. These studies were directed at the expansion of the technology base associated with spacecraft O_2 generation through water electrolysis.

Summary of Activities

The supporting technology studies included the following activities:

1. Determination of whether or not KOH was lost from the SFWEM as an aerosol.
2. Determination of the minimum allowable pressure level at which gas liberation in the water feed compartment does not occur.
3. Determination of the maximum decay rate in subsystem pressure to prevent undesirable fluid shifts within the SFWEM.
4. Determination of the maximum allowable temperature using chrysotile asbestos.
5. Establishment of dehumidifier cell matrix fabrication.
6. Determination of the feasibility of operating a SFWE cell with only water in the feed compartment.

TABLE 8 BASELINE OPERATING CONDITIONS FOR OGS AS PART OF FOUR-PERSON LABORATORY BREADBOARD

Number of Cells	12
Cell Area, cm^2 (ft^2)	92.9 (0.1)
O_2 Production Rate, kg/d (lb/d)	
Nominal	1.29 (2.84)
Range	0.86 to 2.15 (1.89 to 4.73)
H_2 Production Rate, kg/d (lb/d)	
Nominal	0.16 (0.35)
Range	0.11 to 0.27 (0.24 to 0.59)
H_2O Supply Rate, kg/d (lb/d)	
Nominal	1.48 (3.26)
Range	0.98 to 2.46 (2.16 to 5.41)
Current Density, mA/cm^2 (ASF)	
Nominal	161 (150)
Range	108 to 269 (100 to 250)
Operating Pressure, kPa (psia)	1000 (145)
Operating Temperature, K (F)	330 (135)
O_2 to H_2 Pressure Differential, kPa (psid)	13.8 (2.0)
H_2 to H_2O Pressure Differential, kPa (psid)	13.8 (2.0)
Purge Gas (N_2) Pressure, kPa (psia)	310 (45)
Electrical Power	
Type, V	
DC	28
AC	115, 400 Hz
Power, W	380
Interfaces	
O_2	EDC Air Supply Unit
H_2	EDC H_2 Supply

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TABLE 9 NET MASS BALANCE FOR FOUR-PERSON LABORATORY BREADBOARD
kg/d (Lb/Day)

Subsystem		Constituents				
		CO_2	H_2	H_2O	O_2	C
Bosch						
	Reactants	4 (8.8)	0.36 (0.79)			
	Products			3.28 (7.22)		1.08 (2.38)
EDC						
	Reactants	4 (8.8)	0.28 (0.62)		2.24 (4.93)	
	Products	4 (8.8)		2.52 (5.54)		
WES						
	Reactants			6.30 (13.86)		
	Products		0.70 (1.54)		5.60 (12.32)	
Four Persons						
	Needs				3.36 (7.39)	
	Products	4 (8.8)				
Summary		Balanced	0.06 (0.15) Produced	0.50 (1.1) Required	Balanced	1.08 (2.38) Produced

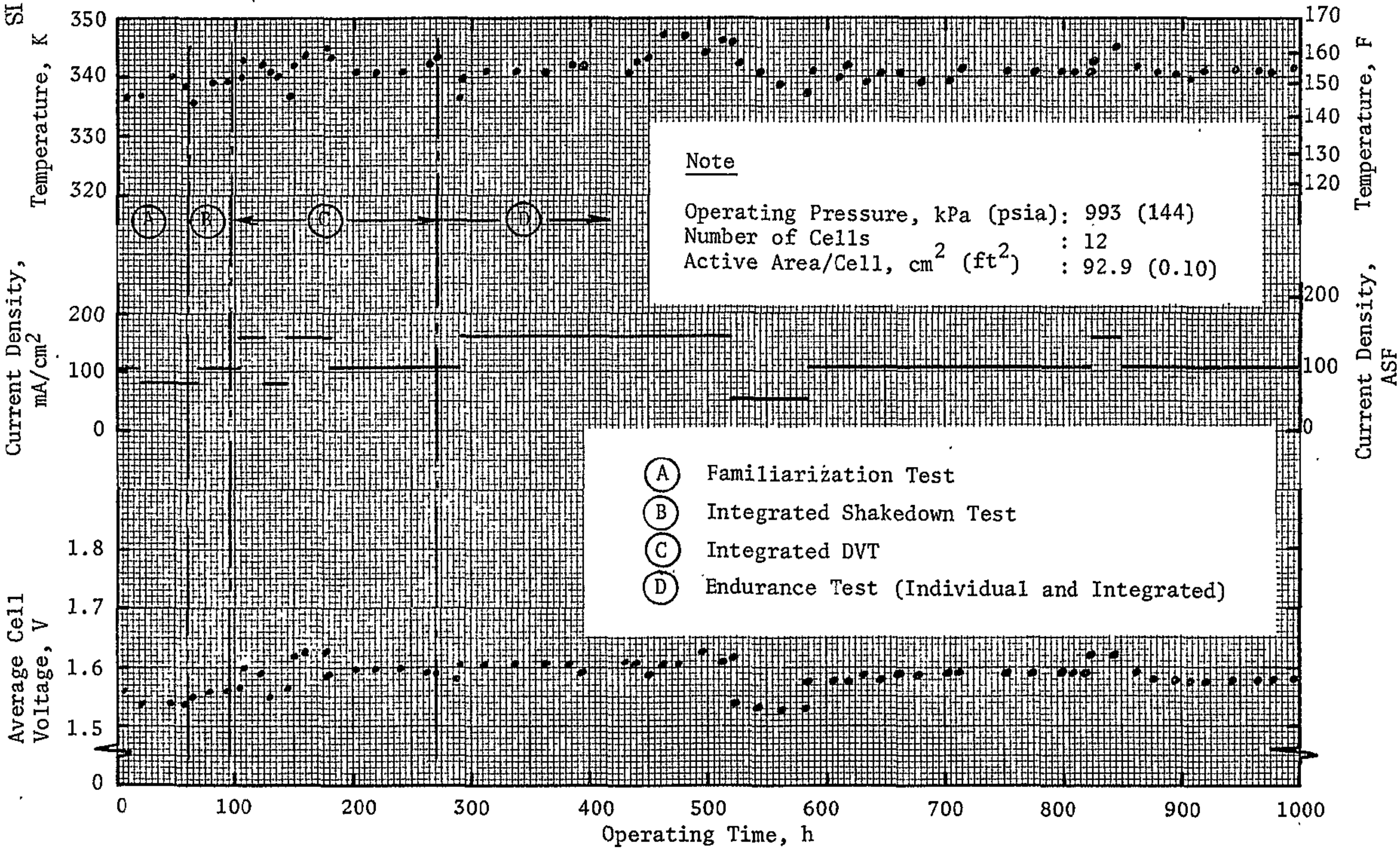

FIGURE 26 OGS PERFORMANCE AS PART OF FOUR-PERSON LABORATORY BREADBOARD (WAB-5 ANODES)

7. Determination of the compatibility of titanium (Ti) with the SFWEM operating conditions.

8. Determination of the compatibility of the power-sharing concept derived previously to use the EDC-generated power to partially offset OGS power requirements.[15]

9. Determination of potential techniques and concepts to increase the power conversion efficiency of OGS power controllers.

