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Development of a Static Feed Water Electrolysis System

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F. H. Schubert
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Life Systems, Inc.

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Prepared for
Ames Research Center
under Contract NAS2-10306

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

N82-25660#

FOREWORD

The development work reported herein was conducted by Life Systems, Inc. at Cleveland, Ohio, under Contract NAS2-10306 during the period August 1, 1979 through December 31, 1981. The Program Manager was Franz H. Schubert. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Ken A. Burke	Test Support Accessories Design and Fabrication
Steve Czernac	Mechanical System and Test Support Accessories Assembly
Robert W. Ellacott	Component Assembly
George S. Ellis	Component Design, Packaging
Tim H. Hallick	Subsystem Evaluation, Module Assembly
John O. Jessup	Electronic Assembly and Checkout
Don W. Johnson	Electronic Assembly and Checkout
Gene P. Koszenski	Electrode and Matrix Fabrication, Supporting Technology Studies
Joel B. Lantz, Ph.D.	Final Report Preparation
J. David Powell	Electronic Hardware Design
Jim Powell III	Software Design, Test Support
Franz H. Schubert	Program Management and Subsystem Design
Richard R. Woods	Feedwater Electrolyte Elimination Studies, Systems Analysis
Rick A. Wynveen, Ph.D.	Contract Administration

The contract's technical monitor was P. D. Quattrone, Chief, Life Support Office, NASA Ames Research Center, Moffett Field, California.

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LIST OF ACRONYMS

ADC	Analog to Digital Converter
CCA	Coolant Control Assembly
C/M I	Control Monitor Instrumentation
CRT	Cathode Ray Tube
DAS	Data Acquisition System
DARS	Data Acquisition and Reduction System
DMA	Direct Memory Access
EC/LSS	Environmental Control/Life Support System
FCA	Fluid Control Assembly
I/O	Input/Output
IRAD	Internal Research and Development
KEC	KOH Elimination Cell
LRU	Line Replaceable Unit
LSI	Life Systems, Inc.
M/E A	Mechanical/Electrochemical Assembly
NASA	National Aeronautics and Space Administration
OGS	Oxygen Generation Subsystem
PFC	Power Failure Control
RTE	Real Time Executive
SFWE	Static Feed Water Electrolysis
SFWEM	Static Feed Water Electrolysis Module
SFWES	Static Feed Water Electrolysis Subsystem
SOC	Space Operations Center
3-FPC	Three Fluid Pressure Controller
TSA	Test Support Accessories
WEM	Water Electrolysis Module
WES	Water Electrolysis Subsystem

SUMMARY

Regenerative processes for the revitalization of spacecraft atmospheres are essential for realization of long-term space missions. These processes include oxygen generation through water electrolysis. The static feed/alkaline electrolyte water electrolysis concept has evolved over the past 14 years under National Aeronautics and Space Administration and Life Systems, Inc. sponsorship. This design has been recognized as capable of reliable oxygen generation with few subsystem components. A complete self-contained water electrolysis subsystem based on this concept was not heretofore developed, however. The objectives of the present program were to: (1) demonstrate the inherent simplicity, reliability and lower power requirements of an Oxygen Generation Subsystem based on this concept by defining and fabricating a self-contained, one-person capacity Static Feed Water Electrolysis Subsystem, (2) evaluate the performance of this subsystem, (3) modify previously developed subsystem components to incorporate improvements identified under past development efforts, and (4) investigate and demonstrate a concept for elimination of electrolyte in the static feed compartment of the water electrolysis cell. These objectives were met.

A one-person level Oxygen Generation Subsystem, called the WS-1, was developed. Production of the one-person oxygen metabolic requirements, 0.82 kg per day (1.81 lb per day) was demonstrated without the need for condenser/separators or electrolyte pumps. The size, weight and complexity of the remaining components was minimized by utilizing specially-developed integrated coolant and pressure control components. During 650 hours of shakedown, design verification and endurance testing, cell voltages averaged 1.62 V at 206 mA/cm^2 (191 ASF) and at average operating temperature as low as 326 K (128 F), virtually corresponding to the state-of-the-art performance previously established for single cells at Life Systems. This high efficiency - and therefore, low waste heat generation - prevented maintenance of the 339 K (150 F) design temperature without supplemental heating (other subsystem waste heat may be harnessed in the future to raise the temperature). Cyclic operation (corresponding to low-earth orbit of a spacecraft) was demonstrated. Nearly all design modification requirements detected during the evaluation of this breadboard-level subsystem were implemented during the test program. Further evaluation of the subsystem is recommended as a follow-on effort. Improved water electrolysis cell frames were designed, new injection molds were fabricated and a series of new frames were molded. Both the module incorporated in the Oxygen Generation Subsystem and a spare were fabricated and assembled.

A modified Three-Fluid Pressure Controller was developed. This controller regulates the overall subsystem operating pressure as well as the differential pressures that must be maintained within the cell. Independent testing of one modified unit demonstrated excellent regulation and smooth transitions over more than 750 simulated subsystem pressurization/depressurization cycles. Additional refinements were implemented in a second unit incorporated into the WS-1 subsystem during its evaluation. Weight, volume and minor configurational modifications are recommended for the next generation unit.

A Static Feed Water Electrolysis Cell that requires no electrolyte in the static feed compartment has been developed and successfully evaluated. This

cell is projected to significantly reduce the complexity of future Oxygen Generation Subsystems by ultimately permitting the feed water to double as the cell coolant.

It is recommended that elimination of the separate coolant compartment and investigation at the multi-cell module level be pursued in the future.

ACCOMPLISHMENTS

The key program accomplishments were as follows:

- Developed the WS-1, the first self-contained Oxygen Generation Subsystem (OGS) that is based on the Static Feed Water Electrolysis (SFWE) concept.
- Successfully demonstrated a total of 1,000 hours of both normal and cyclic (low-earth orbit) operation.
- Achieved sustained one-person level oxygen generation performance with state-of-the-art cell voltages averaging 1.62 V at 206 mA/cm^2 (191 ASF) for an operating temperature of only 326 K (128 F).
- Developed an improved Three-Fluid Pressure Controller (3-FPC) and demonstrated the upgraded performance capabilities.
- Developed an improved SFWE cell frame and incorporated this into the WS-1 electrolysis modules.
- Developed and demonstrated a SFWE cell that eliminates electrolyte in the static water feed compartment, a key step in significally simplifying future OGS units.

INTRODUCTION

Regenerative processes for the revitalization of spacecraft atmospheres are essential for making long-term manned space missions possible. An important step in this overall process is the generation of oxygen (O_2) for metabolic consumption through the electrolysis of water. The by-product hydrogen (H_2) is used to regenerate water from expired carbon dioxide (CO_2).[1] The water is then electrolyzed to generate additional O_2, etc.

An Oxygen Generation Subsystem (OGS) based on the static feed water electrolysis (SFWE) concept and using an alkaline electrolyte has been recognized as a design capable of efficient, reliable O_2 generation with few subsystem components. The static feed concept has evolved over the past 14 years under National Aeronautics and Space Administration (NASA) and Life Systems, Inc. (LSI) sponsorship. During this time, the concept progressed from single-cell operation through the fabrication and testing of multi-person modules and laboratory breadboard systems. Rec-

(1) Superscripted numbers in parenthesis are citations of references listed at the end of this report.

ent developments at LSI have demonstrated substantial reduction in the operating voltage of the electrolysis cells and have allowed for the consolidation of ancillary components resulting in the reduction of power, weight and volume. The overall impact of these state-of-the art advancements is significant, since the OGS is the largest power consuming subsystem of a regenerative Environmental Control/Life Support Systems (EC/LSS).

This report presents the development work that resulted in a self-contained OGS. The subsystem, termed the WS-1, generates 0.82 kg/d (1.81 kg/d) of O_2 equivalent to the metabolic needs of one person. This development, the first complete self-contained SFWE subsystem, enables projection of static feed technology-based hardware for future spacecraft applications, such as needed for the Space Operations Center (SOC).

Background

The technological concepts and prior performance on which the present subsystem is based are described below.

Static Feed Water Electrolysis Concept

Detailed descriptions of the static feed process, its theory of operation and its performance have been discussed previously.[2, 3, 4] The following subsections briefly summarize the subsystem and cell level concepts and the electrochemical reactions involved.

Basic Process. Within a water electrolysis cell, water is broken apart into its component elements by supplying electrons to the hydrogen at a negatively charged electrode (cathode) and removing electrons from the oxygen at a positively charged electrode (anode). The half-cell reactions are as follows for water electrolysis cells using an alkaline electrolyte:

At the cathode:

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

At the anode:

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

These result in the overall reaction of:

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

The Static Feed Water Electrolysis Cell. The extent to which these reactions can be used for practical O_2/H_2 generation is, however, highly dependent on cell technology. Figure 1 is a functional schematic of a SFWE cell. Initially both the water feed cavity and the cell matrix have equal concentrations of electrolyte. As electrical power is supplied to the electrodes, water is electrolyzed from the cell matrix creating a concentration gradient between the electrolyte in the water feed cavity and the electrolyte in the cell matrix. Water vapor diffuses from the water feed matrix into the cell matrix due to this gradient. Consumption of water from the water feed cavity results in its static replenishment from an external water supply tank. Major advantages are that:

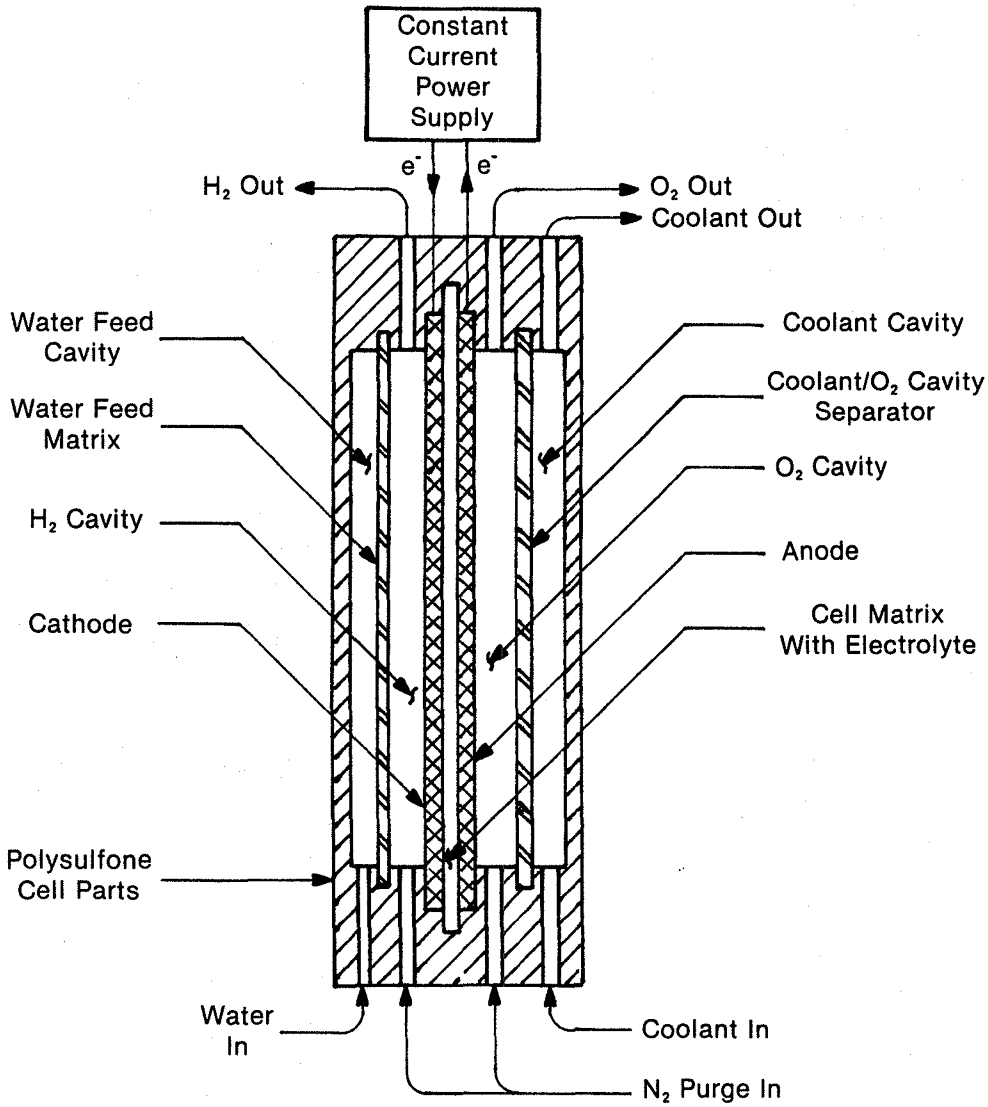


FIGURE 1 CELL FUNCTIONAL SCHEMATIC

1. No moving parts are required since the water feed mechanism is entirely passive and self-regulating based upon the demands of the electrolyzer.

2. No liquid/gas separators are needed.

3. Virtually no feed water pretreatment is needed, because contact between the liquid feed water and the cell electrodes does not occur, thus preventing feed water contaminants from poisoning the electrode catalyst.

These features contribute to simple operation and long life.

As shown in Figure 1, waste heat generated by the electrochemical reaction is removed by the liquid coolant circulating through a compartment adjacent to the O_2 generation cavity. The nitrogen (N_2) purge, not used during normal cell operation, pressurizes and depressurizes the cell during startup and shutdown, respectively. It is also used to maintain pressure during the standby mode.

Subsystem Concept

The basic cells are combined with supporting components to form the subsystem. A functional schematic of a static feed water electrolysis-based OGS is shown in Figure 2. The mechanical portion of the subsystem consists principally of three components: an electrochemical module, a Coolant Control Assembly (CCA) and a Three-Fluid Pressure Controller (3-FPC). The CCA and 3-FPC are special components developed for use with a static feed OGS. The module consists of a series of individual electrochemical cells stacked fluidically in parallel and connected electrically in series to form the Static Feed Water Electrolysis Module (SFWEM). Oxygen and H_2 are generated in the SFWEM from water supplied by the water supply tank.

The CCA (1) supplies a constant flow of controlled, variable temperature liquid coolant to the SFWEM, (2) proportions the coolant flow between a by-pass and a liquid/liquid heat exchanger, and (3) accommodates temperature-induced volume changes in the coolant.

The 3-FPC (1) maintains the absolute pressure of the subsystem, (2) controls the pressure differentials required to establish and maintain liquid/gas interfaces within the individual cells, and (3) controls pressurization and depressurization of the subsystem during mode transitions (e.g., start-ups and shutdowns).

An automatic Control/Monitor Instrumentation (C/M I) unit supplies current to the electrolysis module and regulates and monitors the performance of the entire subsystem.

State-of-the-Art Cell Performance Base

The key performance-indicating parameter of an OGS is the voltage of the individual cells, because the power required to produce O_2 at a given rate is directly proportional to that voltage.

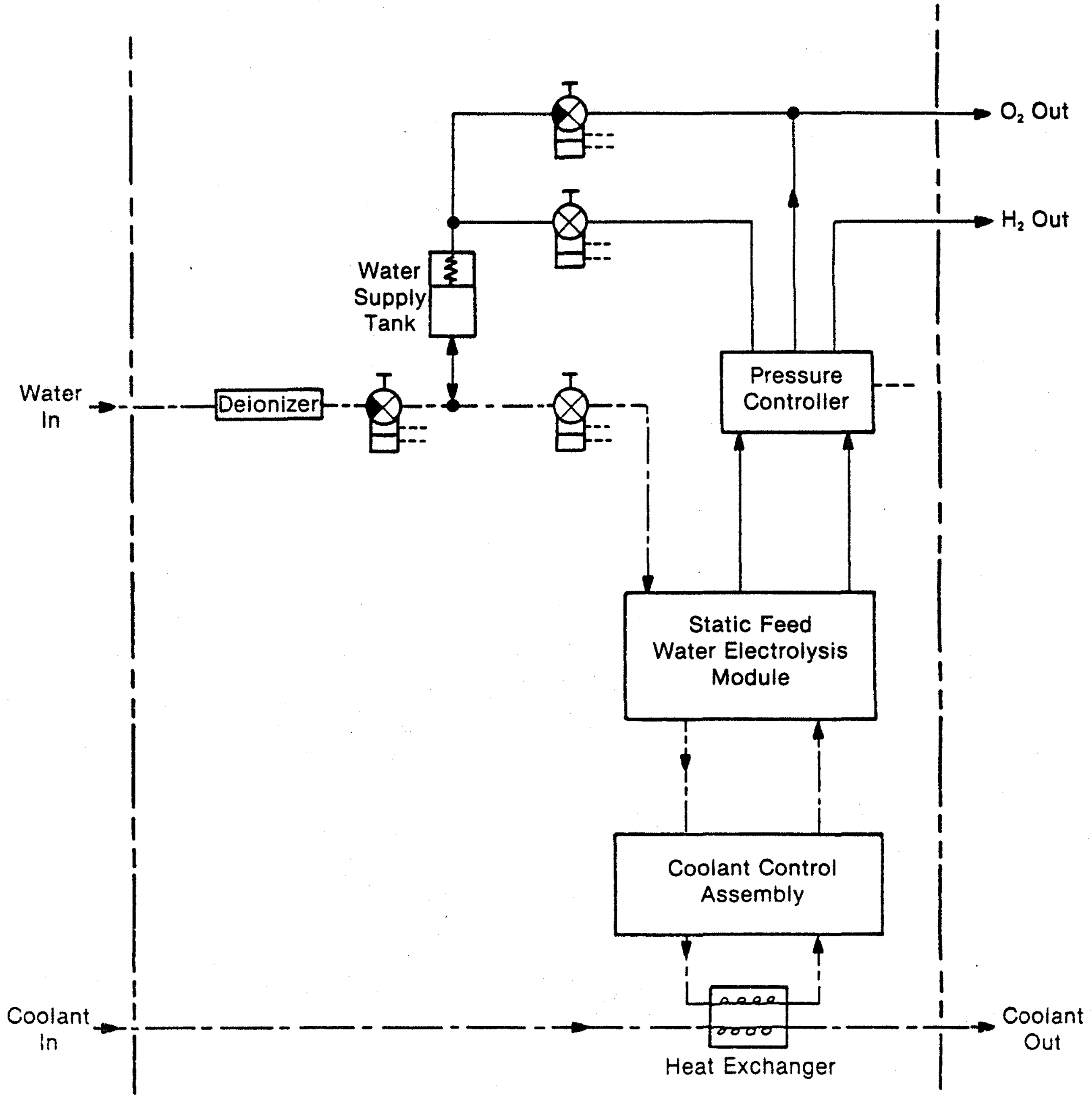


FIGURE 2 STATIC FEED WATER ELECTROLYSIS
SUBSYSTEM FUNCTIONAL SCHEMATIC

Recent OGS development activities at LSI have resulted in substantial improvements in operating cell voltages at practical current density levels. These reductions have been achieved primarily by reducing the overvoltage at the O_2-evolving electrode (anode). Operation with improved anodes has been characterized at cell and module levels.[4] For example, the cell voltage of an ambient pressure single cell operating over a 19,000 hour period at a current density of 161 mA/cm^2 (150 ASF) and a temperature of 355 K (180 F) was initially 1.44 V. It levelled off at 1.49 V after 5,000 hours of operation and remained constant at that value for an additional 14,000 hours. The effect of current density on this cell was measured after 2,691, 7,428 and 16,360 hours of operation. The results, shown in Figure 3, indicate excellent stability in spite of the extensive operating time. The rate of change of cell voltage with increasing temperature after 8,600 hours of operation was -6.1 mV/K (-3.4 mV/F) and -3.4 mV/K (-1.9 mV/F) for temperature ranges of 316 to 339 K (110 to 150 F) and 339 to 361 K (150 to 190 F), respectively, as shown in Figure 4.

These results provided a design basis for the cells of the WS-1 module.

Program Objectives

The primary objectives of the subject program were to:

1. Demonstrate the inherent simplicity, reliability and low power requirements of the Static Feed Water Electrolysis-based OGS by defining and fabricating a self-contained, one-person capacity subsystem (the WS-1).

2. Test the WS-1 to demonstrate hardware maturity and characterize its performance as a function of major operating parameters, including cyclic operation.

3. Modify previously developed subsystem components to incorporate improvements identified under past development efforts.

   a. The Three-Fluid Pressure Controller (3-FPC)
   b. The injection molded cell frame

4. Investigate and demonstrate a potential Static Feed Water Electrolysis concept simplification through the elimination of the need for electrolyte in the water feed compartment of the individual cells.