Product Gas Aerosol

The objective of this study was to determine whether or not KOH was lost from the SFWEM as an aerosol and, if so, in what quantity. Visible aerosol had been noticed in the past following initial module startups.[4] This had been assumed to be due to the "wet" conditions characteristic of a fresh electrolyte charge and the low pressure operation. A break-in period of at least 24 hours of running after a fresh charge always eliminated all visible aerosols. Additional testing was conducted to verify that the elimination of visible aerosol also meant stopping of all aerosoling.

Four areosol collection tests were conducted. The results are summarized in Table 10. The first test used a blank tube to calibrate the equipment. Test No. 2 was run at 108 mA/cm^2 (100 ASF), ambient pressure and 355 K (180 F). Aerosol was visibly present at the time the sample was collected (four hours after startup). A total of 0.0015 grams of KOH was detected. Test Nos. 3 and 4 were conducted after the module had operated for 42 and 64 hours, respectively. No aerosol was visibly detectable. The operating conditions prior to the aerosol testing had been 216 mA/cm^2 (200 ASF), ambient pressure and a temperature of 355 K (180 F). In neither case was KOH aerosol visibly observed or detectable by the analytical technique.

The operating conditions selected for the aerosoling tests were ambient pressures and relatively high current densities. These conditions are considered "worst- case." Low pressures result in large bursting gas bubbles while high current densities generate more vigorous gas evolutions per unit area of electrode. Either condition would be inducive to aerosol formation.

In summary, the detailed comprehensive tests with a one-person capacity module showed that a 42 hour break-in period effectively eliminates all aerosoling.

Minimum Allowable Operating Pressure

The objective of this study was to determine the minimum operating pressure at which gas liberation within the water feed compartments is eliminated. Operating at elevated pressures offsets the loss of solubility of gases experienced in the water feed compartment fluid due to elevated temperatures and the presence of KOH in solution.

The OGS with a 12-cell SFWEM was used for the experimental determination of the minimum pressure level. Steady-state operation was achieved at various pressure levels and the water feed compartment fluid was circulated through an

TABLE 10 AEROSOL TEST RESULTS

Test	Time After Start-up, h	Sample Description (Sample No, Collection Time, SFWEM Current Density)	Aerosol, g of KOH
1	-	Blank	--
2	4	#1, 3 h 20 min @ 108 mA/cm^2	0.0015
3	42	#2, 2 h, @ 216 mA/cm^2	0.0000[(a)]
4	64	#3, 5 h, @ 216 mA/cm^2	0.0000[(a)]

(a) Values were within uncertainty limits of the analytical method and were considered zero.

external one-g liquid-gas separator. Each time the quantity of gases, if present, were measured in a see-through collection vessel. During this testing the system was operated at a temperature of 339 ±3 K (150 ±5F) and a current density of 161 mA/cm^2 (150 ASF).

The results of the testing are shown in Figure 27. As the data shows, gas accumulation ceased at an operating pressure range between 793 to 862 kPa (115 to 125 psia). Based on the data, a safe "no gassing" pressure level of 965 ±69 kPa (140 ±10 psia) was selected. Subsequent to this experimental determination, the OGS was operated for a period of 30 days at an average pressure level of 993 kPa (144 psia). No gassing was observed.

High Pressure Shutdown Demonstration

The objective of the study was to determine a safe rate of pressurization and depressurization for a SFWEM. If a water electrolysis cell containing an aqueous electrolyte solution is depressurized very rapidly gases dissolved in the electrolyte come out of solution quickly and expand causing possible electrolyte shifts and electrolyte/gas interface relocations.

To prevent and/or minimize these detrimental effects, two techniques were devised. First, for automatic shutdowns not caused by pressure-related conditions, the subsystem pressures will be maintained via an external N_2 source. The second technique is employed when depressurization is required. In this concept a preprogrammed depressurization rate is used.

A rate of 207 kPa/min (30 psi/min) was calculated as a safe rate. This rate was verified using a 12-cell module. A subsystem shutdown was initiated and pressure decays were controlled at the calculated rates (manual actuation of regulators). Following the depressurization, the module was repressurized to its original operating pressure of 965 kPa (140 psia). After the pressure excursion the fluid within the water feed compartment was recirculated through the external one-g liquid gas separator. The circulation showed that no gases remained liberated within the feed compartment following the experiment. Based on the results of the test, the above rate was adopted for the eventual use with the Three-Gas Pressure Controller.

Maximum Operating Temperature

The objective of this study was to determine the maximum desirable operating temperature using the baseline chrysotile asbestos (fuel cell grade) as the cell matrix. Elevated operating temperatures decrease OGS power requirement by decreasing cell voltage, but long-term life expectancy of fuel cell grade asbestos decreases above certain temperature levels.

Table 11 is a summary of a literature search which addressed various matrix compositions and their expected use life at indicated temperatures and KOH concentrations. As the results of Table 11 indicate only two matrix materials exhibit acceptable long-life properties at elevated temperatures (greater than 366 K (200 F)). These are PKT and polybenzimadozole (PBI).