End Items

The following end items were developed as a result of the subject program activities:

1. A complete one-person water electrolysis subsystem, incorporating the improved cell frame and 3-FPC designs and including a development-type C/M I.

2. Duplicate SFWE module (SFWEM) as a spare.

3. Duplicate 3-FPC for independent evaluation.

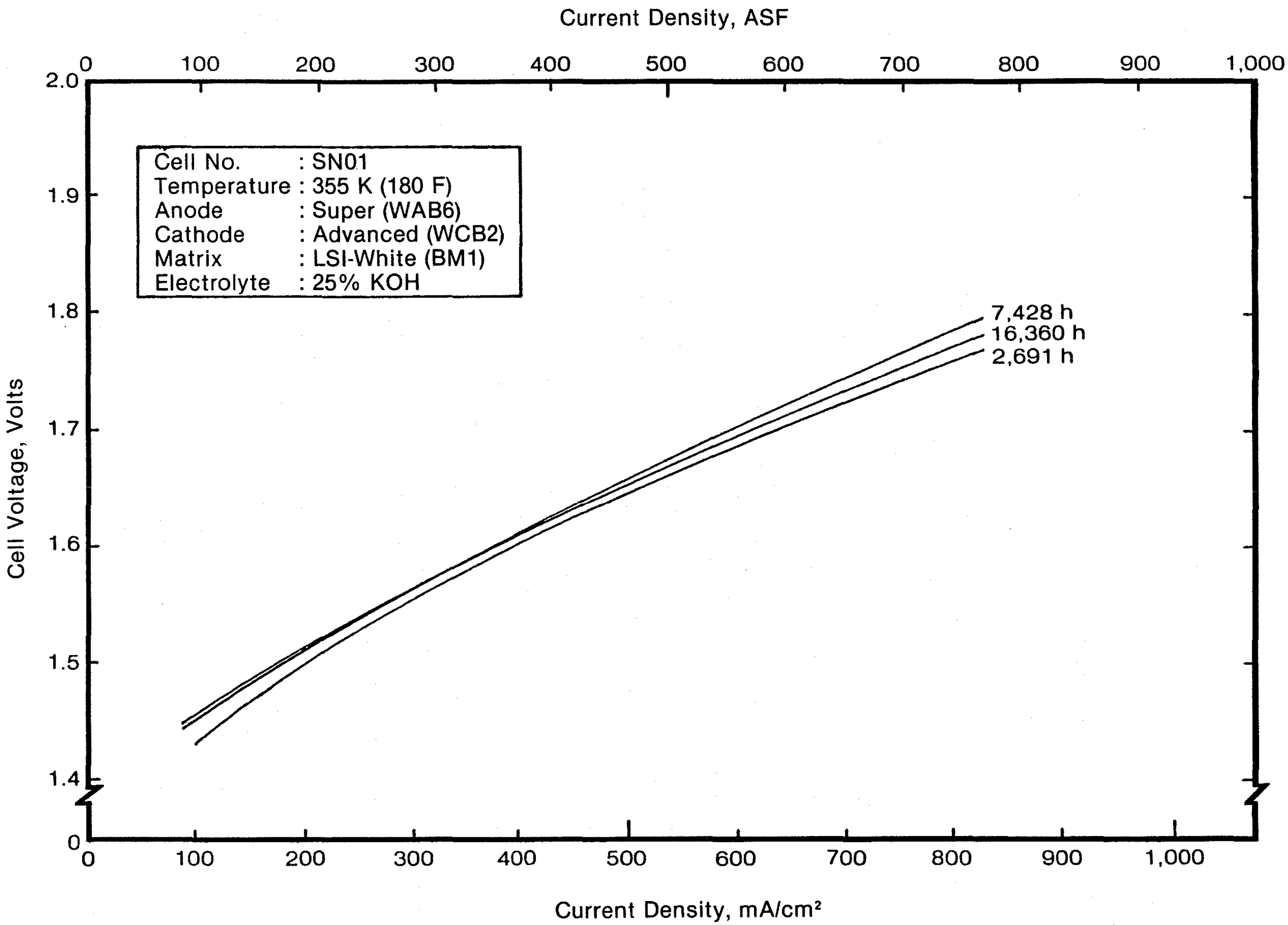


FIGURE 3 SINGLE CELL PERFORMANCE VERSUS CURRENT DENSITY

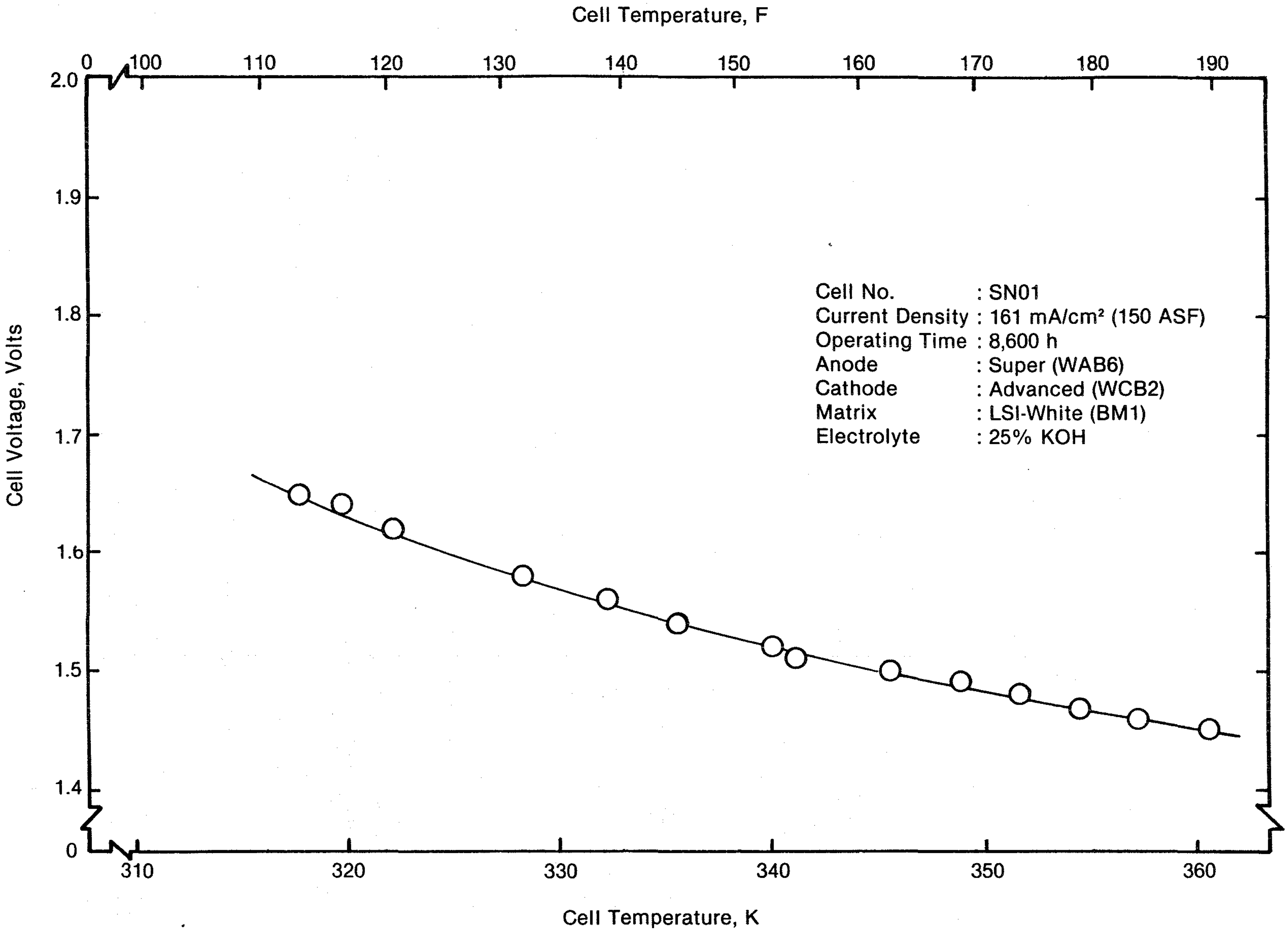


FIGURE 4 SINGLE CELL PERFORMANCE VERSUS TEMPERATURE

Life Systems, Inc.

4. Test Support accessories to evaluate the water electrolysis subsystem and the 3-FPC.

5. Documentation of the progress and results of the effort.

Report Organization

The overall design of the WS-1 Subsystem is followed by a more detailed description of its parts and a discussion of its evaluation. Related advanced technology efforts are then discussed, including development of the improved cell frames, the improved 3-FPC (both incorporated in the WS-1 Subsystem) and a cell that can eliminate the need for electrolyte in the SFWE water feed cavities of future OGS modules. Finally, a mini-Product Assurance effort instituted during the program is described briefly, followed by conclusions drawn from the subject effort, recommendations for future efforts and references cited in the text.

DEVELOPMENT OF A ONE-PERSON OXYGEN GENERATION SUBSYSTEM (WS-1)

The first section of this chapter describes the design objectives for the WS-1 and some general characteristics that apply to the overall subsystem. Subsequent sections describe the results of that design effort in terms of the two primary hardware assemblies: The Mechanical/Electrochemical Assembly (M/EA) and the C/M I.

Overall Subsystem Design

The overall Subsystem design is shown pictorally in Figure 5 and schematically in Figure 6. The M/EA contains the water electrolysis module and all supporting fluid handling components, including the 3-FPC, a CCA, solenoid valves, etc. The C/M I controls all operations of the M/EA and provides for monitoring of critical parameters. Therefore, as shown in Figure 6, these two assemblies are interactive.

Table 1 lists overall goals for the design of the WS-1. More detailed objectives are listed in Table 2 for operational and dimensional characteristics. Fluid interfaces with the M/EA are defined in Table 3.

Optimized packaging, power and hardware weight requirements were imposed on the M/EA package only. Life Systems' standard computer-based development instrumentation, customized for the application, was selected as the Control/Monitor Instrumentation (C/M I) package.[5]

The WS-1 has four different operating modes, as illustrated in Figure 7 and defined in Table 4. Nine different transitions between the operational modes are permissable and are programmed into the C/M I.

Mechanical/Electrochemical Assembly

The M/EA of a SFWE Subsystem was described generally in Figure 2. Specifically, the M/EA of the WS-1 is illustrated pictorially in Figure 8 and schematically in Figure 9. Its weight and power requirements are listed in Tables 5 and 6. Minimization of weight and volume and optimization of Subsystem configuration were performed with the aid of a detailed plastic mock-up.

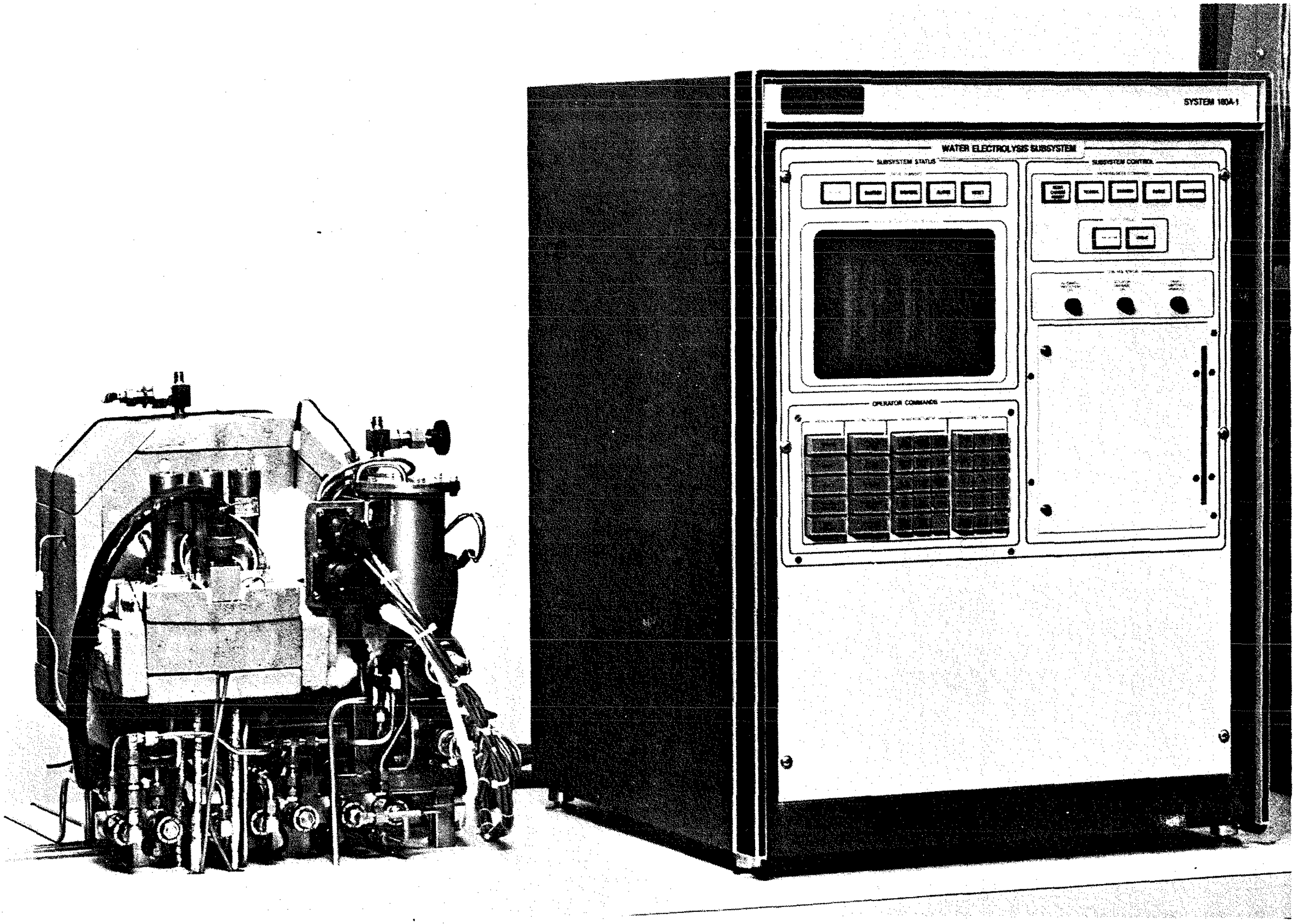


FIGURE 5 WS-1 MECHANICAL/ELECTROCHEMICAL PACKAGE WITH DEVELOPMENTAL CONTROL/MONITOR INSTRUMENTATION

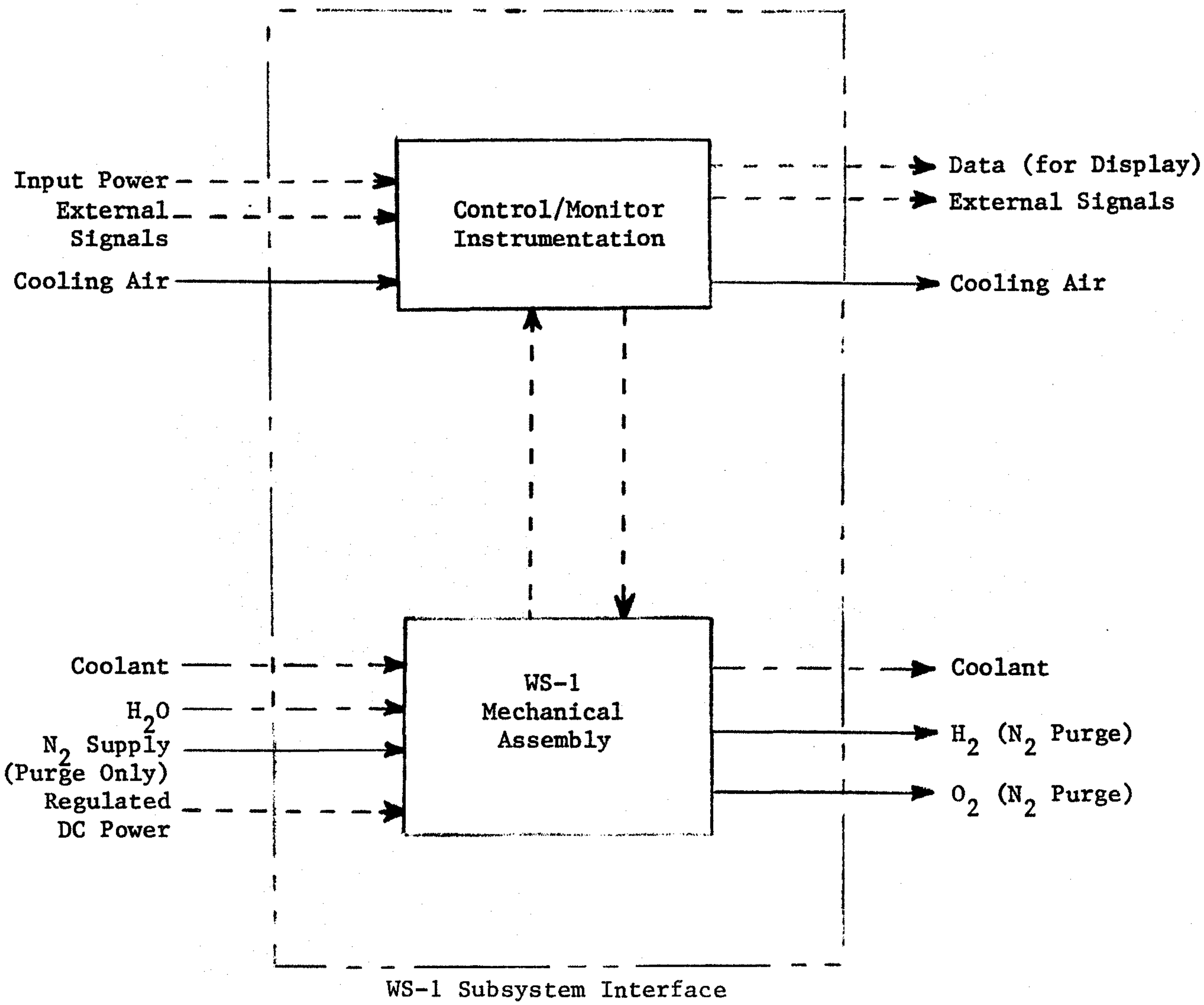


FIGURE 6 WS-1 PROCESS BLOCK DIAGRAM

TABLE 1 GENERAL WS-1 DESIGN OBJECTIVES

Independent Operation as a Subsystem for Testing

Fail-Safe Operation

Automatic Operation

C/M I Packaged Separately

Computer-based Instrumentation with CRT Data Display

Subsystem Design Life of 10 Years

Module Design Life of More Than Five Years

Shelf Life Unlimited

Compatible with Zero and 1 g Testing

Design Specifications

- Operating Parameters
  - O_2 Generation Rate of 0.82 kg/d (1.81 lb/d)
  - Current Density of 206 mA/cm^2 (191 ASF)
- Packaging Goals
  - Volume (Mechanical/Electrochemical) of 0.11 m^3 (3.8 ft^3)
  - Volume (Electrical/Electronic) of 0.20 m^3 (7.0 ft^3)
  - Weight (Mechanical/Electrochemical) of 50 kg (110 lb)