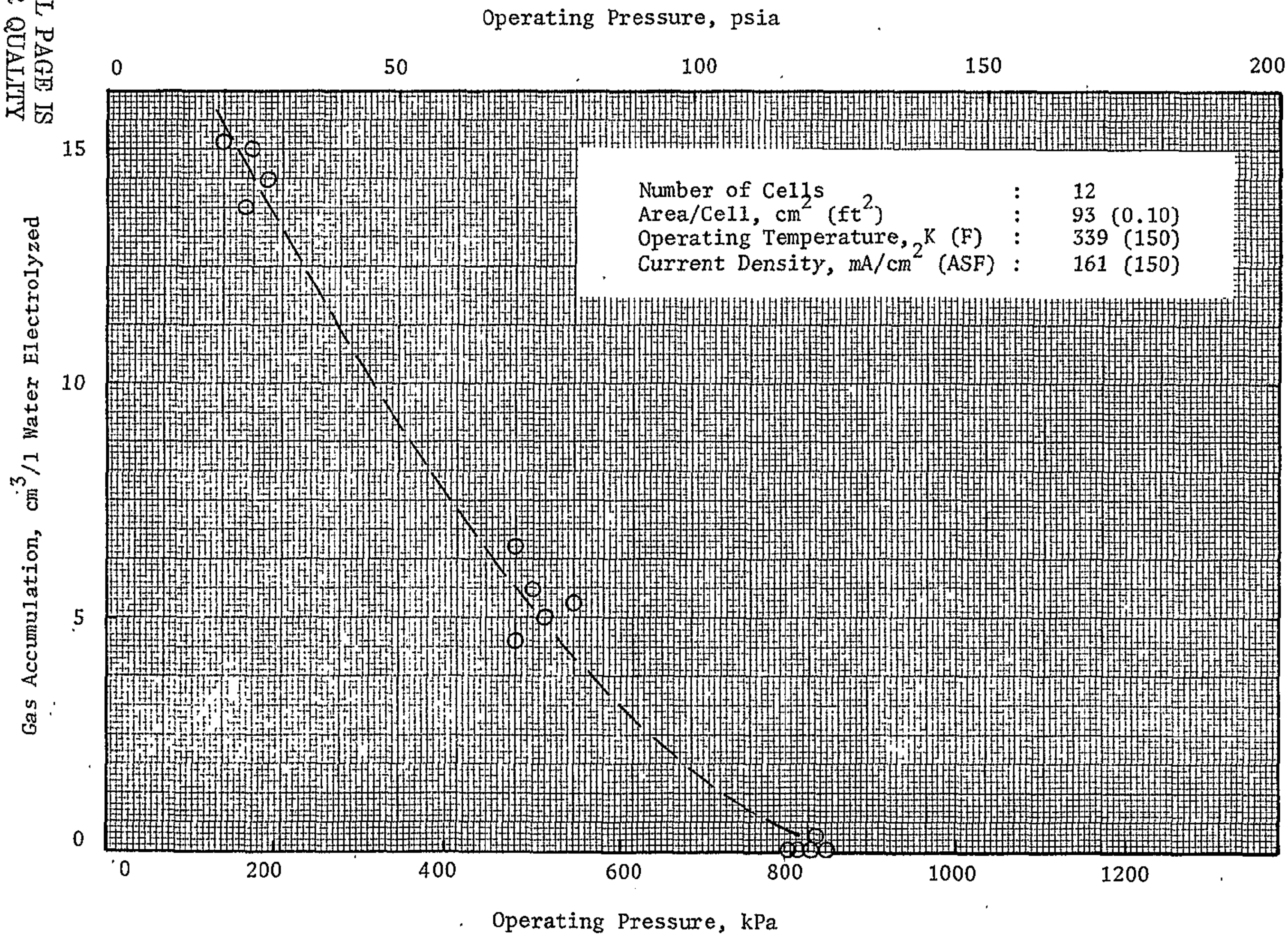

FIGURE 27 HIGH PRESSURE GASSING TEST

TABLE 11 SUMMARY OF RESULTS FOR MAXIMUM TEMPERATURE STUDY

Matrix Material	Expected Use Life Data
Chrysotile Asbestos (Fuel Cell Grade)	<100 Hours at 423 K (302 F), 30 to 60% KOH <1000 Hours at 373 K (212 F), 30 to 60% KOH 13,607 Hours at 355 K (180 F), 30 to 40% KOH
Illinois Institute of Technology Asbestos	8%[(a)] Wt Change in 500 Hours at 394 K (250 F), 42% KOH 8.9%[(a)] Wt Change in 1000 Hours at 394 K (250 F) 42% KOH
Potassium Titanate (PKT Fybex with TFE 3170 Binder)	0% Wt Change in 1000 Hours at 394 K (250 F), 42% KOH
Litofol-S Asbestos	11%[(a)] Wt Change in 1000 Hours at 394 K (250 F), 42% KOH
Silicon Nitride	11%[(a)] Wt Change in 1000 Hours at 394 K (250 F), 42% KOH
Polybenzimadozole (PBI)[(b)]	1.2% Wt Change in 5000 Hours at 394 K (250 F), 42% KOH

(a) Unacceptable for OGS operation.
(b) Fabrication technique not sufficiently advanced for matrix preparation.

The PKT material has been manufactured into matrices with sufficient bubble pressure. However, the mechanical strength of the matrices is rather poor and they are fragile. A recent contact with the manufacturer of PKT fibers has revealed that the product has been taken off the market and as a result is no longer commercially available. The PBI material is not available in a particle size small enough to yield an adequate bubble pressure.

Based on the results of the study, a maximum operating temperature of 355 K (180 F) and chrysotile asbestos were selected as baseline for SFWE cells.

Dehumidifier Matrix Cell Fabrication

The objective of this study was to verify that the Contractor's proprietary technique for manufacturing high-strength chrysotile asbestos matrices is also applicable to manufacturing matrices compatible with an acidic environment (blue or crocidolite asbestos). Since the dehumidifier cell operates with an acid electrolyte the blue asbestos must be used. Ready-made blue asbestos sheet previously commercially available can no longer be obtained.

The Contractor-developed technique to manufacture crocidolite asbestos matrices was employed for the manufacture of blue acid compatible matrix sheets. Only minor corrections were required. Several matrix sheets were fabricated and bubble tested. The results showed that the reconstituted blue asbestos matrices could withstand a pressure differential of 96 kPa (14 psi) for a matrix thickness of 0.025 cm (0.010 in).

Elimination of KOH From Feed Cavities

The objective of this study was to determine the feasibility of operating a SFWE cell using pure water instead of an aqueous solution of KOH in the feed compartment of individual cells. If pure water could be used all free electrolyte within the SFWES would be eliminated.

The concept selected for study consisted of replacing the asbestos water feed matrix with a membrane that is impermeable to KOH but would still allow water transport from the feed compartment to the cell matrix. In addition to meeting these specifications, the membrane must also surpress the water vapor pressure of the feed compartment fluid sufficiently to prevent cell matrix flooding during module standby.

A single cell was constructed using a commercially-available Nafion membrane. The cell matrix was charged with a 25% aqueous solution of KOH. Pure water was circulated through the water feed compartment. A constant voltage of 1.57 V was imposed across the cell electrodes and the current-carrying capability of the cell was measured. Periodic checks of the circulating water stream for KOH backdiffusion were conducted.

The single-cell was operated continuously for a period of three days. At the constant, imposed voltage of 1.57 V a 10.5 A current, equivalent to 113 mA/cm^2 (105 ASF), could be maintained. The temperature required to sustain this current density averaged 350 K (171 F).

Throughout the testing the circulating water loop was monitored for possible pickup of KOH. After approximately two days of operation traces of KOH could be detected. These traces leveled out and no further increases were noted. A possible explanation might be the accumulation of liquid droplets at the bottom of the H_2 cavity forming a liquid bridge between the water feed compartment and the KOH-carrying cell matrix.

The results showed that operation with water in the feed compartment is possible. The activities indicated, however, that additional work is needed to demonstrate the concept's maturity for adoption as a baseline for the SFWES.

Titanium Compatibility Study

The objective of the study was to evaluate the compatibility of Ti with the operating environment of the DM. The evaluation included the use of Ti as structural parts (e.g., current leads, current collectors and gas cavity spacers) and as a porous electrocatalyst substrate for the O_2-evolving electrode.

The results of the study showed that Ti will resist ignition to its melting temperature as long as an oxide film present on the Ti surface is not disturbed. Removal or damage of the oxide film will cause ignition and combustion at room temperatures and at relatively low pressures (345 kPa (50 psia)). The oxide film can be removed either mechanically through accidental scratching of mating surfaces (as might occur during vibration) or by particles traveling in a gas stream impacting a Ti surface. As a result, NASA's ground rules prohibit the use of Ti that is exposed to more than ambient pressures of O_2.

Based on these findings, it is recommended that all Ti parts of the DM be replaced using materials compatible with the DM environment and capable of performing the required structural, electrical or electrochemical functions.

Power-Sharing Scale-Up

The objective of this task was to complete a design that allows the scale-up of the Contractor-developed power-sharing concept from less than 5 cell level to the 12-cell level. The power-sharing concept allows full utilization of the EDC generated power to partially offset the power required by the SFWEM.[15]

The major design problem was to modify existing circuits and components to allow interfacing with the SFWEM current and voltage characteristics of 12 cells operating electrically in series (approximately 19 to 21 VDC).

Following completion of the design, the concept was implemented through the fabrication and debugging of two printed circuit cards. These cards are now available for use in an integrated system using both an EDC and an OGS such as the ARX-1.

High Efficiency Power Controller Concept

The objective of this study was to identify design changes within the baseline power controller that would enable achieving a 90 to 93% power conversion efficiency compared to the present-day demonstrated 85%. The baseline power controller uses a solid state power switch which turns on and off at a fixed rate with a variable duty cycle as determined by a pulse width modulator circuit. A closed-loop feedback network maintains the current at the desired level.

An analysis of the existing circuit network was performed. As a result, three areas for redesign were identified: (1) switching times, (2) on-voltage drops and (3) switching speeds. To achieve the goal of 90 to 93%, efficient power conversion will be required to decrease the switching times and reduce the on- voltage drops in order to minimize internal power losses. Also, switching speeds which are presently in the range of 1 to 20 kHz should be increased to the range of 10 to 20 kHz. Breadboard level circuitry work was performed which indicated that the increase in efficiency goal is attainable. It is recommended that additional activities be performed in this area to demonstrate the improvements at the subsystem level.

CONCLUSIONS

The following conclusions are a direct result of the program activities.

1. An OGS can be fabricated based on present-day technology that would occupy a volume of 0.108 m^3 (3.8 ft^3), have a fixed hardware weight of 54.6 kg (120 lb) and would generate sufficient O_2 to satisfy the metabolic O_2 requirements of a three-person crew while supplying the O_2 necessary for an EDC for CO_2 removal and for cabin leakage (4.20 kg/d (9.24 lb/d)). The estimated total power for the three-person OGS is 1.1 kW.

2. The alkaline electrolyte-based SFWES has a potential for one of the lowest power-consuming electrolysis-based OGSs. A new electrode, WAB-6, has been developed by the Contractor for use in alkaline systems. At the end of 130 days of testing the cell voltage was only 1.45 V at 161 mA/cm^2 (150 ASF) and a temperature of 355 K (180 F).

3. An OGS using the static feed water electrolysis concept can be readily integrated with an EDC and either a Sabatier or a Bosch CO_2 Reduction Subsystem (CRS) using state-of-the-art hardware. No problems have been identified when using OGS generated H_2 and O_2 in the EDC, or either of the two CRSs.

4. The total and two differential pressure levels of a SFWES can be controlled and monitored using a single controller instead of six components previously needed. Such a Three-Gas Pressure Controller can be packaged into a unit weighing only 3.64 kg (8.0 lb) and occupying a volume of 1.58 dm^3 (96 in^3). Electrical motor-driven actuators allow the Three-Gas Pressure Controller to be used with microprocessor- or minicomputer-based C/M I.

5. High temperature operation (greater than 355 K (180 F)) of low voltage, alkaline electrolysis cells has been demonstrated although the practicality of using external waste heat that is required to

maintain these temperatures is in question. The external heat requirement is due to recent advances in electrode technology. Cells operating at very low cell voltages produce very little waste heat.

6. The SFWEM does not release an aerosol of the cell electrolyte into the product gas streams after a minimal module breaking period of 42 h. This removes the possibility of depletion of electrolyte or contamination of downstream components such as the DM and Three-Gas Pressure Controller.

7. Operation of SFWE cells with water only in the feed compartments using water vapor depressing, KOH impermeable membranes is possible thus eliminating any bulk electrolyte from the SFWES. Diffusion of KOH from the cell matrix into the water feed compartment must still be resolved.

8. Titanium as a structural or electrode substrate material is not compatible with the operating conditions of the DM (high pressure O_2).

9. Increasing the present day demonstrated power conversion efficiency of 85% to a goal of 90 to 93% appears feasible by implementing design changes in power controller switching times, on-voltage drops and switching speeds.

10. The SFWE-based OGS has undergone a series of hardware, component, instrumentation and control improvements which have moved the total development effort another step closer toward meeting the program's overall goals and objectives.

RECOMMENDATIONS

Based on the work completed, the following recommendations are made:

1. Incorporate the single cell, module, component and subystem technology advancements achieved under the present program into an OGS having a O_2 generation capacity equivalent to one-person (metabolic plus CO_2 collection requirements). Considerations should be included in the development of this OGS to allow for its ready integration into a one-person capacity laboratory breadboard Air Revitalization System (ARX-1).

2. The WAB-6 electrode developed by the Contractor has shown promise as a very low power-consuming electrode. The 12-cell SFWEM fabricated as part of this program for the ARX-1 should be equipped with the new WAB-6 electrodes to demonstrate the low power levels at the scaled-up, one-person capacity level.

3. Develop advanced instrumentation needed to control and monitor an OGS as part of an ARS. Emphasis should be placed on pressurization and depressurization of the subsystem using the Three-Gas Pressure

Controller. The C/M I should employ the latest developments in operator/subsystem interfaces and maintenance aids. A minicomputer-based instrumentation concept should be implemented.