TABLE 2 DETAILED WS-1 DESIGN OBJECTIVES

Crew Size	1
O_2 Generation Rate, kg/d (lb/d)	0.821 (1.81)
H_2 Generation Rate, kg/d (lb/d)	0.103 (0.23)
H_2O Consumption Rate, kg/d (lb/d)	0.951 (2.09)
Product Pressure, kPa (psia)	138 (20)
Product Temperature, K (F)	294 to 339 (70 to 150)
Water Supply	
Pressure, kPa (psia)	207 (30)
Temperature, K (F)	277 to 300 (40 to 80)
Quality	Filtered with Activated Carbon/ Saturated with Air at 14.7 psia
Cabin Environment	
Pressure, kPa (psia)	101 to 105 (14.7 to 15.2)
Temperature, K (F)	291 to 300 (65 to 80)
Relative Humidity, %	70 to 26
Dew Point - Minimum, K (F)	279 (42)
Purge Supply and Pressurization Source	
Type of Gas	N_2
Pressure, kPa (psia)	1,255 (182)
Coolant	
Fluid	Water
Pressure, kPa (psia)	207 (30)
Temperature, Maximum, K (F)	338 (145)
Flow, kg/h (lb/h)	60 (132)
Electrical Power	
DC	
Voltage, Maximum	28
Power, W	241
AC	
Voltage, V	115
Frequency, Hz	400; 60
Phases	1
Power, W	544

continued -

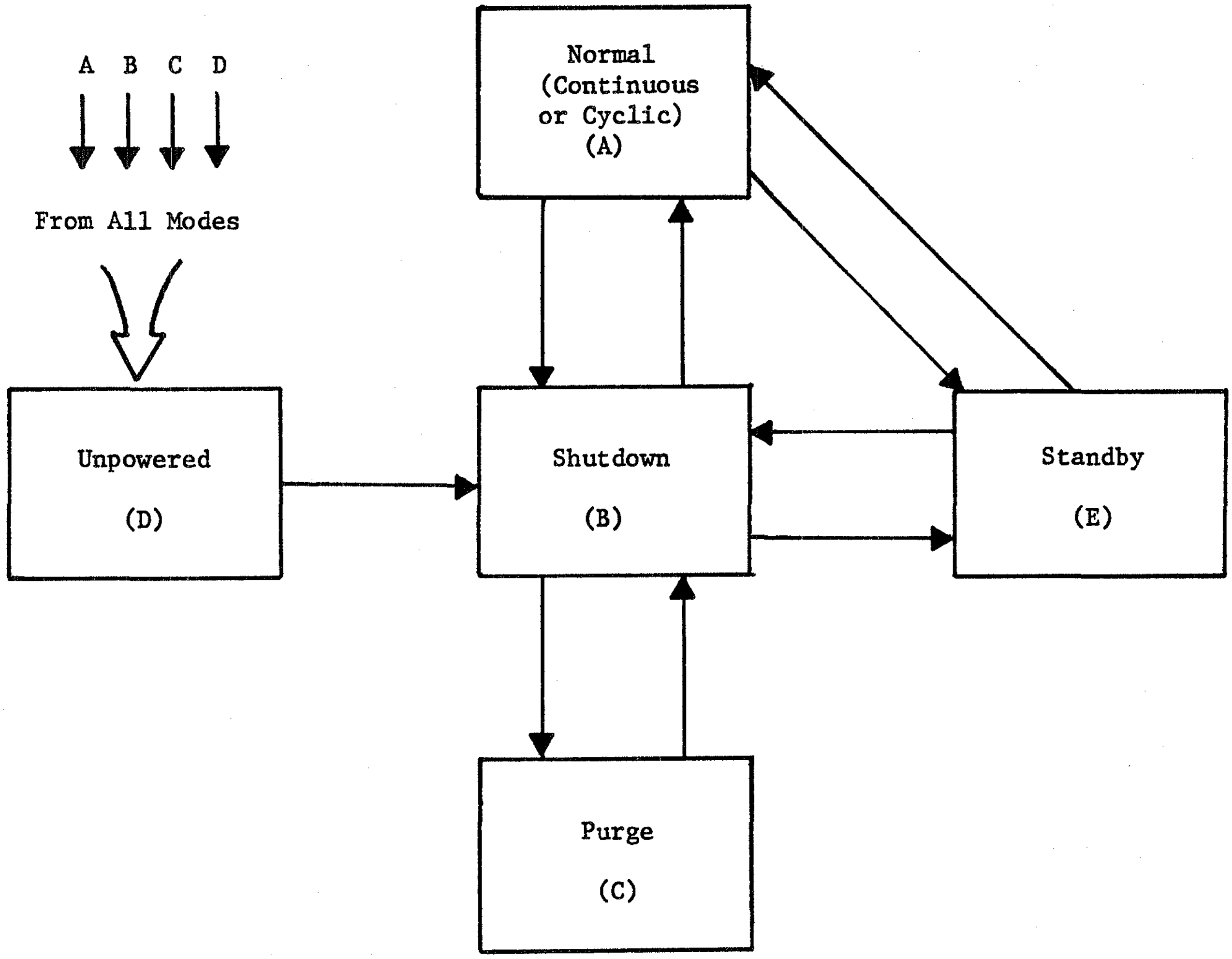
Table 2 - continued

Packaging	
Volume,[a] m^3 (ft^3)	0.044 (1.56)
Volume,[b] m^3 (ft^3)	0.202 (7.1)
Weight,[a] kg (lb)	50 (110)
Weight,[b] kg (lb)	113 (250)
Allowable Downtime, h	24
Duty Cycle	Continuous/Cyclic

(a) The mechanical/electrochemical hardware only.
(b) The electrical/electronic development-level hardware only.

TABLE 3 NOMINAL WS-1 MECHANICAL ASSEMBLY FLUID INTERFACES

1. Influent Water	
Flow Rate, kg/d (lb/d)	0.95 (2.1)
Pressure, kPa (psia)	207 (30)
Temperature, K (F)	277 to 300 (40 to 80)
2. Nitrogen Purge (Only During Purge Cycle)	
Flow Rate, kg/d (lb/d)	≤0.67 (≤1.5)
Pressure, kPa (psia)	1,255 (182)
Temperature, K (F)	294 (70)
Purge Duration, min	5
3. Hydrogen Product	
Flow Rate, kg/d (lb/d)	0.10 (0.23)
Pressure, kPa (psia)	101 (14.7)
Temperature, K (F)	291 to 300 (65 to 80)
Dew Point Max., K (F)	287 (58)
4. Oxygen Product	
Flow Rate, kg/d (lb/d)	0.82 (1.81)
Pressure, kPa (psia)	101 (14.7)
Temperature, K (F)	291 to 300 (65 to 80)
Dew Point Max., K (F)	287 (58)
5. Coolant (Liquid)	
Flow Rate, kg/h (lb/h)	60 (132)
Pressure, kPa (psia)	207 (30)
Temperature, K (F)	Ambient to 338 (145)



- 5 Modes
- 4 Operating Modes
- 13 Mode Transitions
- 9 Programmable, Allowable Mode Transitions

FIGURE 7 WS-1 MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 4 WS-1 OPERATING MODES AND UNPOWERED MODE DEFINITIONS

Mode (Code)	Definition
Shutdown (B)	The WS-1 is not generating O_2 and H_2. Module current is zero and the system is depressurized and at ambient temperature. All valves are deactivated except the N_2 purge valves V4 and V5. The subsystem is powered and all sensors are working. The Shutdown Mode is called for by: • Manual actuation • Low H_2O Feed Pressure • High WEM Temperature • High Subsystem Pressure • Low Subsystem Pressure • High WEM Cell Voltage • Low WEM Cell Voltage • Power on reset (POR) from Unpowered Mode (D) • Mode transition from Shutdown Mode (B) to Normal (A), Standby (E), or Purge (C) was not successful. All transitions to the Shutdown Mode except POR and Purge include a timed purge sequence as part of the mode transition sequence.
Normal (A) (Continual/ Cyclic)	The WS-1 is performing its function of generating O_2 at the one-person rate. The subsystem is at temperature and pressure. The Normal Mode is called for by: • Manual actuation • Incomplete transition from Normal (A) to Standby (E) Mode The WS-1 can operate continuously or cyclicly.
Standby (E)	The WS-1 is ready to generate H_2 and O_2. The subsystem is powered, all valves are at running position except the N_2 purge valves V4 and V5 which are open to maintain subsystem pressure. The module current is off standby mode is called for by: • Manual actuation • Incomplete transition from Standby (E) to Normal (A) Mode
Purge (C)	The WS-1 is being purged with N_2 through the gas lines and compartments. Module current is off and the H_2O inlet valve is closed. The subsystem is at low pressure and the temperature is ambient. This is a continuous purge until a new mode is called. The Purge Mode is called for by: • Manual actuation

continued -

Table 4 - continued

Mode (Code)	Definition
Unpowered (D)	No electrical power is applied to the WS-1. Actuator positions can only be verified visually. There will be no water flow. There will be N_2 purge flow unless the TSA has a shutoff valve to control the N_2 feed. The Unpowered Mode is called for by: • Manual actuation (circuit breaker in TSA) • Electrical Power failure • C/M I failure as detected by the external Supplementary Shutdown Controller

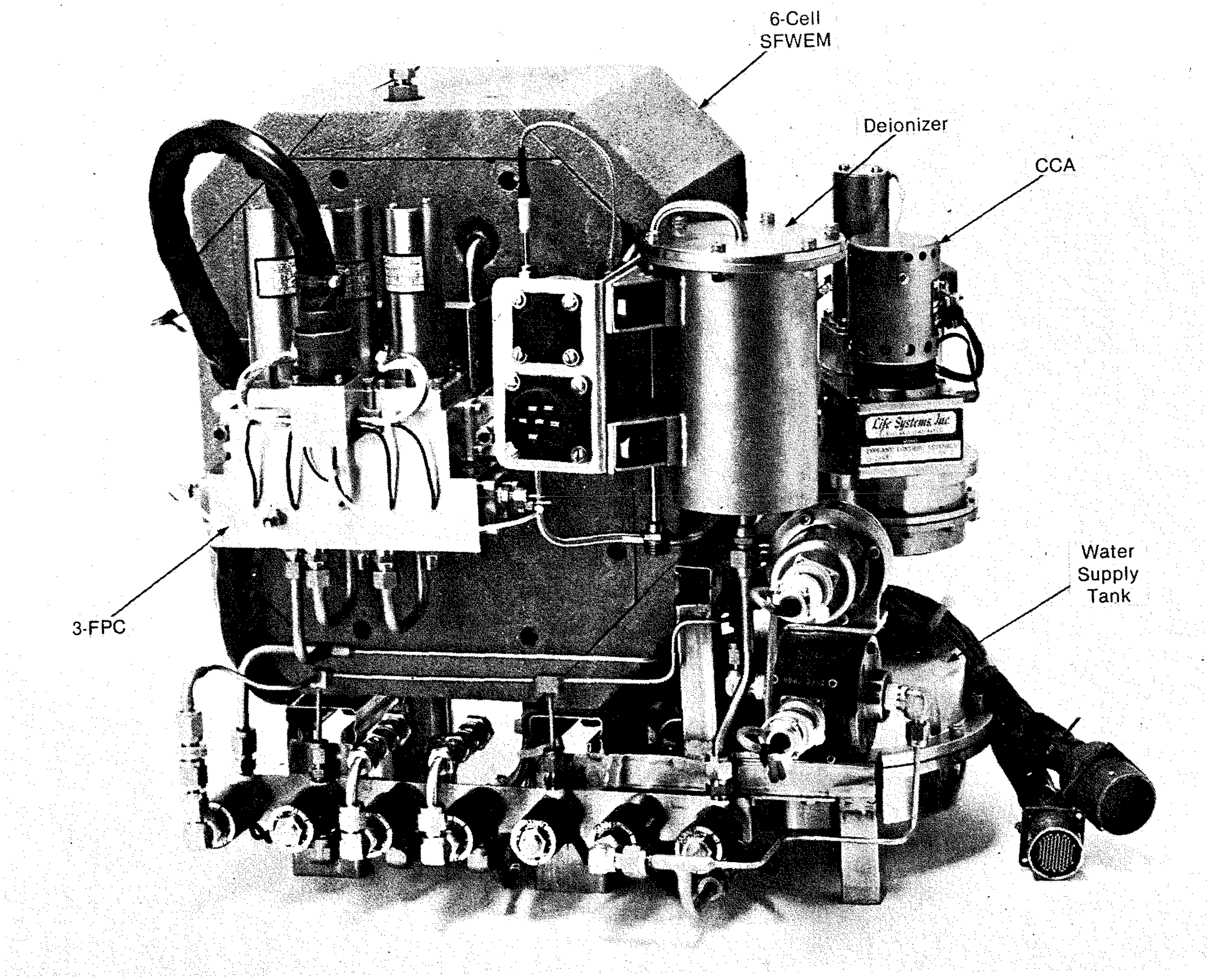


FIGURE 8 WS-1 MECHANICAL/ELECTROCHEMICAL ASSEMBLY

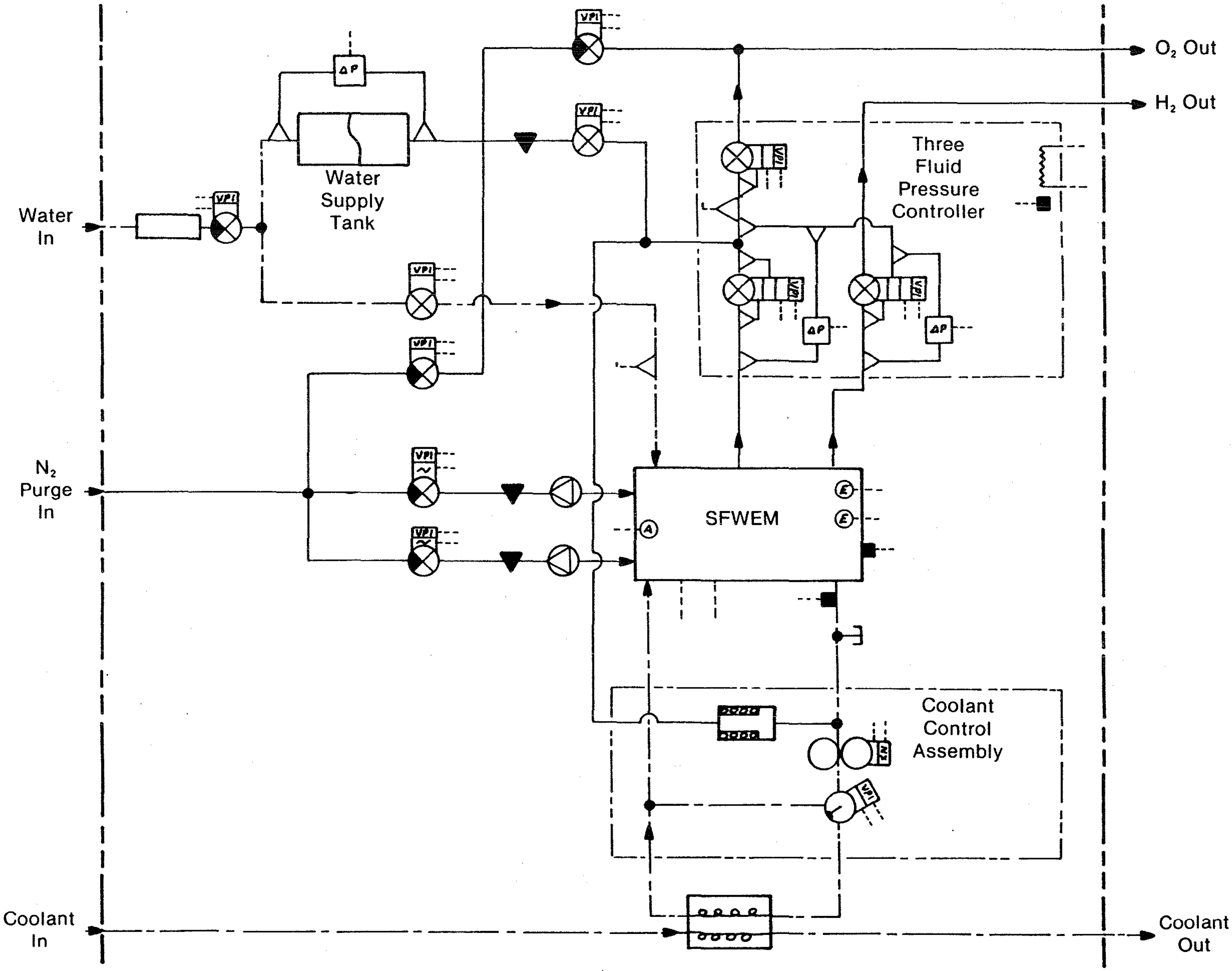


FIGURE 9 WS-1 SCHEMATIC

TABLE 5 WS-1 COMPONENT CHARACTERISTICS

Component	Weight, kg (lb)	Power, W		Heat Rejection, W
		AC	DC	
SFWEM	25.5 (56.0)	—	205[a]	36
3-FPC	4.9 (10.7)		20	20
Water Feed Tank	3.4 (7.5)	—	—	—
Heat Exchanger	0.7 (1.5)	—	—	—
CCA	4.2 (9.3)	20	—	20
Deionizer	2.0 (4.4)	—	—	—
Ancillary Components and Packaging	6.8 (15.0)		16	16
Total	47.5 (104.4)	20	241	92

(a) Including losses due to 85% power conversion efficiency.

TABLE 6 WS-1 TOTAL EQUIVALENT WEIGHT FOR SPACECRAFT APPLICATION

Fixed Hardware Weight, kg (lb)	47.5 (104.4)
Power Penalty,[a] kg (lb)	
AC	6.5 (14.2)
DC	64.4 (142.2)
Heat Rejection Penalty,[b] kg (lb)	13.9 (30.5)
Total, kg (lb)	132.3 (291.3)

(a) Based on 0.322 kg/W (0.710 lb/W) power penalty for AC power and 0.268 kg/W (0.590 lb/W) for DC power.
(b) Based on 0.198 kg/W (0.436 lb/W) heat rejection penalty for rejection directly to cabin air and 0.083 kg/W (0.184 lb/W) for rejection to liquid coolant loop.

Figure 9 illustrates the functions of the various components. The electrochemical module is liquid-cooled, using the CCA. Waste heat of the SFWEM is rejected through the CCA coolant to an external liquid coolant loop via a liquid/liquid heat exchanger. Product gas pressures and the water supply tank and CCA accumulator reference pressures are controlled by a 3-FPC. The feed water is cyclically replenished through automatic filling of the water supply tank. No feed water pump is needed, because the tank is depressurized during filling and spacecraft water supply pressure (typically 207 kPa (30 psia)), is sufficient to fill the tank in less than one minute.

A deionizer cartridge is included in the water supply line to remove dissolved carbon dioxide (CO_2). Safety N_2 purge is included with flow rates fixed by orifices.

The Subsystem components are described in greater detail below.

Water Electrolysis Module

As described previously, the water electrolysis cells are the heart of the Subsystem. Practical levels of oxygen-generation typically require multiple cells stacked in series to form a SFWE module (SFWEM). The module for the WS-1, shown in Figure 10, is comprised of six SFWE cells similar to the state-of-the-art cells discussed in the Introduction. A comparable cell is shown disassembled in Figure 11. Module design characteristics are listed in Table 7.

The assembled module weighs 25.5 kg (56 lb) using non-optimized endplates. The weight of each cell is 0.71 kg (1.56 lb). For purposes of scale-up this means 4.3 kg (9.4 lb) of cell hardware is required to produce the metabolic oxygen required by one-person.

The cells in the present module incorporate improved plastic frames, developed during the subject program. These are discussed in more detail in the Technology Advancement Studies chapter.

Three-Fluid Pressure Controller

A 3-FPC was developed to meet the unique fluid and pressure control requirements of a SFWEM. The differential pressures between the three primary compartments in the cell (see Figure 1) - the water feed compartment, the hydrogen cavity and the oxygen cavity - are only several kPa (psid), whereas the water feed reference pressure varies between 0 and 1240 kPa (0 to 180 psia). Such regulation is ideally suited to the use of feedback-controlled motor-driven regulators.

These functions could be performed by discreet components. However, to optimize subsystem weight, volume and simplicity the controller combines these in a single assembly. It includes the sensors and actuators necessary to control and monitor fluid levels and differentials during all operating modes, including both steady-state and cyclic operation and startups and shutdowns. Three motor driven regulators are used, together with one total pressure level sensor, two differential pressure sensors and three feedback position indicators. These components are illustrated schematically in Figure 9. The overall unit, weighing only 4.86 kg (10.7 lb) and occupying only 1.56 dm^3 (95 in^3) (not including the connector block), is shown pictorally in Figure 12.