4. Development activities to demonstrate a 90 to 93% efficient power controller should be continued. The equivalent weight calculations indicate a significant weight savings is possible due to reductions in the OGS power controller heat rejection and power levels.

5. Continued activities should be expected in replacing the water feed fluid within a SFWE cell with pure water. By having only water in the feed compartments, the heat removal function can be combined with the water feed function while eliminating any bulk electrolyte from the subsystem.

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APPENDIX 1 SUPPORTING ANALYSES FOR THE PRELIMINARY DESIGN OF THE THREE-PERSON CAPACITY OGS

A preliminary design analysis was completed for a three-person capacity OGS for spacecraft application. A summary of the results was presented in the main text of this report. Additional information supporting the design is presented below.

OGS Mass Balance

A mass balance was performed for the three-person capacity OGS. This balance was based on the OGS configuration as shown in Figure A1-1. Table A1-1 summarizes the mass flow rates for locations 1 through 10 identified in Figure A1-1. Also listed in Table A1-1 are the baseline temperatures and pressures for the ten location points indicated in the schematic.

OGS Interfaces

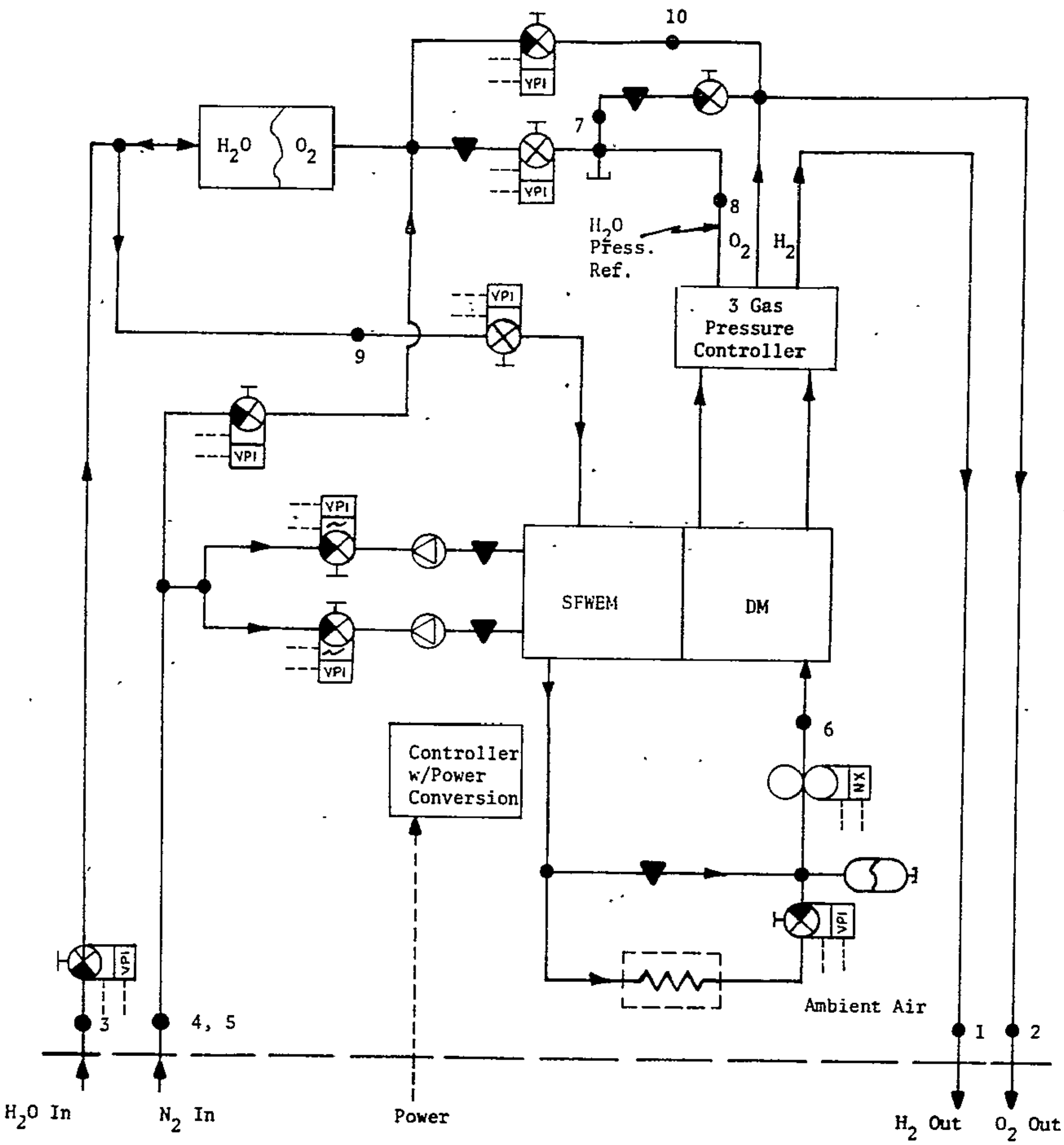
Six fluidic and electrical interfaces were identified for the three-person capacity OGS. These interfaces are listed in Table A1-2.

Controlled and Monitored OGS Parameters

A total of eight controlled and eight monitored parameters were identified for the three-person capacity OGS. These parameters are listed in Table A1-3 and A1-4, respectively.

Three-Person OGS Reliability Analysis

A reliability analysis was performed using a spared subsystem reliability goal of 0.9975 and a mission duration of 180 days. For the three-person subsystem a mean-time-between failure (MTBF) of 15,806 hours was projected. The detailed results of the analyses are presented in Table A1-5.



Note: See Table A1-1 for parameters of above indicated locations.

FIGURE A1-1 OGS MASS BALANCE SCHEMATIC

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TABLE A1-1 OGS MASS BALANCE[a]

Location	Fluid	Flow Rate, kg/person-day lb/person-day	Temperature, K (F)	Pressure kPa (psia)
1	H_2 Gas	0.17 (0.38)	316 (110)	Ambient
2	O_2 Gas	1.40 (3.08)	316 (110)	Ambient
3	Deionized Water	1.57 (3.46)	Ambient	207 (30)
4	N_2 Purge Gas	(b)	Ambient	861 (125)
5	N_2 Gas (press. Ref.)	Nil	Ambient	848 (123)
6	Coolant (Water)	<1360 (<3000)[c]	344 (160)	345 (50)
7	O_2 Gas (Depowered Tank Bleed)	None	Ambient	-
8	O_2 Gas (Tank Pressure Ref.)	Nil	Ambient	848 (123)
9	Deionized Water	1.57 (3.46)	Ambient	848 (123)
10	O_2 Gas (Tank Bleed During Fill)	Nil	Ambient	Ambient

(a) Refer to Figure A1-1.
(b) Not continuous, flowing only during purge cycle, approximately 0.027 kg N_2/min-person.
(c) Dependent on module and line heat loss to cabin air stream before the heat exchanger.

TABLE A1-2 OGS INTERFACES

1. Water Feed
2. N_2 (Purge and Pressurization)
3. O_2 to Cabin
4. H_2 to EDC
5. Power
6. Heat Rejection to Ambient Air

TABLE A1-3 PARAMETERS CONTROLLED IN THE OGS

1. SFWEM Current
2. DM Current/Voltage
3. Temperature (Modules)
4. H_2 to System ΔP
5. O_2 to System ΔP
6. System Pressure
7. Water Fill Sequence
8. Mode Transition Sequencing

TABLE A1-4 PARAMETERS MONITORED IN THE OGS

1. H_2 to System ΔP
2. O_2 to System ΔP
3. System Pressure
4. SFWEM, Individual Cell Voltages
5. DM, Individual Cell Voltages
6. N_2 Purge Pressure Standby Level
7. SFWEM Temperature
8. DM Temperature

TABLE A1-5 THREE-PERSON OGS RELIABILITY ANALYSIS

Item No	Component	No Req'd	λ Failure Rate x 10^{-6} h^{-1}	nλt[(a)]	No of Spares	Weight Spares, kg	Total Volume Spares cm^3	Component/ Spares Reliability
1	SFWEM	1	4.83	0.0209	1	23.92	22936	0.99979
2	DM	1	1.40	0.0037	1	6.56	8484	0.99999
3	Three Gas Pressure Controller	1	6.80	0.0294	1	3.63	1576	0.99960
4	Pressure Transducer (gas)	3	3.31	0.0286	1	0.077	8	0.99960
5	Product Gas Filter	2	0.20	0.0017	1	0.156	72	0.99999
6	Solenoid Valve w/VPI and Manual Override (Latched when Normally Energized)	8	2.17	0.0656	2	0.636	344	0.99996
7	Power Controller	1	3.65	0.0158	1	9.31	9504	0.99987
8	Coolant Pump	1	10.89	0.0470	2	0.794	54	0.99998
9	Flow Restricter	5	0.27	0.0058	1	0.018	2	0.99998
10	Pressure Transducer (water)	2	3.30	0.0285	1	0.041	8	0.99960
11	Check Valves	2	0.56	0.0048	1	0.073	12	0.99998
12	Hand Valve	1	0.84	0.0036	1	0.059	8	0.99999
13	Water Storage Tank	1	0.05	0.0002	0	-	-	0.99980
14	Heat Exchanger	1	0.10	0.0004	0	-	-	0.99960
15	Temperature Probe	4	1.00	0.0173	1	0.016	0.57	0.99983
16	Accumulator	1	0.05	0.0002	0	-	-	0.99980

(a) Mission time 180 days = 4320 hours

- Σ nλt = 0.2733
- MTBF = 15,806 hours
- Spares Reliability = 0.9975

APPENDIX 2 OGS SCHEMATIC AND MASS FLOW CONDITIONS FOR FOUR-PERSON LABORATORY BREADBOARD

The detailed schematic of the OGS used to support the testing for the four-person laboratory breadboard is shown in Figure A2-1.

A block diagram showing the relationship of the EDC, OGS and B-CRS and associated TSA is shown in Figure A2-2. The flow conditions for the integrated system are presented in Table A2-1. Eleven locations were selected as indicated in Table A2-1.