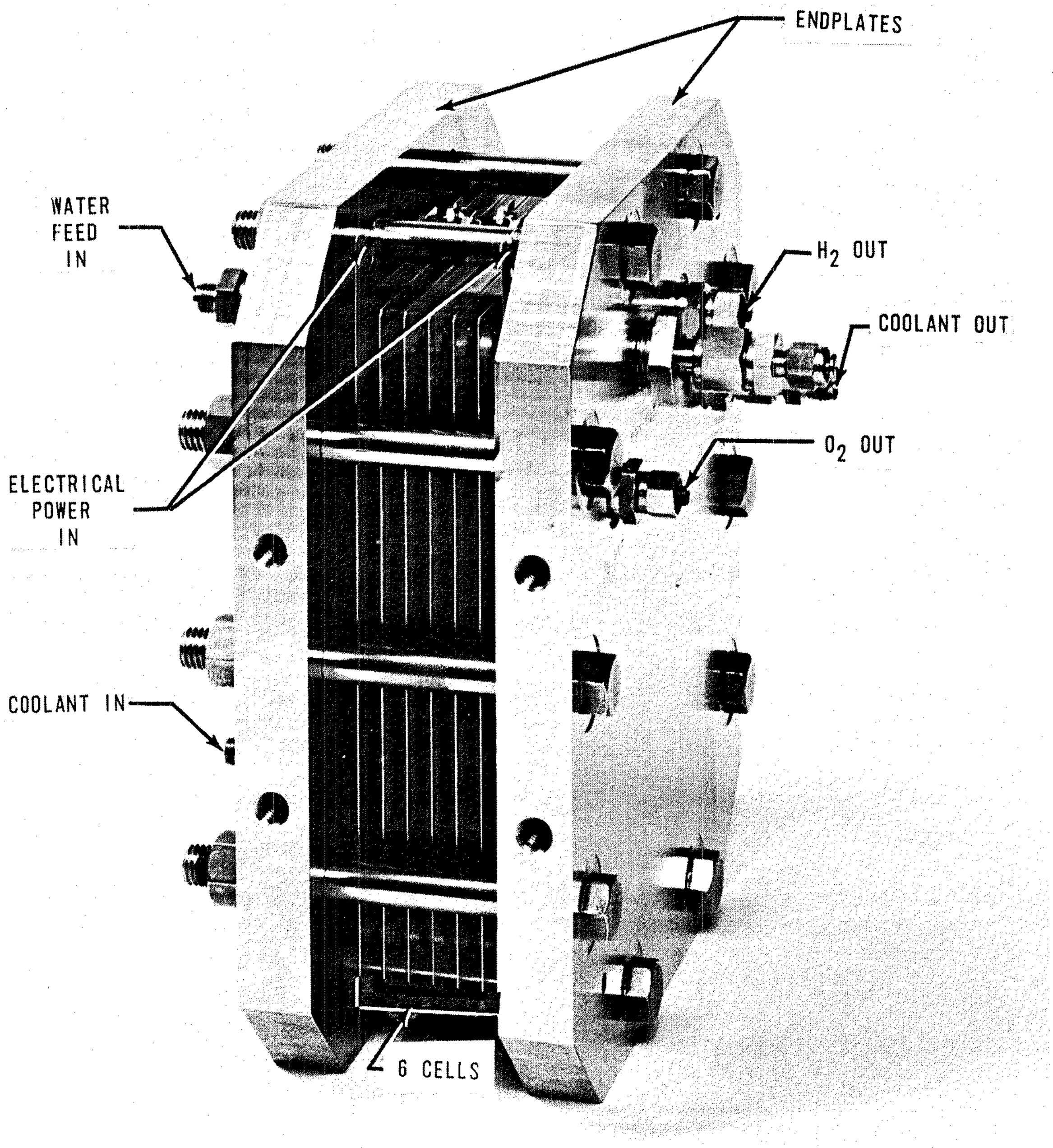


FIGURE 10 SIX-CELL WATER ELECTROLYSIS MODULE

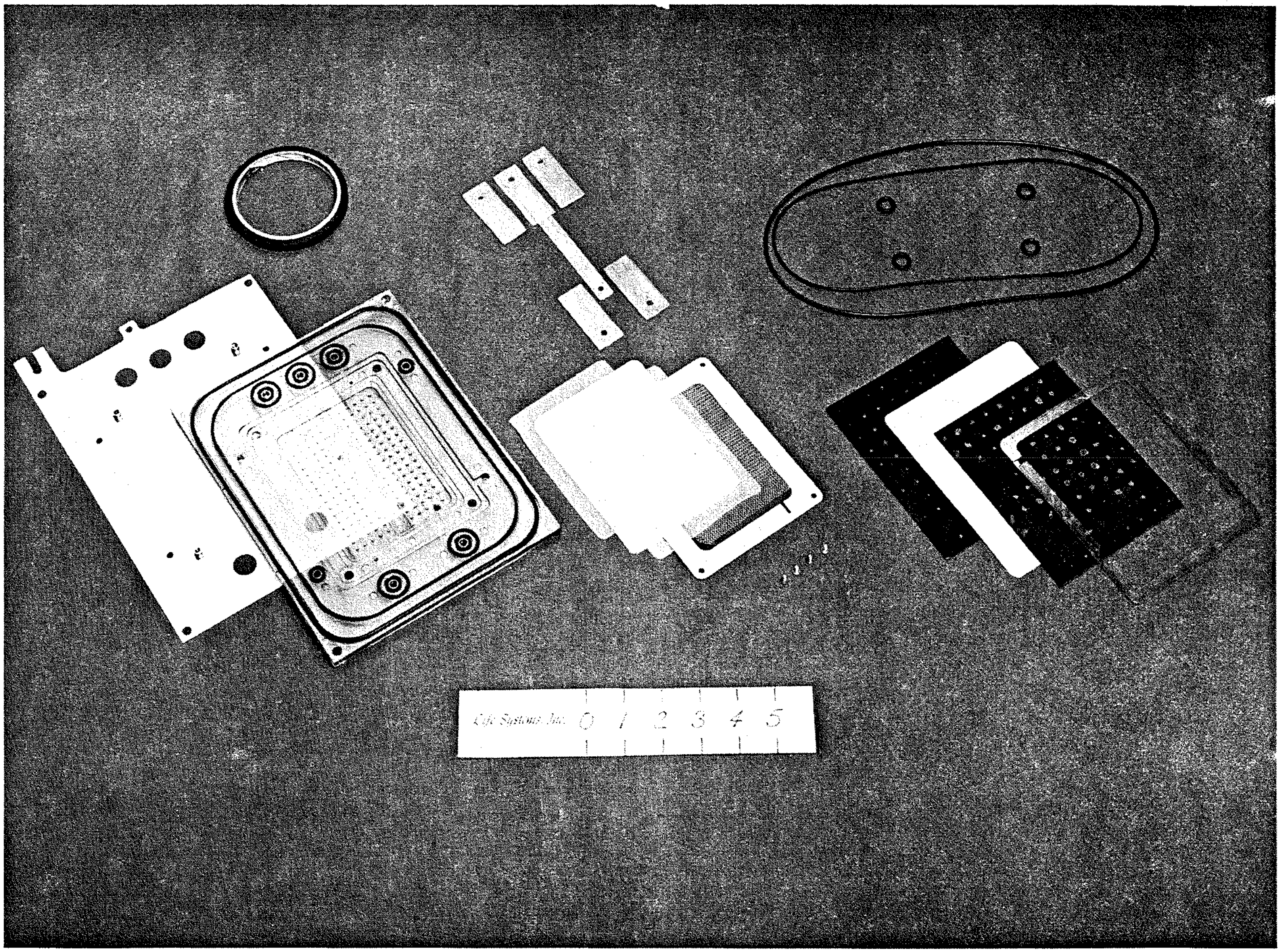


FIGURE 11 DISASSEMBLED SINGLE CELL

TABLE 7 WS-1 MODULE DESIGN CHARACTERISTICS

	SFWEM
Module, kg (lb)	25 (56)
Module Dimensions, cm (in)	13 x 25 x 30 (5 x 10 x 12)
Number of Cells	6
Active Area Per Cell, cm^2 (ft^2)	92.9 (0.1)
Current Density (Nominal), mA/cm^2 (ASF)	206 (191)
Current, A	19.1
Cell Voltage, V	1.52
Power Consumed, W	174
Temperature, K (F)	339 (150)
Waste Heat Produced, W	4.6
O_2 Generated, kg/d (lb/d)	0.82 (1.81)
H_2O Consumed, kg/d (lb/d)	1.0 (2.1)
Pressure, kPa (psia)	
O_2	1281 (186)
H_2	1261 (183)
Water Feed/Reference	1240 (180)
Specific Power, W per kg O_2/d (W per lb O_2/d)	212 (96)

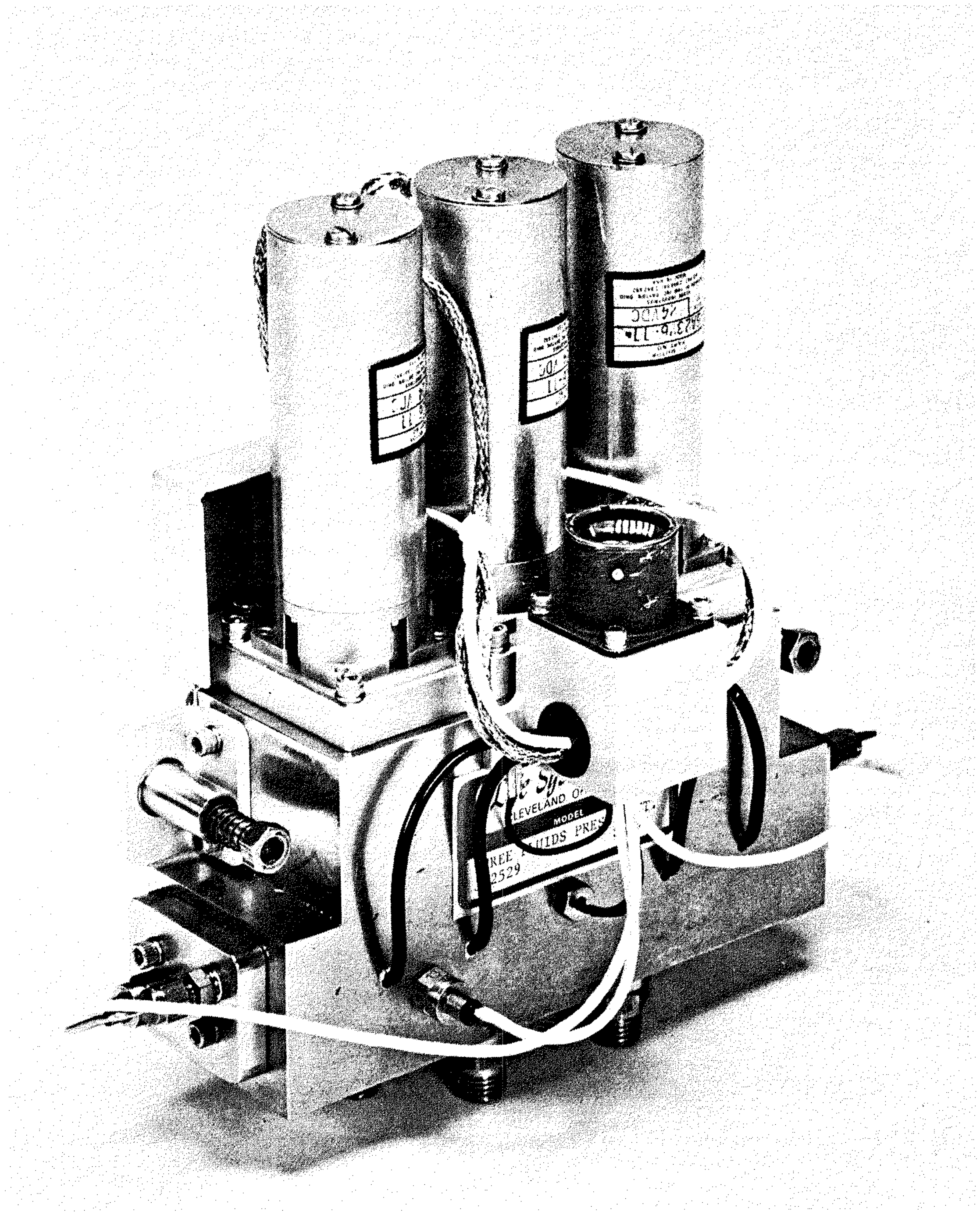


FIGURE 12 THREE FLUID PRESSURE CONTROLLER

The 3-FPC has five fluid interfaces, H_2 and O_2 inlets, H_2 and O_2 outlets and a pressure reference to the water feed tank and the CCA. All other fluid connections are manifolded internally. The regulating characteristics and conditions at these interfaces for which the 3-FPC was designed are listed in Table 8.

The temperature of the 3-FPC is controlled to a value slightly above that of the dewpoint of the product gases to prevent condensation prior to gas expansion. However, expansion of the gas downstream from the 3-FPC from operating pressure to ambient lowers the product gas dewpoint sufficiently to eliminate the need for any condenser/separators. This is of key significance relative to subsystem complexity.

The 3-FPC incorporated into the WS-1 is an improved version that was developed during the subject program. This device is discussed in more detail in the Technology Advancement Studies Chapter.

Coolant Control Assembly

The CCA was developed to meet the temperature control needs of the SFWEM and other liquid-cooled electrochemical modules while minimizing the Subsystem complexity.[6] It combines, in a single-integrated assembly, the sensors and actuators necessary to maintain a constant, preset module temperature despite varying heat loads of the module. The CCA contains a motor, a pump, a motor-actuated mixing valve, an accumulator to compensate for coolant expansion and contraction and sensors to register the speed of the pump and the position of the mixing valve. The three primary mechanical components, the pump, valve and accumulator were shown schematically in Figure 9.

It can be seen that the CCA has four liquid interface connections: to and from the SFWEM and to and from the heat exchanger. The CCA regulates temperature of the module by varying the ratio of coolant flow through the heat exchanger to that through an internal bypass. A photograph of the CCA is shown in Figure 13.

Weight, volume and power were partially optimized. The unit weights 4.2 kg (9.3 lb), occupies 3.34 cm^3 (204 in^3) and consumes 20 W of power. Both the pump motor and the valve positioning motor can be easily replaced without breaking into a liquid line, thereby promoting component maintenance.

Ancillary Components

The ancillary components consist essentially of a deionizer to remove CO_2 from the water (to prevent carbonate formation in the basic electrolyte of the module), a water supply tank to feed water to the SFWEM at operating pressure, seven solenoid valves to control system operation, a liquid/liquid heat exchanger and standard temperature and pressure sensors. Unlike many water electrolysis systems, no condenser/separators are required, because expansion from the operating pressure of the gas product to ambient pressure lowers the dewpoint sufficiently to eliminate condensation. Also, the static water feed principal eliminates the need for water feed circulating pumps. Finally, cooling of the product gases during expansion and temperature equilibration in the subsystem are sufficient to eliminate

TABLE 8 THREE-FLUID PRESSURE CONTROLLER OPERATING CHARACTERISTICS AND CONDITIONS

	Range
Subsystem Pressure, kPa (psig)	103 to 1379 (15 to 200)
H_2 to Subsystem Pressure, kPa (psid)	11 to 17 (1.6 to 2.4)
O_2 to Subsystem Pressure, kPa (psid)	25 to 30 (3.6 to 4.4)
H_2 Flow Rate, kg/d (lb/d)	0.06 to 0.34 (0.13 to 0.88)
O_2 Flow Rate, kg/d (lb/d)	0.45 to 3.2 (1.0 to 7.0)
Operating Temperature, K (F)	291 to 355 (65 to 180)
Rate of Pressure Change, kPa/min (psi/min)	
Backpressure Regulator (Normal Operation)	17 (2.5)
Backpressure Regulator (Startup)	69 (10.0)
Differential Regulators	1.4 (0.2)
Proof Pressure, kPa (psia)	2,068 (300)
Burst Pressure, kPa (psia)	5,170 (750)

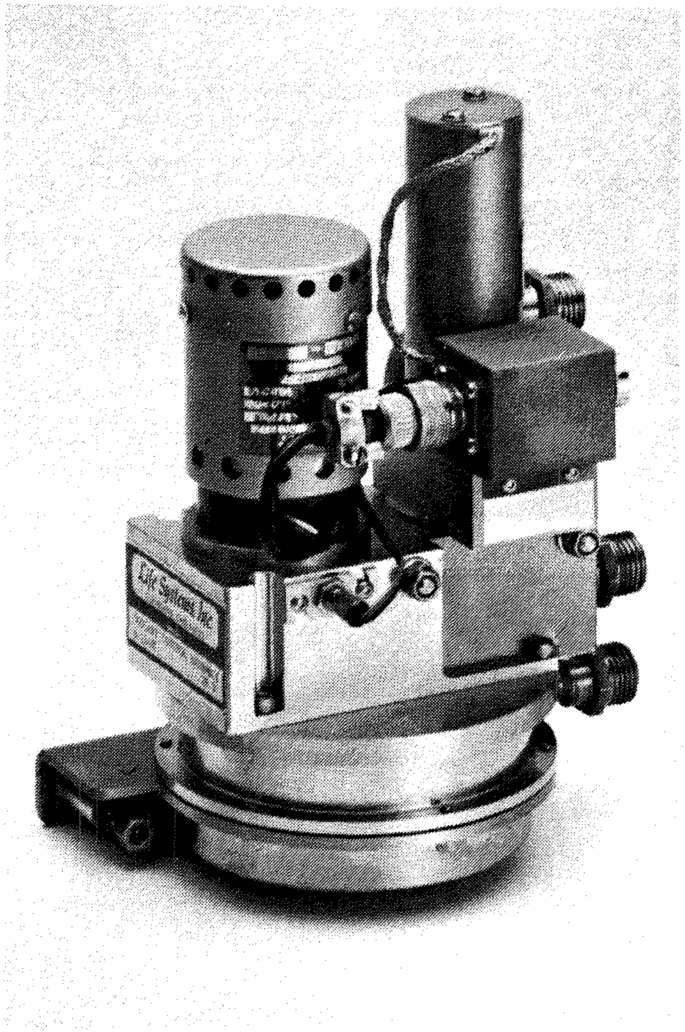


FIGURE 13 COOLANT CONTROL ASSEMBLY

the need for product gas heat exchangers. Additional simplification is projected in the future, based on the development of an SFWE cell that eliminates the requirement for electrolyte in the water feed compartment (see Technology Advancement Studies Chapter).

Control/Monitor Instrumentation

A mini-computer based instrumentation hardware concept was selected to provide for parameter control, automatic mode and mode transition control, automatic shutdown for self-protection, monitoring of subsystem parameters and interfacing with data acquisition facilities. Life Systems' standard development instrumentation package, programmable to perform these functions, was used. This unit is illustrated in Figures 5 and 14. Figure 15 is a block diagram of the interactive sections and interfaces. Design characteristics are listed in Table 9.

General Description

The C/M I receives or transmits signals from or to the M/EA sensors and actuators. Through these it controls and monitors subsystem pressures, flow rates, temperatures, voltages, currents and valve positions in each operating mode (shown in Figure 7 and described in Table 4). It implements each mode as initiated automatically or manually and provides fail-safe operational changes to protect the subsystem if malfunctions occur.

Internally, process operating mode control is a relatively complex operation. It includes selection of different unit processes, selection of valve positions, sequencing of valve positions, sequencing of actuators and checking parametric conditions as the transition proceeds. However, this procedure for control is fully automated by the C/M I so that the operator only needs to press the Mode Change request buttons to initiate transition sequences.

The hardware and software design permits real-time communication between the operator and the M/EA. On the operator/subsystem interface side, the C/M I provides the operator a front panel with a keyboard and a cathode ray tube (CRT) display designed to accept operator commands and display subsystem messages, respectively. This panel is depicted in Figure 16. On the process side, an analog and digital interface board is used for communication between the minicomputer and the sensors and actuators of the subsystem. A static trend analysis is included that compares parameter readings with setpoints that indicate Caution, Warning, and Alarm thresholds. Visual displays indicating whether a parameter is in the Normal, Caution, Warning or Alarm range are provided on the front panel.

Subsystem Control. Control algorithms/concepts were defined for specific subsystem parameters and sequences. Module current, module temperature, subsystem pressure, product gas pressure differentials and 3-FPC temperature are controlled to pre-set values using closed loop, feedback controls. All of the above parameters are controlled during normal mode (cyclic or steady state operation). Several parameters, such as pressure levels and pressure differentials, are also controlled during mode transitions, i.e. start-up or shutdown.