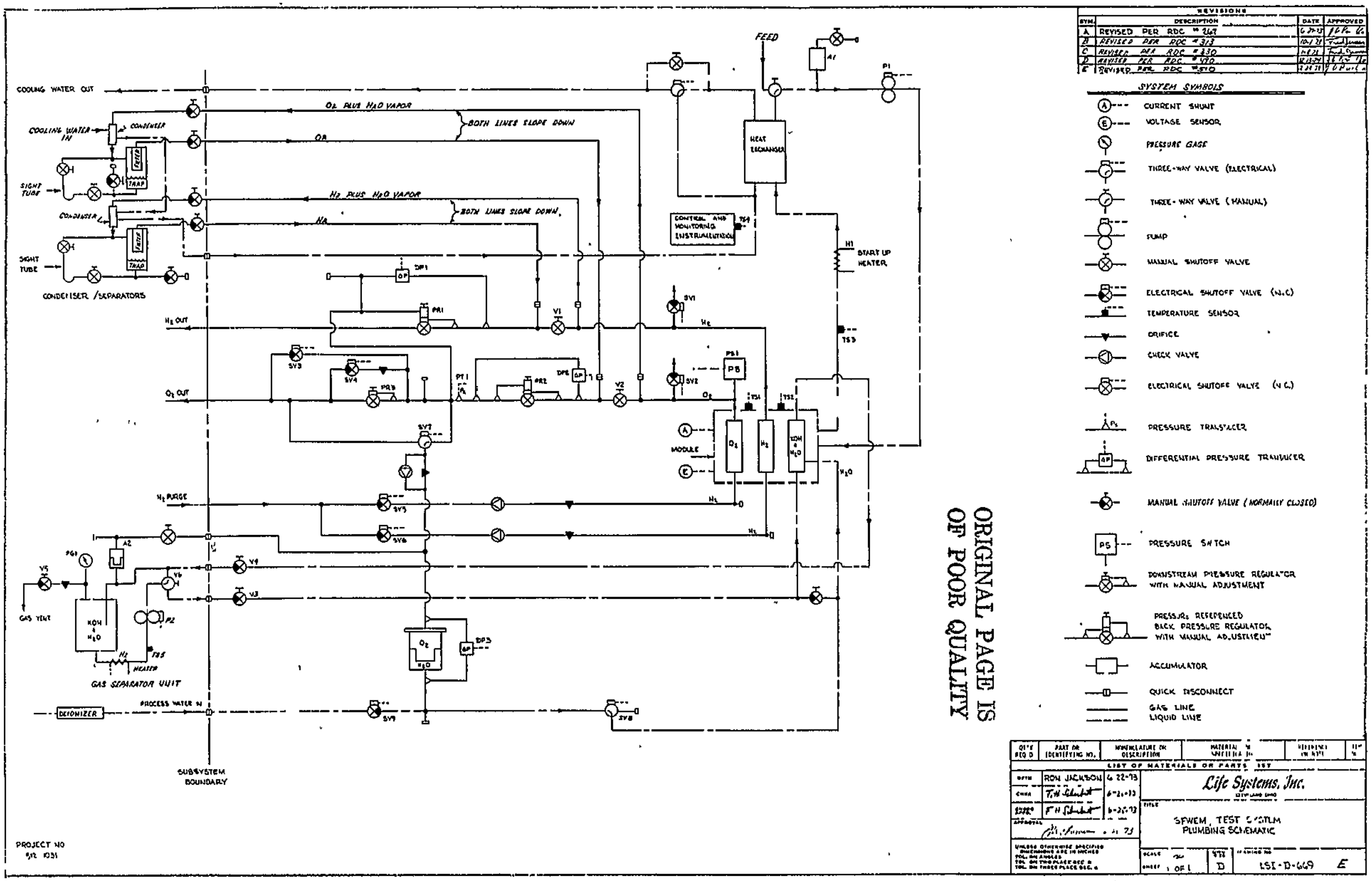
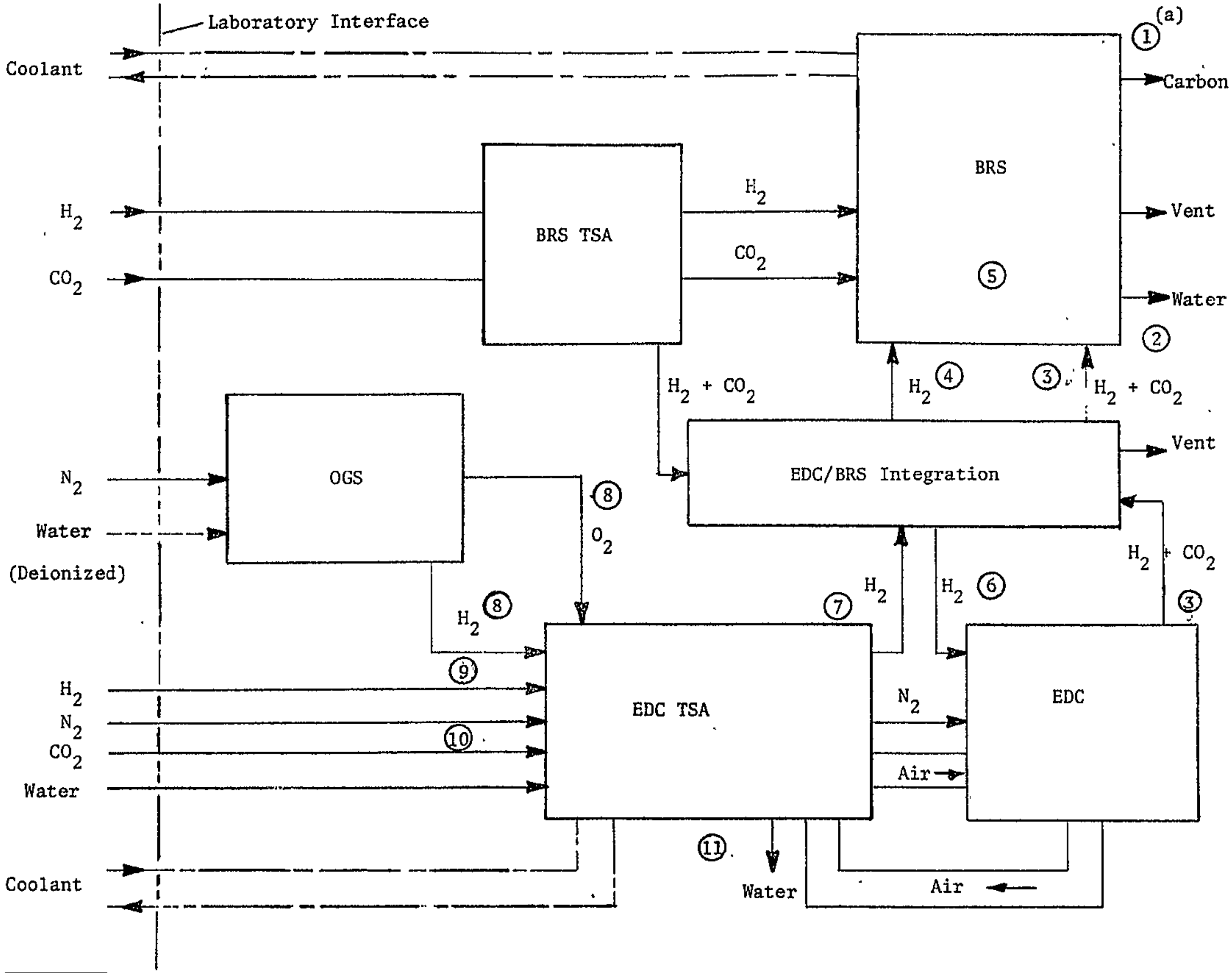


FIGURE A2-1 OGS FOR FOUR-PERSON ORS, DETAILED SCHEMATIC



(a) See Table A2-1 for Values.

FIGURE A2-2 EDC/OGS/B-CRS INTEGRATION BLOCK DIAGRAM

TABLE A2-1 EDC/OGS/B-CRS INTEGRATION FLOW CONDITIONS

System Location[a]	Species	Mass Flow Rate kg/h	Mass Flow Rate (lb/h)	Volumetric Flow Rate dm^3/min	Volumetric Flow Rate (ft^3/min)
1. Bosch Reactor	Carbon	0.045	(0.099)	-	-
2. Bosch Reactor	H_2O (1)	0.137	(0.30)	0.0023	(8.1×10^{-5})
3. Feed Gas/ Exhaust EDC	H_2O	0.002	(0.004)	0.065	
	H_2	0.0095	(0.021)	1.85	(0.065
	CO_2	0.167	(0.365)	1.52	(0.054)
4. Tylan Supply	H_2	0.006	(0.0132)	1.19	(0.042)
5. Loop Composition	Mixture ($H_2/CO_2/CH_4/CO/H_2O$)	3.08	(6.78)	73.6	(2.60)
6. EDC Anode	H_2	0.021	(0.046)	4.09	(0.144)
7. H_2 Flow	H_2	0.027	(0.059)	5.26	(0.186)
8. Exhaust	H_2	0.0117	(0.026)	2.27	(0.080)
	O_2	0.093	(0.205)	1.23	(0.043)
9. TSA	H_2	0.015	(0.033)	2.91	(0.103)
10. TSA	CO_2	0.167	(0.365)	1.52	(0.054)
11. EDC Condensate	H_2O(1)	0.103	(0.23)	0.00172	(6.1×10^{-5})

(a) See Figure A2-2 for location.