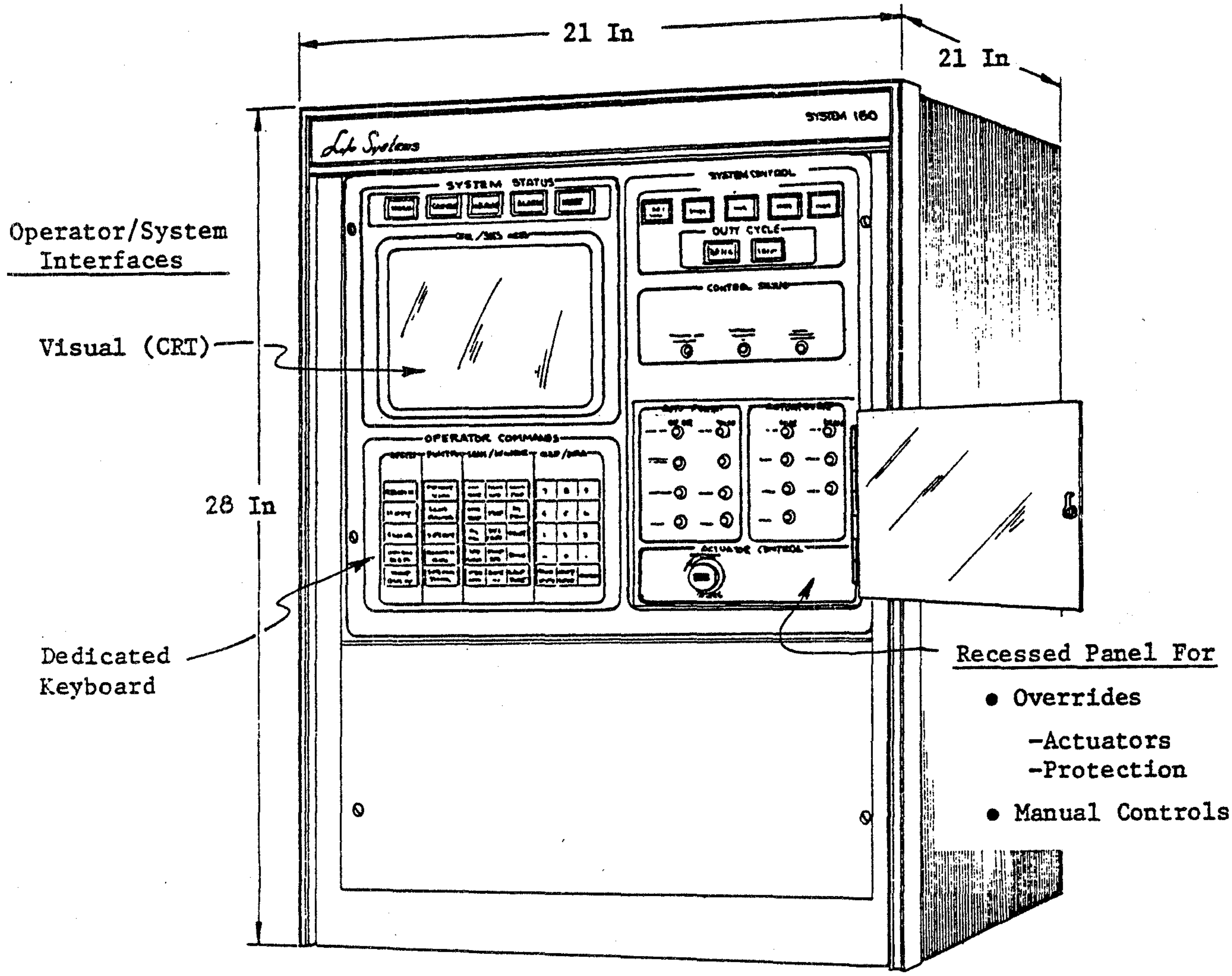


FIGURE 14 C/M I PACKAGE

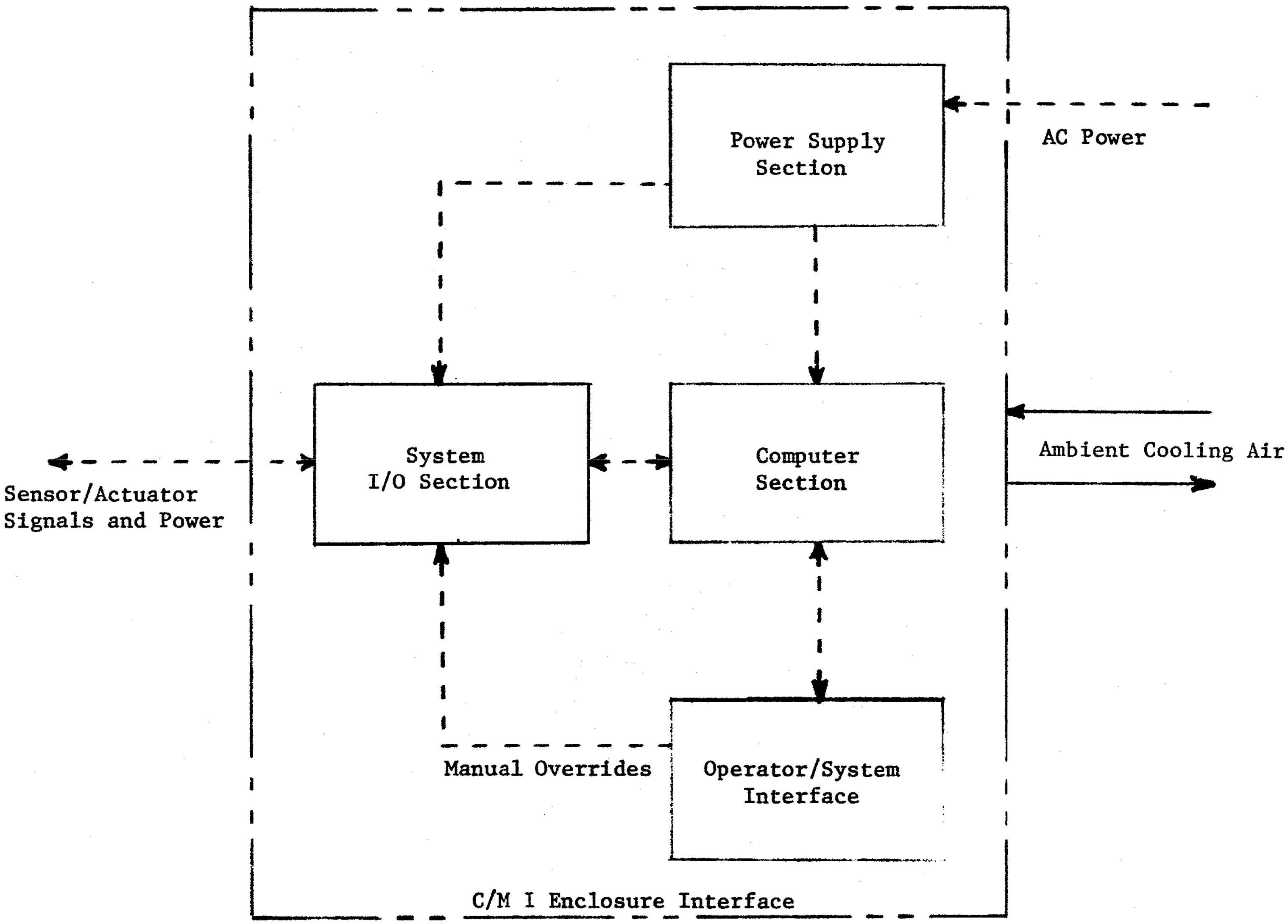


FIGURE 15. CS-1 C/M I HARDWARE FUNCTIONAL BLOCK DIAGRAM

TABLE 9 WS-1 CONTROL/MONITOR INSTRUMENTATION DESIGN CHARACTERISTICS

Dimensions (D x W x H), cm (in)	53.3 x 53.3 x 71.3 (21 x 21 x 28.6)
Weight, kg (lb)	102 (225)
Power Input, W	712
Power Consumption, W	522
Line Voltage, V	115, 1Ø
Line Frequency, Hz	400 and 60
Input Sensor Signal Range, VDC	0 to 5
Output Actuator Signal Range, VDC	0 to 5
Processor	
Type of Computer	CAI LSI-2/20 Minicomputer
Word Size, Bits	16
Memory Size, K Words of Core	16
Memory Speed, ns	1200
Instruction Cycle Time, ns	150
I/O Transfer Rate, Megawords/s	1.67
Other Important Features	• Real Time Clock • DMA Channels • Hardware Multiply/Divide • Stack Processing • Automatic and Blocked I/O • Power Fail Restart
Input/Output	
Number of Analog Inputs	17
Number of Analog Outputs	1
Number of Digital Inputs	16
Number of Digital Outputs	14
Front Panel	
Command Inputs	Pushbutton Switches
Message Display	Color-Coded Indicators and CRT Display
Display CRT Capacity, Characters	1,920 (80 x 24)
Number of Manual Overrides	13
Operating Modes	
Number of Operating Modes	4
Number of Allowable Mode Transitions	9
Number of Normal Mode Duty Cycles	2

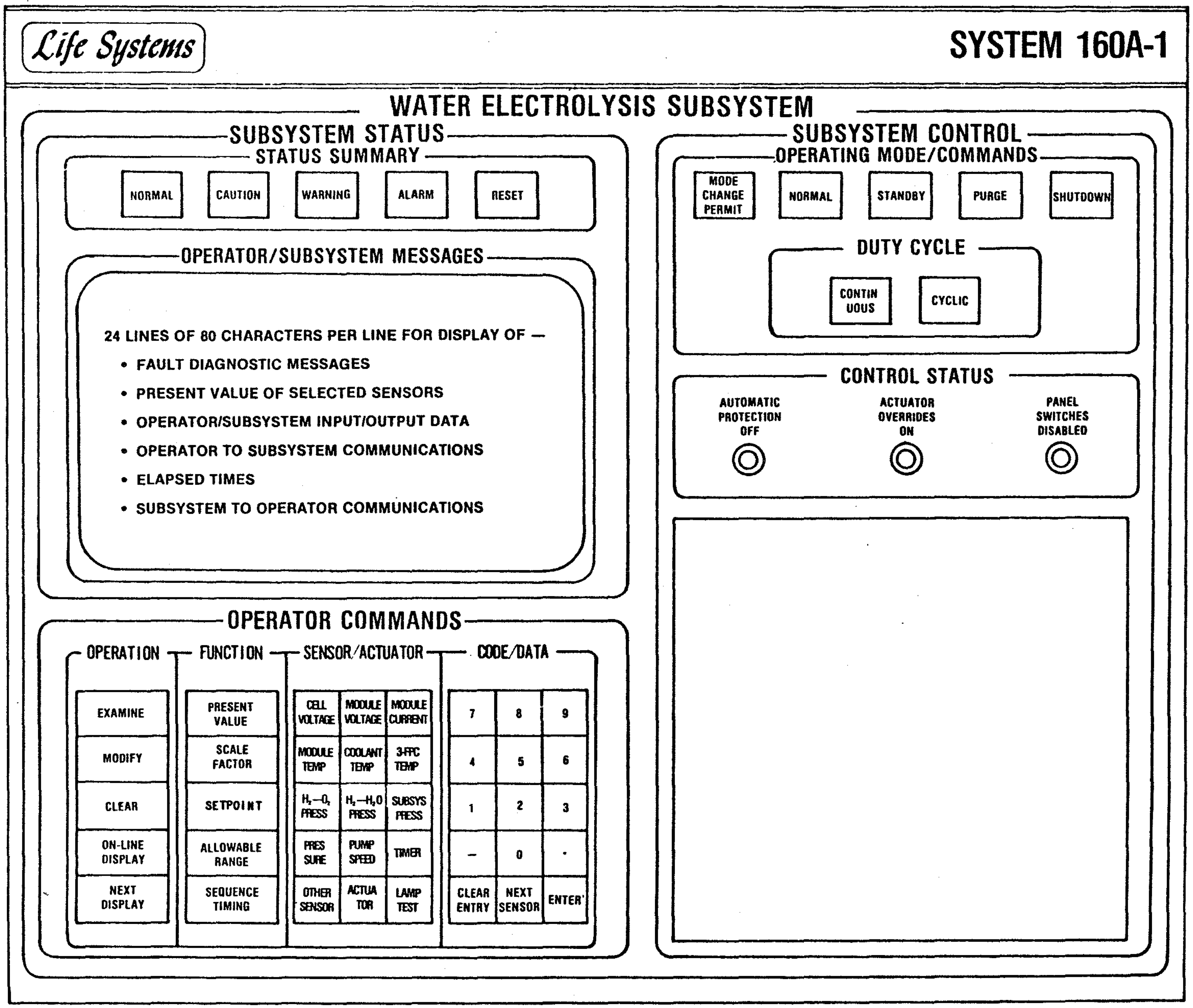


FIGURE 16 C/M I FRONT CONTROL/INTERFACE PANEL

Subsystem Monitoring. Critical subsystem parameters were selected for monitoring to provide for automatic shutdown for self-protection. These parameters are shown in Table 10 for the normal operating mode. Shutdown levels were selected for above and/or below nominal operating values. Only temperatures and pressures are monitored during other than normal operation and during selected mode transitions.

Software

The software manages the entire operation of the C/M I as shown in Figure 17. Each of the major elements is listed below.

a. Power-Failure Control (PFC)
b. Real-Time Executive (RTE)
c. Front Panel Command Handler
d. Operating Mode Control
e. Mode Transition Control
f. Process Parameter Control
g. Fault Detection and Trend Analysis
h. Input/Output (I/O)
i. Data Acquisition System (DAS) Handler

These items are discussed in more detail as follows.

a. Power-Failure Control

The PFC resets the system conditions when power is applied to the C/M I.

b. Real-Time Executive

The RTE is the heart and "chief executive" of the software. It is driven by the real-time clock (a hardware function) and is designed to execute different programs in a timely fashion.

c. Front Panel Command Handler

The Front Panel Command Handler allows the operator to communicate with the subsystem through the front panel buttons.

d. Operating Mode Control

Operating mode control will be designed to resolve all mode change requests in this subsystem. Whenever power is first applied to the C/M I, the computer will go through the startup procedure as programmed in the power failure control module such that the C/M I is in Shutdown operating mode when completed. Any mode change requests, either manually generated or subystem generated, will be checked by the operating mode control module.

e. Mode Transition Control

Mode transition control modules will provide the necessary transition sequences from one operating mode to another.

TABLE 10 WS-1 SHUTDOWN PARAMETERS

Parameter	Shutdown Level Low	Shutdown Level High
Cell Voltage	√	√
Subsystem Pressure	√	√
O_2 to H_2 ΔP	√	√
H_2 to H_2O ΔP	√	√
Water Tank ΔP		√
Coolant Temperature		√
Module Temperature		√
3-FPC Temperature		√

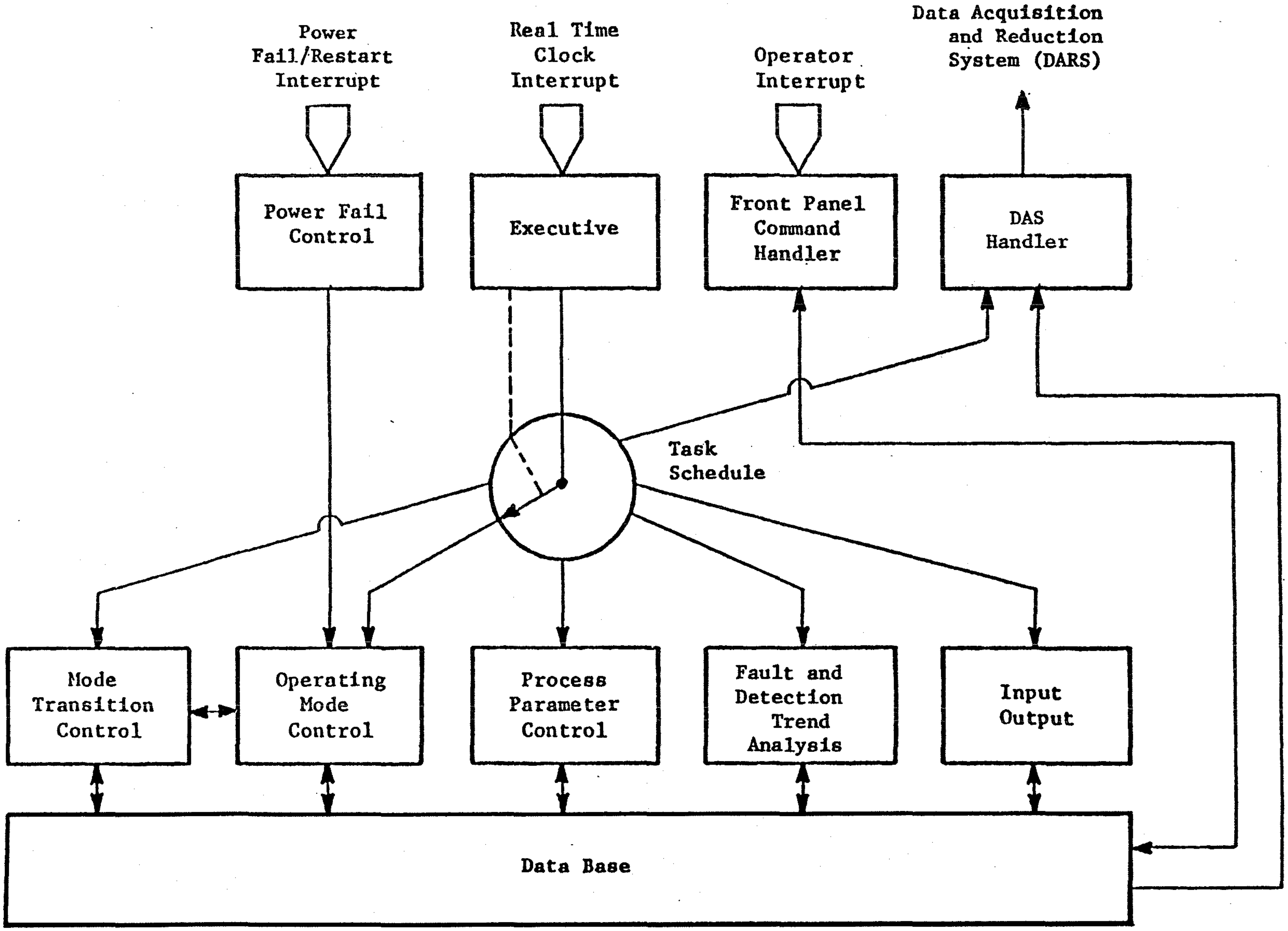


FIGURE 17 WS-1C/M I SOFTWARE BLOCK DIAGRAM (LEVEL I)

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f. Process Parameter Control

The process parameter control and monitor routines will be designed for specific applications and will be running under the RTE to maintain the parameters within the specified ranges. The type of controls available will include: (1) Open-loop programmed control, (2) Feedback on/off control,(3) Supervisory control, (4) Feedback proportional control and (5) Feedback proportional, integral and differential (PID) control.

g. Fault Detection and Trend Analysis

One of the most important requirements of the C/M I is the protection of equipment and operator. The instrumentation is capable of detecting symptoms of component failures. In order to detect the symptoms, sensors are incorporated to monitor the key parameters of the subsystem. When a parameter reaches a certain limit, the subsystem will be shut down to prevent any damage. Normal, Caution, Warning and Alarm indicators are provided on the front panel.

h. Input/Output

The I/O modules will be under RTE control. The input routine will read all data from the Analog to Digital Converter (ADC) channels and put them into the input buffer. The output routine will transfer all the data in the output buffer to the output channels of the digital (I/O) interface. Each analog input has a 12-bit resolution and occupies 2 bytes in the buffer.

i. DAS Handler

The DAS Handler provides for external communication with a Data Acquisition and Reduction System (DARS) for monitoring of process variables

SUBSYSTEM EVALUATION

The WS-1 was evaluated to determine its performance under variable operating conditions and modes. This chapter describes both the evaluation and the applicable test hardware.

Test Support Accessories

The highly flexible developmental C/M I of the WS-1 provides a large variety of parametric readouts in addition to controlling all aspects of the M/EA performance. Therefore, all that is needed to complete the Test Support Accessories (TSA) is a DARS to permit automatic recording of performance parameters and auxillary equipment to supply and monitor fluids and power to the subsystem and provide redundant monitoring of certain key operational parameters. The required components are illustrated pictorially in Figure 18 and schematically in Figure 19.