APPENDIX 3

THREE GAS PRESSURE CONTROLLER SPECIFICATION

Life Systems, Inc. CLEVELAND, OHIO 44122	SPECIFICATION / LINE REPLACEABLE UNIT	NO. SP-100-1 / PAGE 1 OF 3	REVISION LTR. B / DATE 11/17/77
TITLE THREE-GAS PRESSURE CONTROLLER		PART DRAWING NO. J-1511	

FUNCTION

To monitor and regulate pressures of product H_2 and O_2 gas venting from the O_2 Generation Subsystem (OGS).

DESCRIPTION

The compact unit consists of a pressure transducer, two differential pressure tranducers and three pressure regulators, which control H_2, O_2 and system pressure. The regulators are controlled by DC gear motors and sensed by internal pressure transducers. The absolute system pressure is controlled by the motor-driven system regulator and O_2 and H_2 ΔP's are referenced to the inlet of the system regulator.

DESIGN DATA

Performance Characteristics

Working fluid	H_2, O_2 and N_2 (pure gas)
Flow rate,	
O_2, kg/d (lb/d)	0 to 10.9 (0 to 24)
H_2, kg/d (lb/d)	0 to 2.7 (0 to 6)
Operating temperature, K (F)	294 to 394 (70 to 250)
Maximum Inlet Dew Point	Ambient regulator temperature
Pressures,	
Proof, Pa (psia)	4.83×10^6 (700)
Burst, Pa (psia)	12.4×10^6 (1800)
Safety Factor	Burst/System = 3.00
System Regulator	
Inlet Pressure Range, Pa, (psia)	0 to 4.14×10^6 (0 to 600)
Inlet Control Tolerance, %	±1
Outlet Pressure	Ambient

Differential Control:

Inlet Pressure Range, Pa x 10^{-6} (psia)	O_2 Regulator ΔP Control Tolerances, Pa x 10^{-3} (psia)	H_2 Regulator ΔP Control Tolerances, Pa x 10^{-3} (psid)
0 to 0.52 (0 to 75)	±3.45 (±0.50)	±3.45 (±0.50)
0.52 to 1.72 (75 to 250)	±2.41 (±0.35)	±2.41 (±0.35)
1.72 to 4.14 (250 to 600)	±10.3 (±1.50)	±10.3 (±1.50)

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Response Rates

Systems regulator, Pa/sec (psi/sec)	29.3×10^3 (4.254)
ΔP regulator, Pa/sec (psi/sec)	219 (0.0317)

Physical Characteristics

Weight, kg (lb)	3.64 (8.00)
Volume, dm^3 (in^3)	1.58 (96.3)
Basic configuration, cm (in)	17.8 x 12.7 x 7.0 (7.00 x 5.00 x 2.75)

Material Characteristics

A. Nonmetallic
   Teflon, EPR
B. Metallic
   Aluminum, Copper and Stainless Steel
C. All Wetted Parts
   316 Stainless Steel or EP Rubber

Electrical Characteristics

Motors (Quantity 3); VDC	24
Rated Load, Amp/Motor	0.45
Nominal Stall Current, Amp/Motor	1.20

INTERFACES

Mechanical

Inlet and outlet lines, cm (in)	0.64 (0.25)
Fittings	CPV

Electrical — Amphenol 14-37 connectors

Mounting — Line mounts on CPV fittings

ENVIRONMENT

Cabin Atmosphere

MAINTENANCE LEVEL AND METHOD

Replacement of this Line Replaceable Unit is the first level of maintenance.

Time Required: 0.2 hr (estimate)

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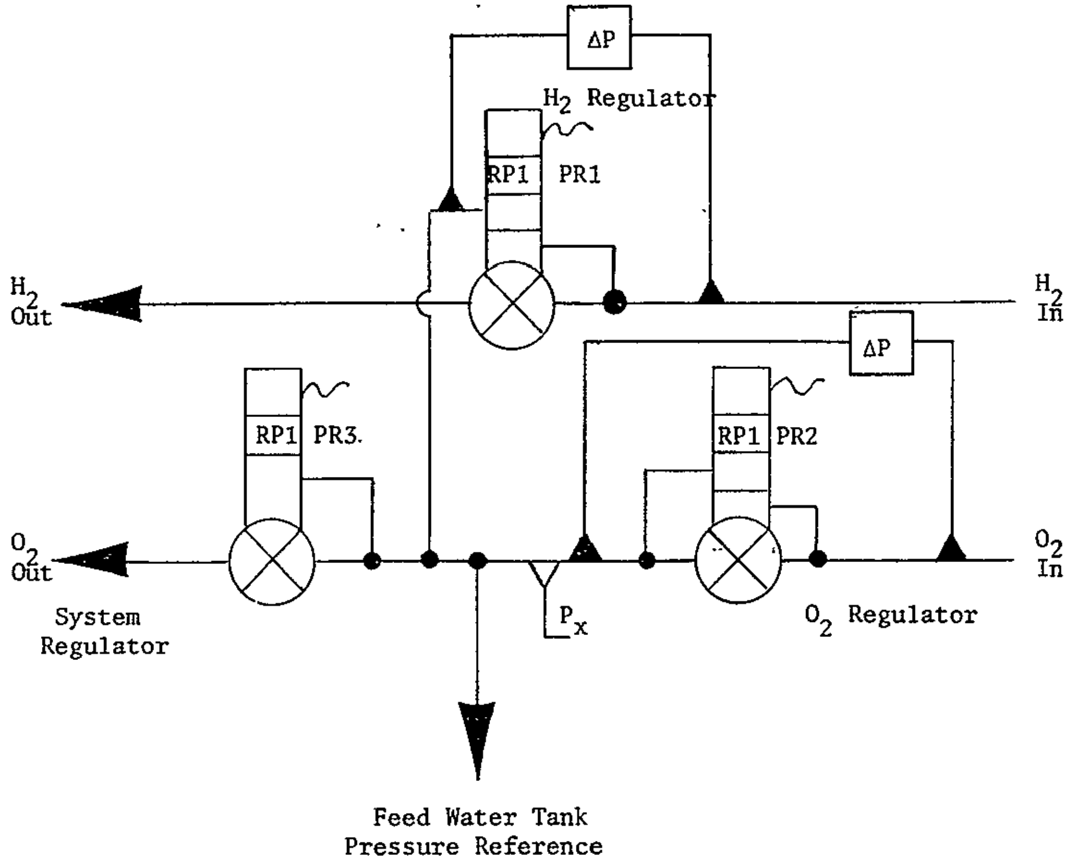
REGULATOR SCHEMATIC



RPI = Regulator Position Indicator
P_x = Pressure Transducer
ΔP = Differential Transducer