The DARS was developed under Life Systems' IRAD Programs and made available for automated data storage and retrieval during this test program. The DARS

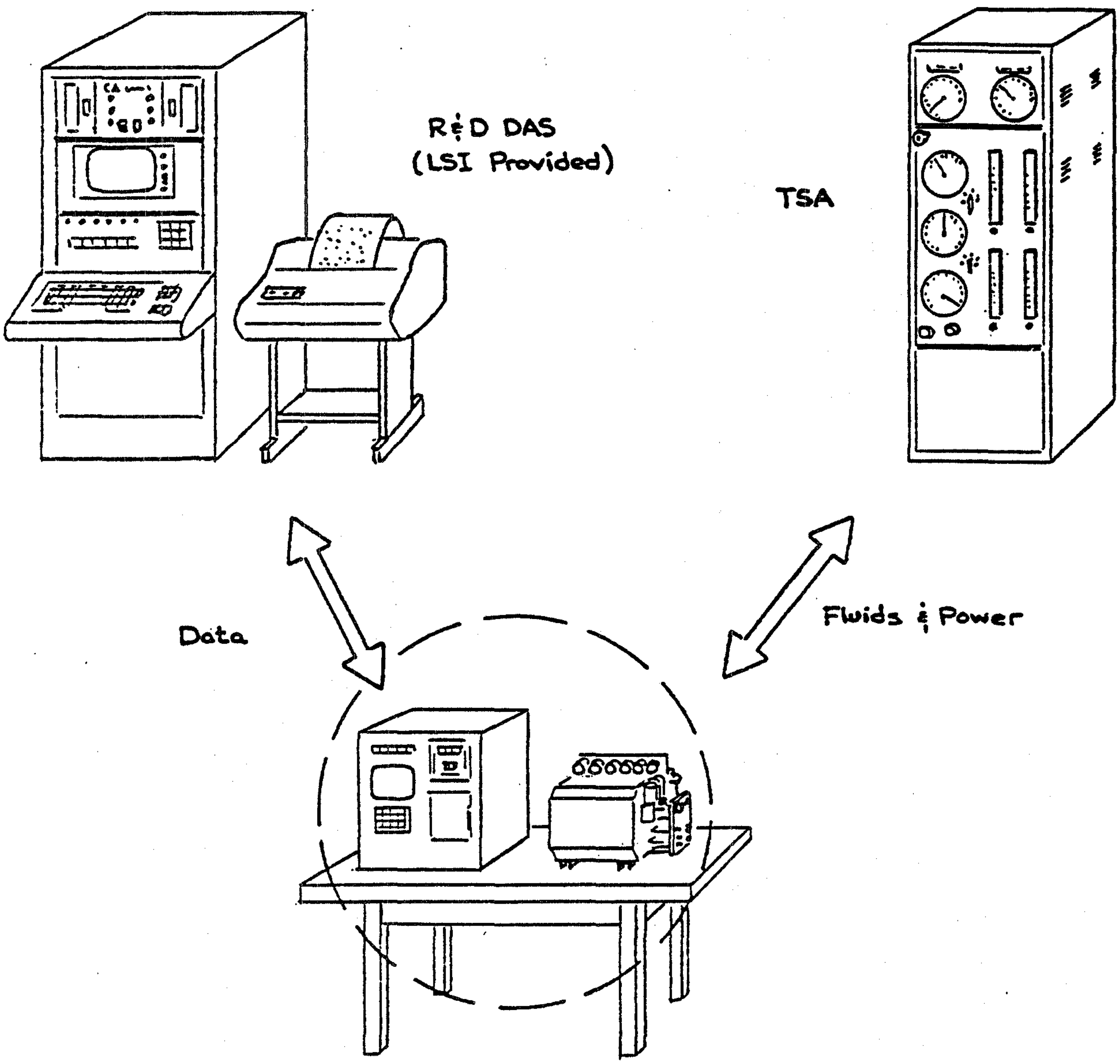

FIGURE 18 PROGRAM HARDWARE: WS-1 AND TSA

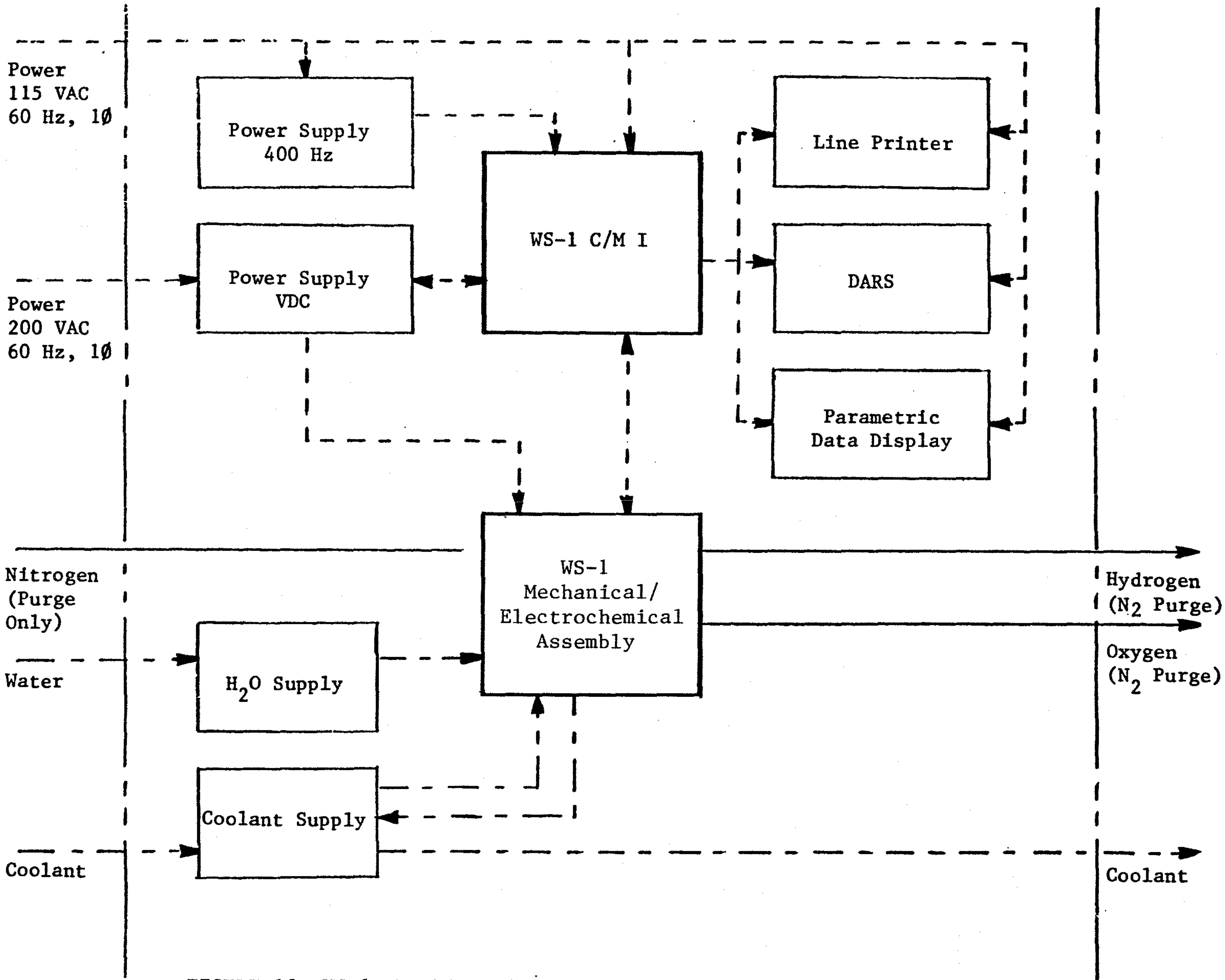

FIGURE 19 WS-1 SUBSYSTEM AS INTEGRATED WITH TEST SUPPORT ACCESSORIES

provides data retrieval, scaling and formal presentation by means of analog-to-digital converters, a minicomputer, dual diskette data storage and both CRT and line-printer readouts. The DARS is capable of recording data from up to 32 analog parametric inputs (0 to 5 VDC) from the C/M I or other test instrumentation. It can also accept up to 16 single digit binary inputs (0/5 VDC) for recording status indications. The period between data sampling and storage can be adjusted from between one second to 18 hours. Use of the DARS permits unattended evaluation of the WS-1 and subsequent cost-effective retrieval and reduction of data.

The fluid supply TSA includes: a purified water source (water tank, feed pump and pressure gauge); a N_2 purge supply, including a N_2 pressure gauge; a coolant supply tank and pump; gauges for measuring O_2 pressure and O_2/H_2 differential pressure at the module; and a soap bubble flow meter for checking O_2 and H_2 outputs. Electrical TSA includes power supplies and analog meters for independent monitoring of individual cell voltages, module voltage and module current.

Test Program

The test program consisted of checkout, shakedown, design verification/endurance and cyclic testing. The testing included 40 days of accumulated operation. The various types of tests are discussed below.

Checkout Testing

Checkout Testing of the WS-1 was performed initially. This phase of the testing program included calibrations, mechanical and electrical integrity checks, and verification that components and subassemblies are correctly integrated.

Shakedown Testing

This phase of testing included correction of any premature component failures, setting of conservative C/M I trend analysis and fault detection setpoints, maintenance of stable interface conditions and 24-hour uninterrupted subsystem operation at the nominal design point. Over 250 hours of total test time were accumulated in the course of combined shakedown and checkout testing, as shown in Figure 20. No major problems were encountered.

Design Verification/Endurance Testing

During this testing the subsystem performance was observed over 20 days of cumulative operation and variable conditions. The design O_2 production rate of 0.82 kg per day (1.81 lb/day) at 206 mA/cm^2 (191 ASF) was verified. No condensate was detected in the product gas outlet lines, indicate that heating of the 3-FPC to 327 K (130 F) and expanding the gas from high pressure to ambient eliminates the need for condenser/separators.

The low waste heat available in the module at the design current density was insufficient to maintain the design operating temperature of 339 K (150 F), because of the high cell efficiency (i.e., low cell voltage). A steady-state average temperature of 326 K (128 F) was typical at an ambient temperature of 294 K (70 F). The present design does not call for utilization of external

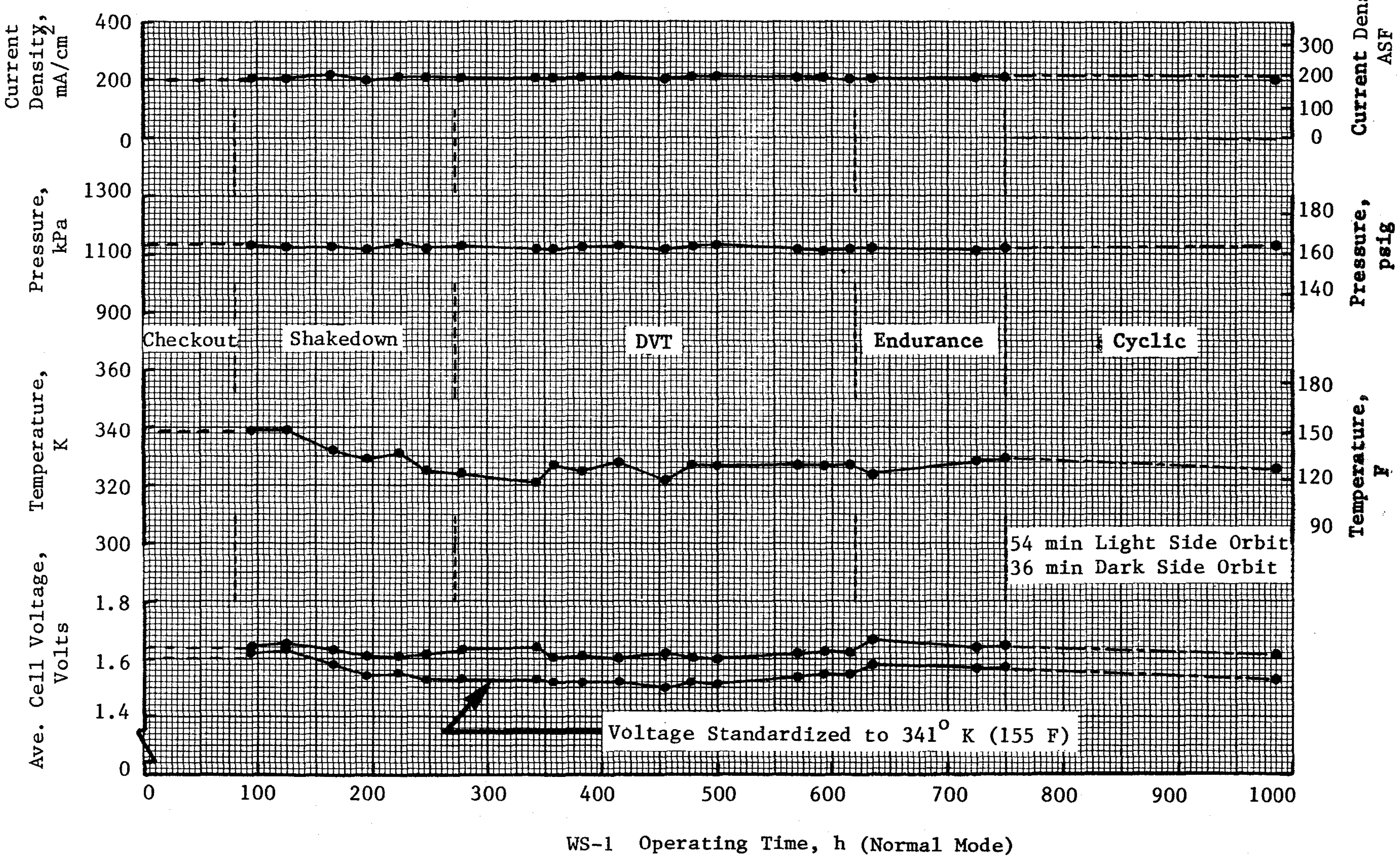

FIGURE 20 WS-1 MODULE PERFORMANCE

heat input at the "coolant" interface. Cell voltages at these conditions, averaged 1.62V, as shown in Figure 20, virtually corresponding to the state-of-the-art performance represented in Figure 4 (1.61V if adjusted approximately for current density via Figure 3). Channeling of waste heat from other WS-1 components and additional insulation have been considered to elevate the module temperature.

One purpose of the test program is to search out design weaknesses. This is especially important during first-level subsystem development. The WS-1 represents the first time that a complete self-contained SFWE subsystem has been assembled. Key improvements of WS-1 components both identified and implemented during the course of this testing are listed in Table 11. Migrations of water into some of the gas lines/cavities during one shutdown, resulting in cell flooding, required a module recharge. It is recommended that the improvement already implemented be further evaluated and that the cause of water migration be investigated during a subsequent follow-on effort.

Cyclic Testing

The WS-1 Susbystem was tested for 250 h in the cyclic mode. While in this mode the C/M I is programmed to operate the M/EA as if a spacecraft incorporating the subsystem were in low earth orbit. This means it is in the Normal Mode for 54 minutes, after which it enters a passive, non-gas producing, Standby Mode for 36 minutes. Two typical cycles of this operation are shown in Figure 21. Overall operation is represented in Figure 20.

The module current is controlled between 19.3 A and 0 A during Normal and Standby, respectively. The pressure is maintained by opening the purge valves to allow a small amount of N_2 to flow through the 3-FPC. As this occurs the module temperature slowly decreases due to the heat loss during the passive phase of the cyclic mode. The heat buildup when current is re-established does not offset the heat loss, causing the progressively lower module temperature shown. This can be lessened with added insulation. The increase in the cell efficiency (lower voltage) is due to cell depolarization during the passive phase.

Conclusions

It is concluded that the evaluation demonstrated and enhanced successful development of the WS-1 and provides a strong basis for subsequent development of a preprototype level Subsystem.

TECHNOLOGY ADVANCEMENT STUDIES

Previously developed subsystem components were modified to incorporate improvements identified during past development efforts. A method to eliminate feed water electrolyte was also evaluated. These efforts are discussed in the following sections.

Improved Cell Frame Development

Several modifications to the cell frame were identified during previous testing of static feed water electrolysis cells. In the past, these changes were incor-

TABLE 11 KEY IMPROVEMENTS IMPLEMENTED DURING DESIGN VERIFICATION TESTING

- Replaced existing, moisture-intolerant 3-FPC pressure transucers with moisture tolerant versions and implemented required C/M I changes.
- Replaced water coolant with electrically nonconducting fluid (Fluorinert) to end possibility of stray electrolysis (and flow-disrupting gas bubbles) in coolant passages. Reduced pump speed from 11,000 rpm to 3,000 rpm to accommodate modified fluid properties.
- Increased diameter of depressurization/repressurization gas lines to water feed tank system from 3.2 mm to 6.4 mm (1/8" to 1/4") to permit more rapid completion of the depressurization/repressurization cycle. Readjusted subsystem component settings influenced by the change.
- Improved 3-FPC valve seating design.
    - Added valve stem guides to the retainer seats to insure positive alignment of the valve stem with the hole in the valve seat.
    - Bevelled the surfaces around valve seat hole to provide for a smoother final adjustment of the alignment of the valve stem and seat.
    - Increased the length of the valve stem to provide for pivotal rotation of the stem when being aligned with the valve seat.
    - Increased screwdriver slot to span entire length of retainer seat to prevent the screwdriver damaging the valve seat when tightening the retainer seat.
    - Decreased valve seat thickness to keep the internal dimensions of the regulator unchanged.
    - Recessed valve seat to accommodate the increased length of the valve stem.
    - Changed from Teflon to KEL-F valve seat material to provide better resistance to cold flow.

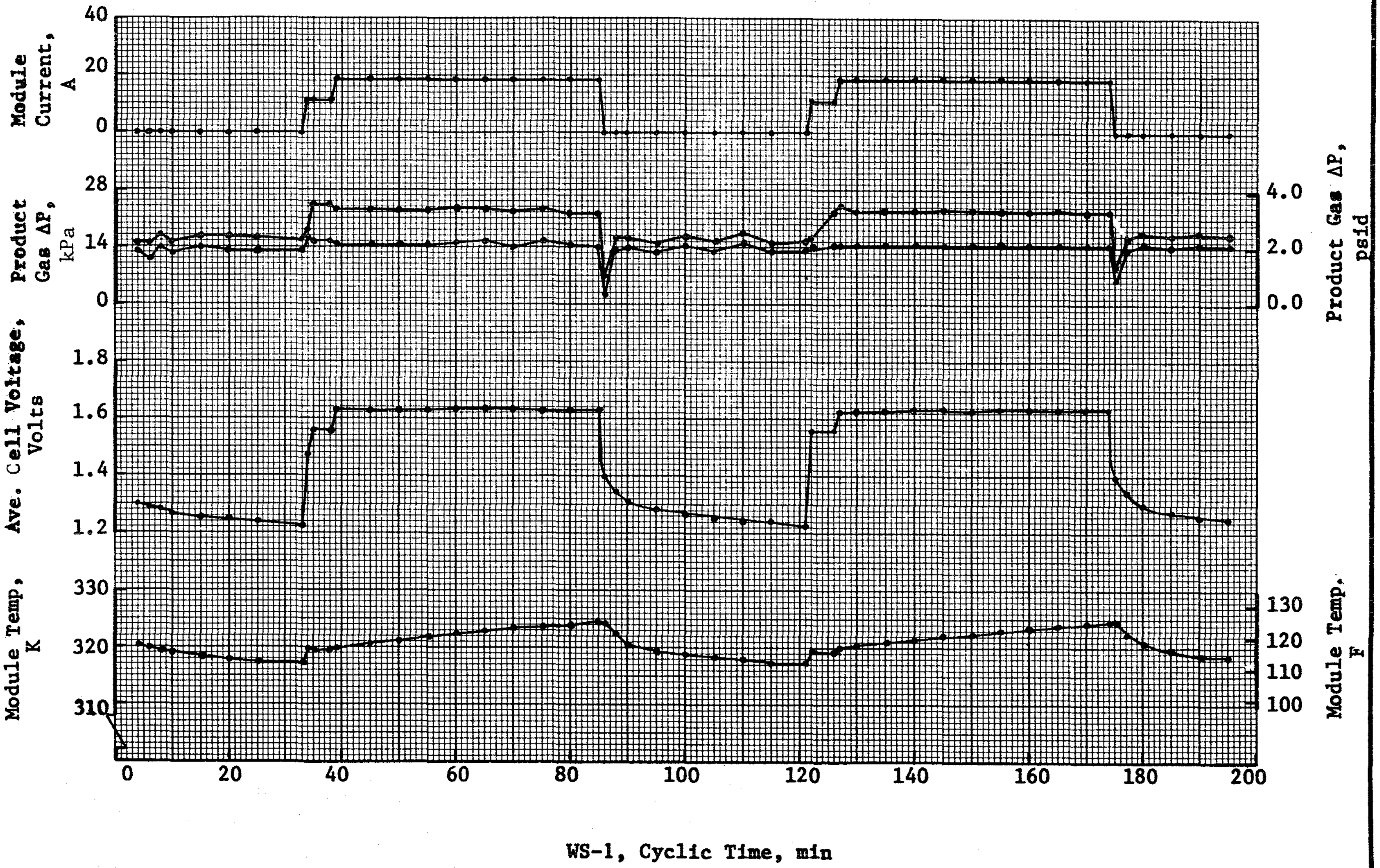

FIGURE 21 RESULTS OF A TYPICAL CYCLIC TEST INTERVAL

porated in existing cell frames through machining and the use of inserts. In the subject program these modifications were permanently incorporated in the design by modifying the cell frame injection molds. A total of five individual changes were made to three mold cavities:

1. A modification to the compression ring mold to provide extra support at the O_2 manifold and eliminate a weakspot for potential gas cross-over.

2. Modification to the injection mold of the water feed insert to decrease the diameter of the water feed manifold from 0.475 cm (0.187 in) diameter to 0.254 cm (0.100 in) diameter to lessen chances for possible gas bubble hand-up in the water feed manifold.

3. Modification to the cell frame injection mold to:
   a. Provide matrix retention at the O_2 manifold (eliminate asbestos extrusion into the O_2 manifold).
   b. Eliminate the need for an insert to decrease the effective diameter of the water feed manifold.
   c. Decrease the width of the water feed channel from 0.475 cm (0.187 in) to 0.152 cm (0.060 in).

Following these modifications, enough frames, inserts and compression rings were molded for two six-cell modules for the WS-1. A cell incorporating the new frames was successfully checked out while running overnight at the nominal design point current.

Improved Three-Fluid Pressure Controller Development

The application and general characteristics of the 3-FPC, as incorporated into the WS-1, were discussed in the Subsystem Development chapter. The present section discusses the component developments that lead to that design, as well as the independent evaluation of a duplicate unit.

Background

The 3-FPC was originally developed during a previous effort.[(4)] Prior testing identified needed improvements, resulting in a list of design objectives, Table 12. These were implemented during the subject program.

Controller Design

The improved controller is shown assembled and disassembled in Figures 12 and 22, respectively. Features of the new design and operating characteristics and conditions are listed in Tables 13 and 8, respectively. Two improved 3-FPC units were fabricated and assembled, one for the WS-1 and the other for independent evaluation.

Test Stand Development

A 3-FPC test stand, shown in Figure 23, was developed for the characterization and endurance testing of the 3-FPC. The main objective of the test stand was to enable operation of the 3-FPC under various simulated OGS operating modes and conditions. The 3-FPC test stand mechanical schematic is shown in Figure 24.

TABLE 12 THREE FLUID PRESSURE CONTROLLER DESIGN OBJECTIVES

- Combine into a single unit the following components:
  - 1 backpressure regulator
  - 2 differential pressure regulators
  - 1 absolute pressure sensor
  - 2 differential pressure sensors
  - 4 heating elements
  - 1 thermistor
  - 3 regulator position indicators
- Line Replaceable Unit
- Weight, 3.6 kg (8 lb)
- Volume, 3.21 dm^3 (196 in^3)
- Increase sensitivity
- Heat regulator body
- Increase pressure sensor accuracy and reliability
- Reduce component complexity
- Restrict spring cap rotation throughout entire stroke
- Implement line replaceable unit (LRU)-type mounting and fluid connections

TABLE 13 RESULTS OF THREE-FLUID PRESSURE CONTROLLER REDESIGN

- Decreased number of seals from 9 to 4 per regulator.
- Increased regulator sensitivity from 28 kPa (4.1 psid) to 2.4 kPa (0.35 psid).
- Changed from rolling to flat diaphragm.
- Heated regulator body to prevent condensation.
- Utilized more accurate and reliable pressure transducers.
- Implemented LRU type mounting and fluid connections.
- Reduced component complexity.
- Assured spring cap rotation is restricted throughout entire stroke.
- Provided independent manual override capability on each regulator.
- Changed environment of adjustment screw threads from pure O_2 to ambient atmosphere.
- Almost eliminated linear travel of reference side O-ring seal.
- Insulated to reduce heat loss.
- Reduced switching power from 32.4 to 21.9 W.
- Weight and volume of 4.9 kg (10.7 lb) and 1.56 dm^3 (95 in^3) (without connector block), respectively.

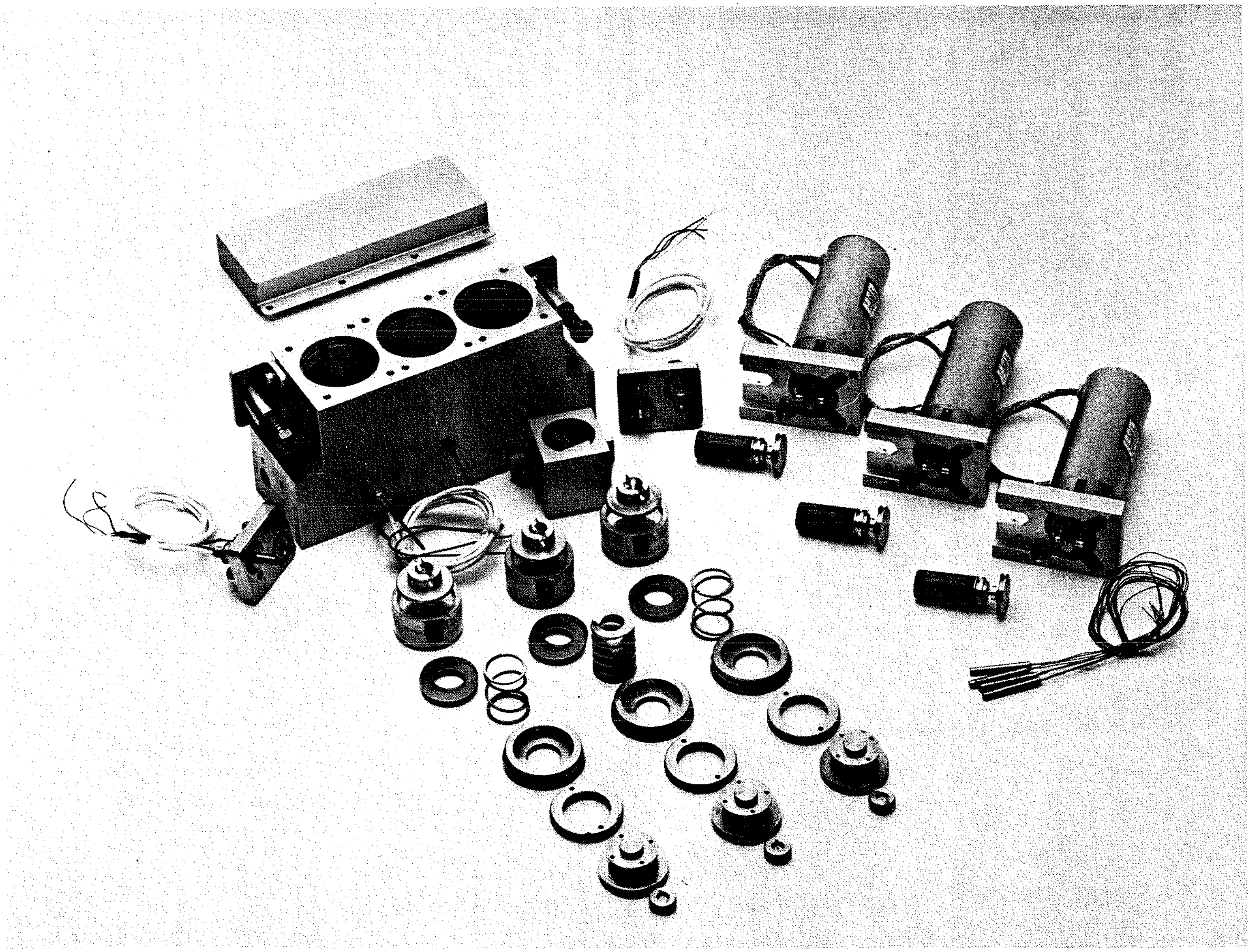

FIGURE 22 THREE FLUID PRESSURE CONTROLLER PARTS

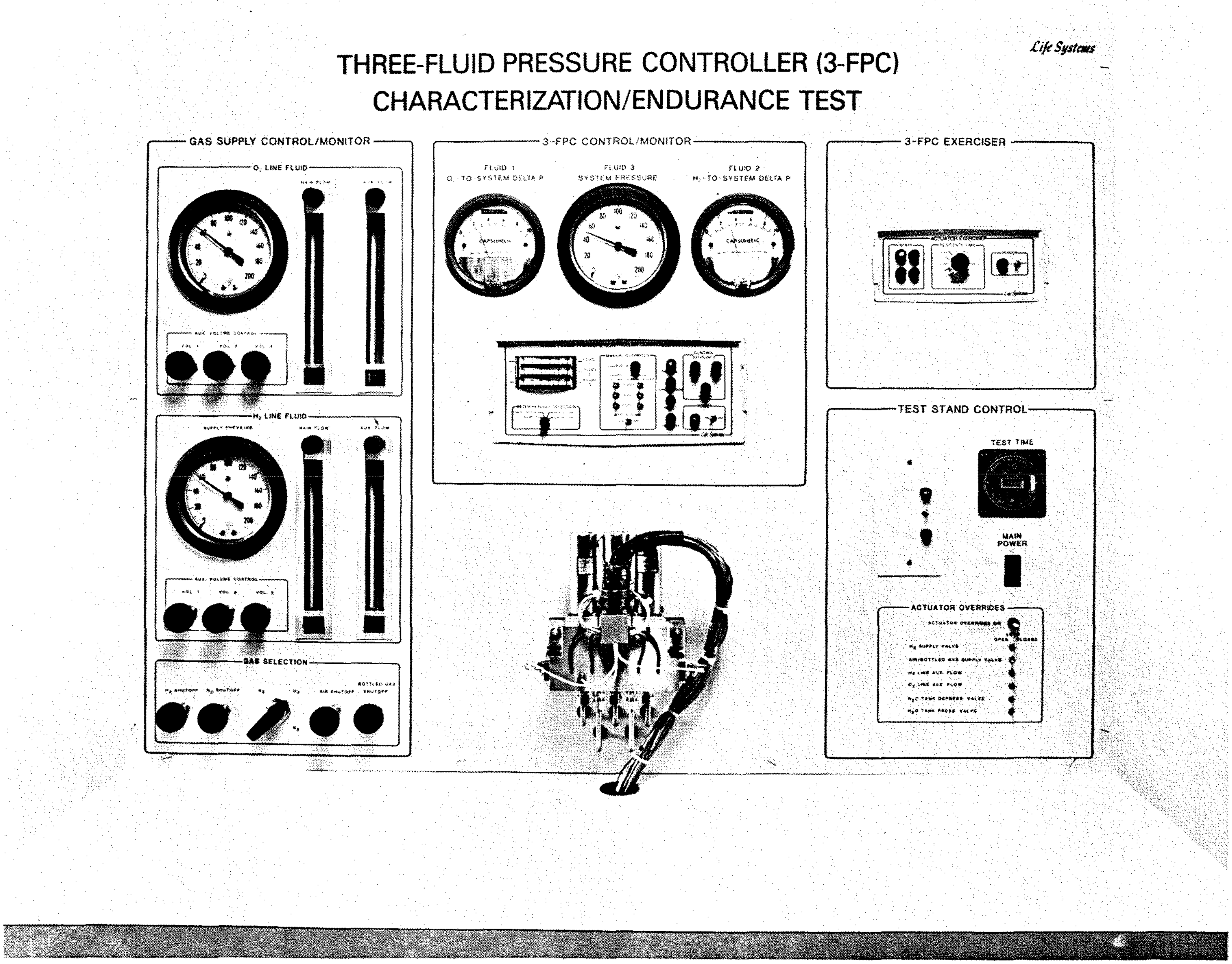

FIGURE 23 THREE-FLUID PRESSURE CONTROLLER TEST STAND

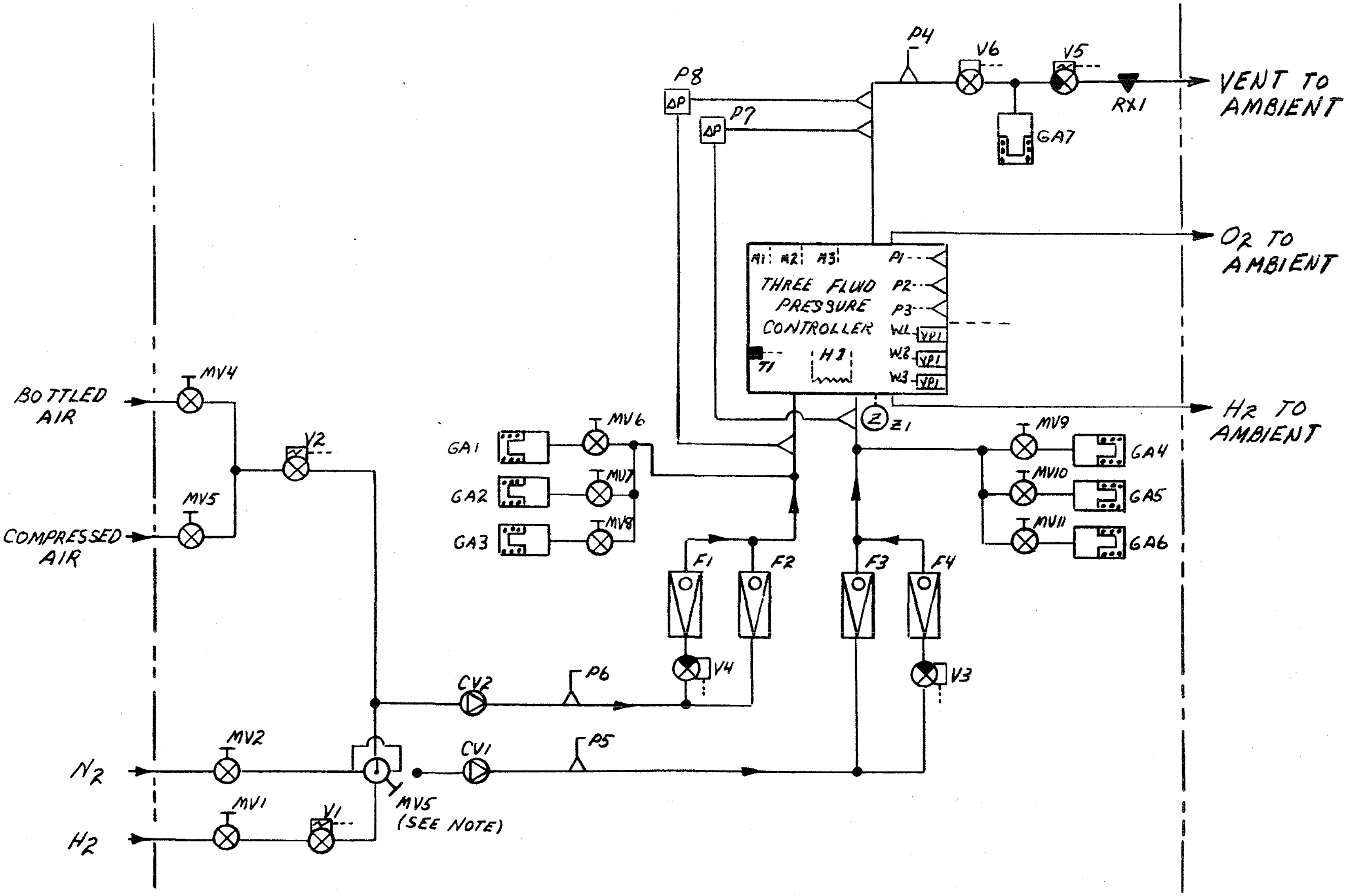

FIGURE 24 THREE-FLUID PRESSURE CONTROLLER TEST STAND MECHANICAL SCHEMATIC

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High pressure bottled air, compressed air or N_2 are provided to simulate the flow of (O_2) through the 3-FPC. Either high pressure H_2, N_2 or air simulate the flow of H_2. The selection of the particular gases to be used was made using the five-way valve MV5. Gas pressures and flow rates were measured upstream of the 3-FPC via F1 through F4. Additional gas volumes are available both in the simulated O_2 stream (GA1-3) and in the simulated H_2 stream (GA4-6). An extra gas volume (GA7) is provided to the downstream side of the 3-FPC to simulate the void volume over the OGS water tank. The 3-FPC was exposed to this void volume periodically during testing by opening V6. The periodic opening of V6 as well as V1, V2, V3, V4 and V5 was done using an Actuator Exerciser which simulated the various operating modes of the OGS. Simulated OGS differential pressures P7 and P8 as well as the simulated OGS system pressure P4 are monitored with Bourdon-tube pressure gauges. These are also displayed on the front panel of the 3-FPC electronic controller via the sensors integrated into the 3-FPC.

3-FPC Controller. The 3-FPC electronic controller, shown in Figure 25 and in the center of Figure 23, was developed specifically for operating the 3-FPC as a separate unit on a test stand. The controller is an analog electronic controller which simulates the 3-FPC control portion of an OGS C/M I. The front panel of the controller provides readouts of the three pressures and adjustments of the pressure control setpoints. Manual overrides are provided for each of the three motor drives.

Actuator Exerciser. An actuator exerciser, shown in the upper right corner of Figure 23, was developed to simulate OGS operating mode changes. The actuator exerciser controls the opening and closing of solenoid valves on the test stand in a timed sequence. The exerciser simulates the shutdown, standby, normal, purge and water fill portions of OGS operation.

Controller Evaluation

One 3-FPC unit was evaluated for over 1,000 hours to determine its ability to regulate pressure under variable conditions and during extended cycling. These tests are described below.

Checkout/Shakedown Tests. As a part of Checkout Testing, all components were inspected as received. After the unit was assembled, an internal to external pressure check was successfully performed and the unit was operated for four hours at nominal conditions.

The shakedown test was conducted to ensure integrated 3-FPC/test stand operation. It consisted of trial startups and shutdowns and continuous operation at baseline conditions for 24 hours.

The checkout and shakedown testing of the 3-FPC revealed the importance of matching the control circuit gain to the mechanical system fluid dynamics: specifically the ratio of the pressure controlled volume to the product gas flow. Also, it was determined that increasing the orifice diameter in two of the regulators from 0.81 mm (0.032 in) to 1.60 mm (0.063 in) improved the 3-FPC performance.

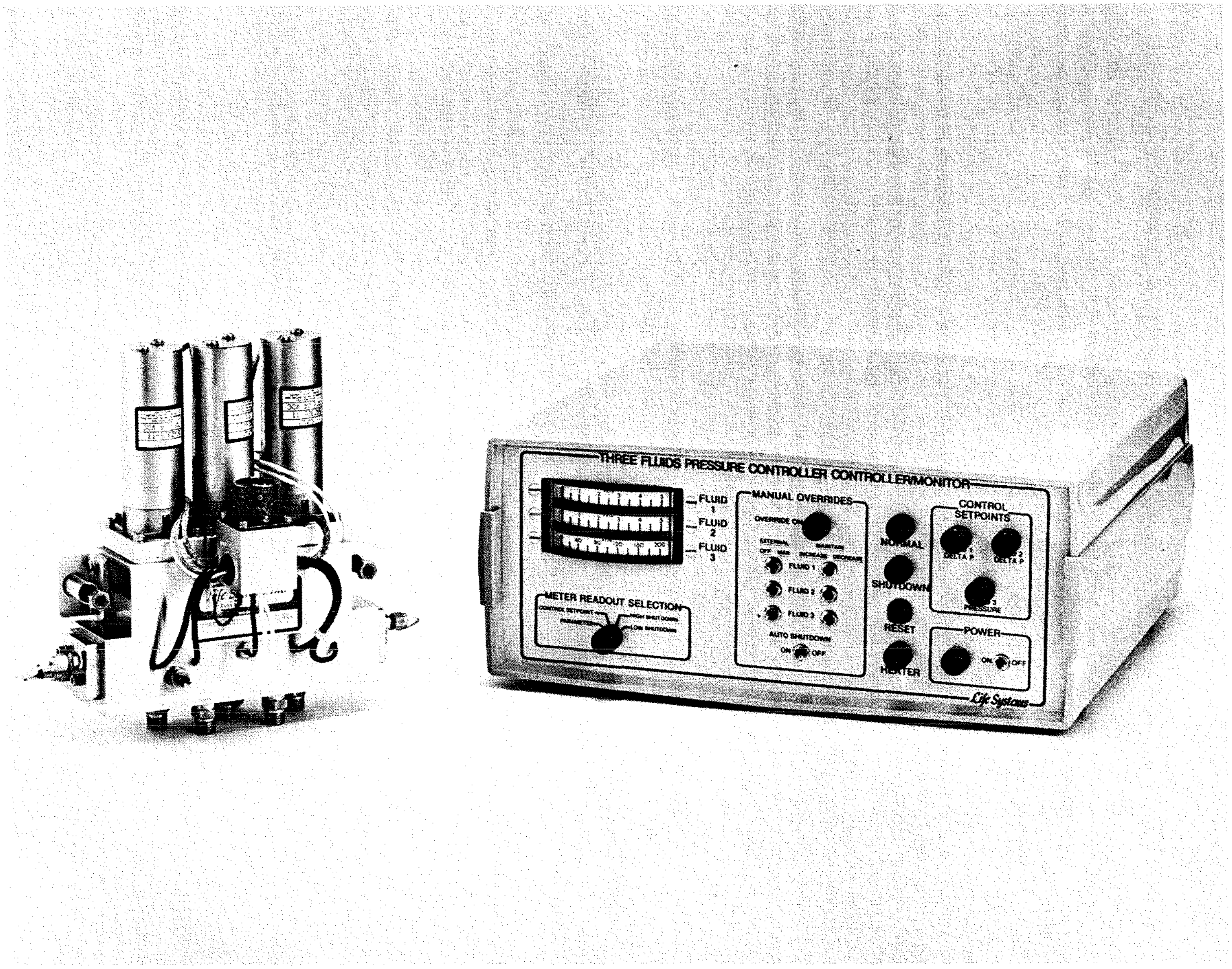

FIGURE 25 THREE-FLUID PRESSURE CONTROLLER WITH CONTROL AND MONITOR INSTRUMENTATION

Parametric/Endurance Tests. The objective of these tests was to characterize component performance over at least 30 days of operation, including periodic water fill simulations, using the actuator exerciser.

The parametric testing consisted of observing 3-FPC performance while cycling from ambient to module operating pressure and returning to ambient pressure. The objective was to verify maintenance of simulated cell compartment pressure differentials to within specified limits. The controller was cycled with H_2 and N_2 at the H_2 and O_2 ports, respectively and with auxilliary volumes in the test stand excluded. The performance shown in Figure 26 was typical. Reference pressure transitions during both pressurization and depressurization were very smooth. Differential pressures were regulated closely. No hysteresis was evident.

Additionally, gas flow rates were varied up to approximately 10 times the WS-1 levels to determine the ability of the 3-FPC to operate with larger O_2 generation subsystems. Hydrogen and O_2 pressure differentials, relative to a reference pressure of 965 kPa (140 psia), were essentially invariant (worst case variation: 0.07 kPa (0.01 psid)).

The same type of test cycles were repeated during the endurance test, except that lower pressure, compressed air was utilized in place of the commercial bottled H_2 and N_2. This measure avoided frequent, costly replacement of gas cylinders. Consistent differential pressures were measured at various points within the repetitive pressurization/depressurization cycles (corresponding to different system reference pressures), as shown in Figure 27. Only after 1,200 hours of testing (over 750 pressurization/depressurization cycles) did an unscheduled shutdown occur, due to shearing of the shearpin of the reference pressure regulator. This may have been caused by slippage of the position potentiometer drive belt. It is recommended that in the future a more positive drive belt (versus an O-ring) be used to couple the potentiometer to the regulator.

Conclusions and Recommendations

The 3-FPC performed very well during the independent testing. On this basis, the 3-FPC has been shown to be a viable device for the control of SFWES gas pressures. In addition to recommending use of a positive drive belt for the position potentiometer in future FPC's, modifications are suggested to minimize weight and volume and improve mounting characteristics. This includes removal of excess body material, location of the differential pressure transducers on the top of the unit (rather than protruding from the ends - see Figure 12) and securing the drive motor assembly with a front-accessed fastener.

Feed Water Electrolyte Elimination

Elimination of KOH electrolyte from the water feed compartment will greatly simplify SFWES design by ultimately permitting elimination of the separate coolant compartment. The feed water itself would be circulated to provide cooling or heating.

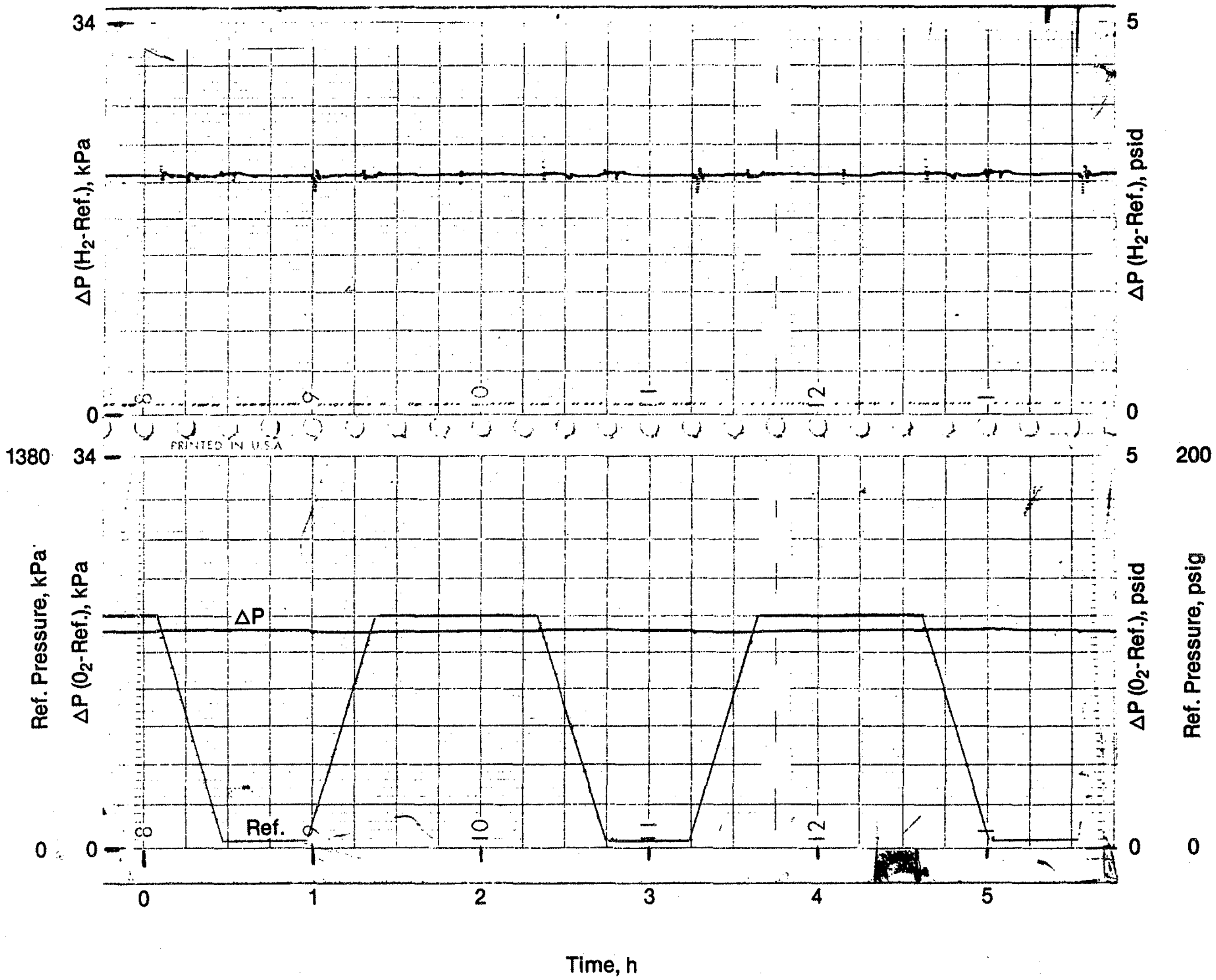

FIGURE 26 THREE-FLUID PRESSURE CONTROLLER PARAMETRIC PERFORMANCE

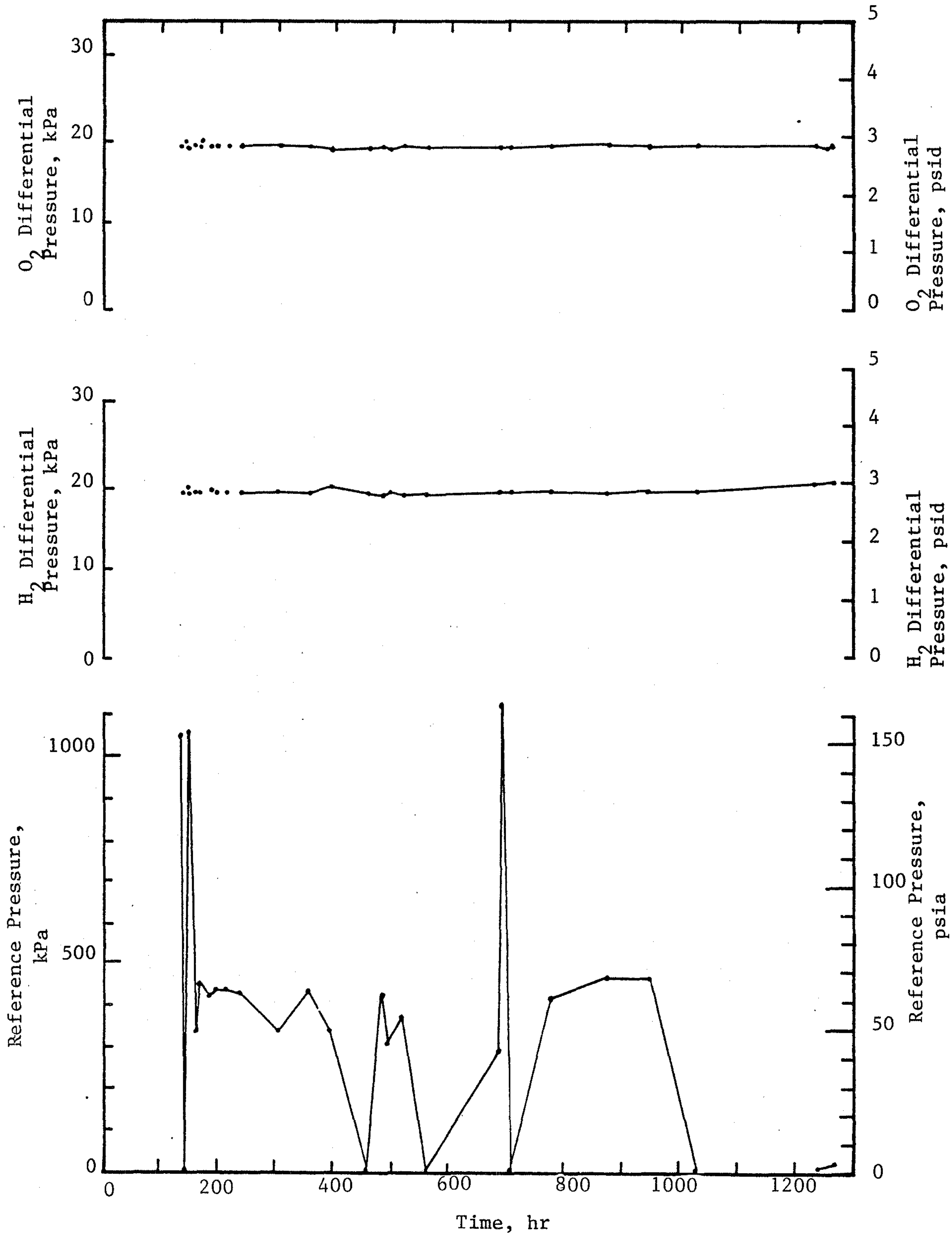

FIGURE 27 LONG TERM THREE FLUIDS PRESSURE CONTROLLER PERFORMANCE

A technique for eliminating KOH from the water feed compartment was first evaluated under Contract NAS2-8682. Only limited operation could then be maintained, however, before unacceptble levels of KOH back-diffused into the feed compartment. The objective of the present efforts was to develop an improved KOH elimination concept and demonstrate, as a goal, 30 days or more of operation.

Cell Design

The KOH Elimination Cell (KEC) design and operation are similar to the SFWE baseline cell design (see Figure 1) and operation. The KEC that was tested contained LSI "advanced" electrodes and used baseline SFWE electrolyte and cell matrix material. However, there are some significant differences.

A porous membrane, which is highly resistant to bulk liquid flow, is incorporated between the cathode and the water feed matrix. This modification ensures isolation of the water feed cavity from the electrochemical cell while allowing water vapor transport. It provides a barrier resistance to the nonvolatile contaminants in the feed water and prevents cell electrolyte from contaminating the feed water.

To maintain the separation between H_2 gas and feed water the feed water compartment is typically 1.7 to 6.9 kPa (0.25 to 1.0 psi) above the H_2 gas pressure, versus roughly 14 kPa (2 psi) below in the baseline cell. Also, the feed water is circulated through the static feed compartment, and its temperature is controlled to maintain proper water flux to the electrochemical cell. For present experimental purposes the temperature of the balance of the cell is maintained by circulation of water through a separate coolant compartment, as for the baseline cell. The ultimate objective will be to perform all temperature regulation via the feed water, however.

Detailed Cell Operation

Since the KEC operates without the electrolyte concentration stabilizing effect of KOH in the water feed compartment, adjustments in cell operation are required to maintain the electrolyte at optimum or near optimum concentration. The factors which influence the electrolyte concentration are those which influence the way the cell handles the water. These factors are temperature, current density and pressures.

Increasing temperature of the feedwater tends to both increase the amounts of water transferred from the water feed compartment and the amount of water transferred to the product gases for humidifcation.

Increasing the current density increases the water produced at the anode which must be transferred either to the cathode or to the O_2 leaving the cell.

Increasing the pressure decreases the amount of water removed through humidification. It probably reduces the amount of water transferred from the water feed compartment (although this must still be tested).

Controlling the electrolyte concentration at the KEC anode and cathode during electrolysis requires control over these parameters. The precise definition of operation ranges is at its early stage and requires further testing over broader operating conditions. Also, further investigation is required to define a water feed membrane that produces an apparent water vapor depression for the water feed cavity fluid. This characteristic is needed so that flooding, due to a continuous water vapor pressure driving force, is not encountered in operations where it is impractical or undesirable to empty the water feed compartment when shut down.

Test Support Accessories

Figures 28 and 29 show the KOH elimination test stand pictorially and schematically. Basically the test stand has two liquid circulation loops: one loop for the liquid coolant that maintains the cell operating temperature and a second loop for delivering feed water to the cell. The cell coolant (water) is circulated by M2 through the KEC. Manual valves and a flow meter control the coolant flow. A water tank (WT2) allows for coolant expansion and temperature control. Feed water is circulated through the KEC by pump M1. A manual valve and flow meter control the feed water flow. Water flows statically to the water accumulator (WA1) from the water feed tank (WT1) to compensate water consumed in the electrolysis process. A positive pressure is maintained in the feed water cavity of the KEC by the feed water pump.

A significant amount of water vapor is removed with the product gases when operating at both ambient pressure and high temperature. This tends to condense in the product gas lines. To remove condensed water the gases pass through condensate traps (TR1 and TR2) prior to entering water back pressure regulators (PR1 and PR2).

Evaluation

The evaluation consisted of two major testing efforts. The first was to examine contamination (back diffusion) rates of KOH into the feed water compartment using a baseline cell configuration incorporating an asbestos feed matrix. The resulting data provided a basis with which to compare the performance of modified cell designs. The second testing effort evaluated the modified cell incorporating a membrane.

The results of the first effort were better than expected. The baseline cell was successfully operated without KOH in the water feed compartment for approximately 1,200 hours. The average cell voltage was 1.78 volts at 161 mA/cm^2 (150 ASF) between the operating temperatures of 160 and 170 F. The average rate of increase in KOH concentration in the water feed cavity corresponded to a flux of 4.0×10^{-6} gram-moles of KOH per hour. At this rate the baseline design could operate for 100 days before the initial charge concentration of 25% KOH decreased to 20% KOH. The required 30 days of operation without bulk KOH electrolyte in the water feed compartment was demonstrated.

The second testing effort was completed using the cell with a porous membrane in addition to the asbestos feed matrix, as described above. Dramatic improvements were observed over the baseline cell performance. As shown in Figure 30, the KEC operated for a total of 1,720 hours at current densities between 215 and 158 mA/cm^2 (200 and 240 ASF) and nominal voltages between 1.67 and 1.73 volts. This performance is far superior to that obtained in the first

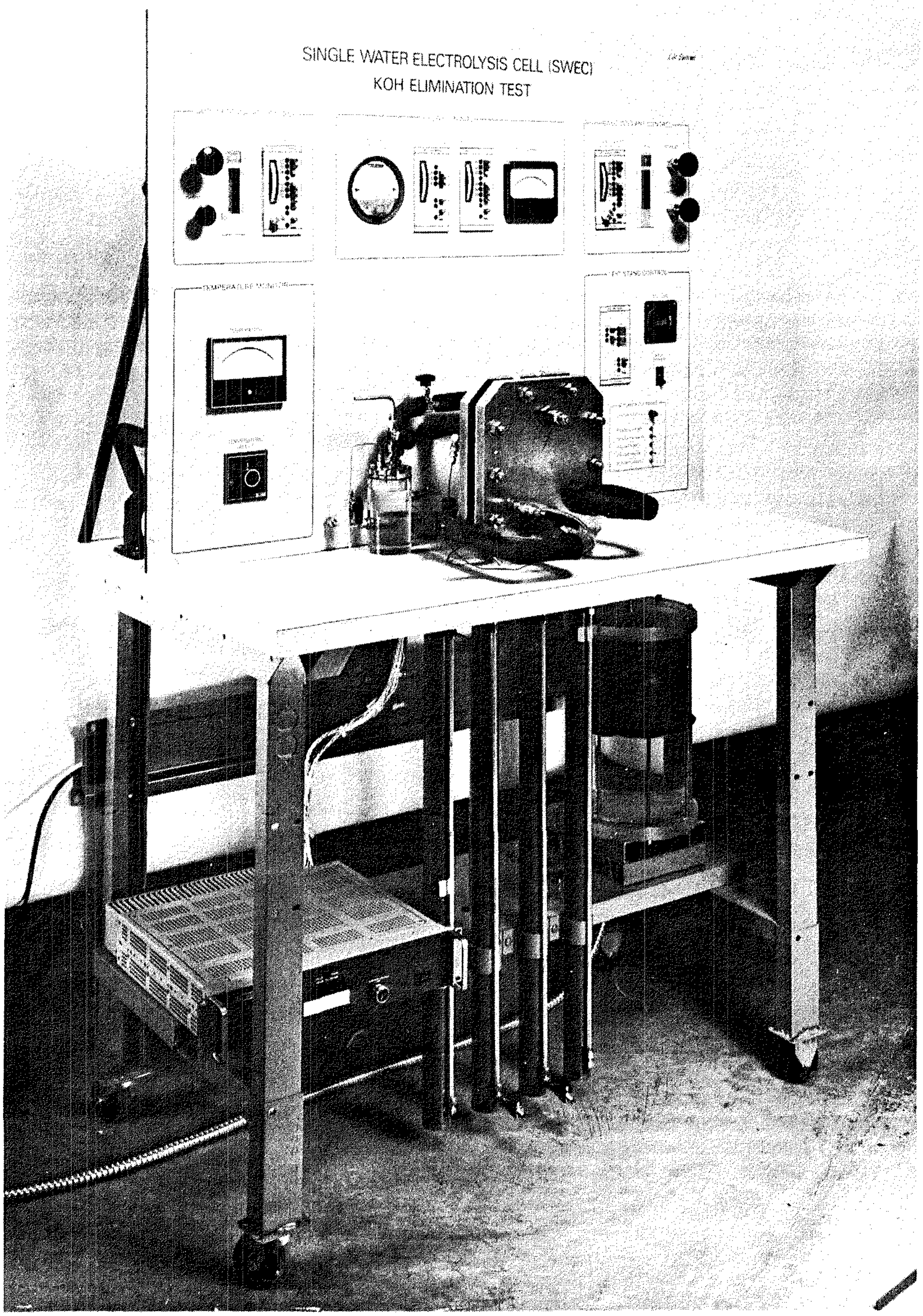

FIGURE 28 KOH ELIMINATION TEST STAND

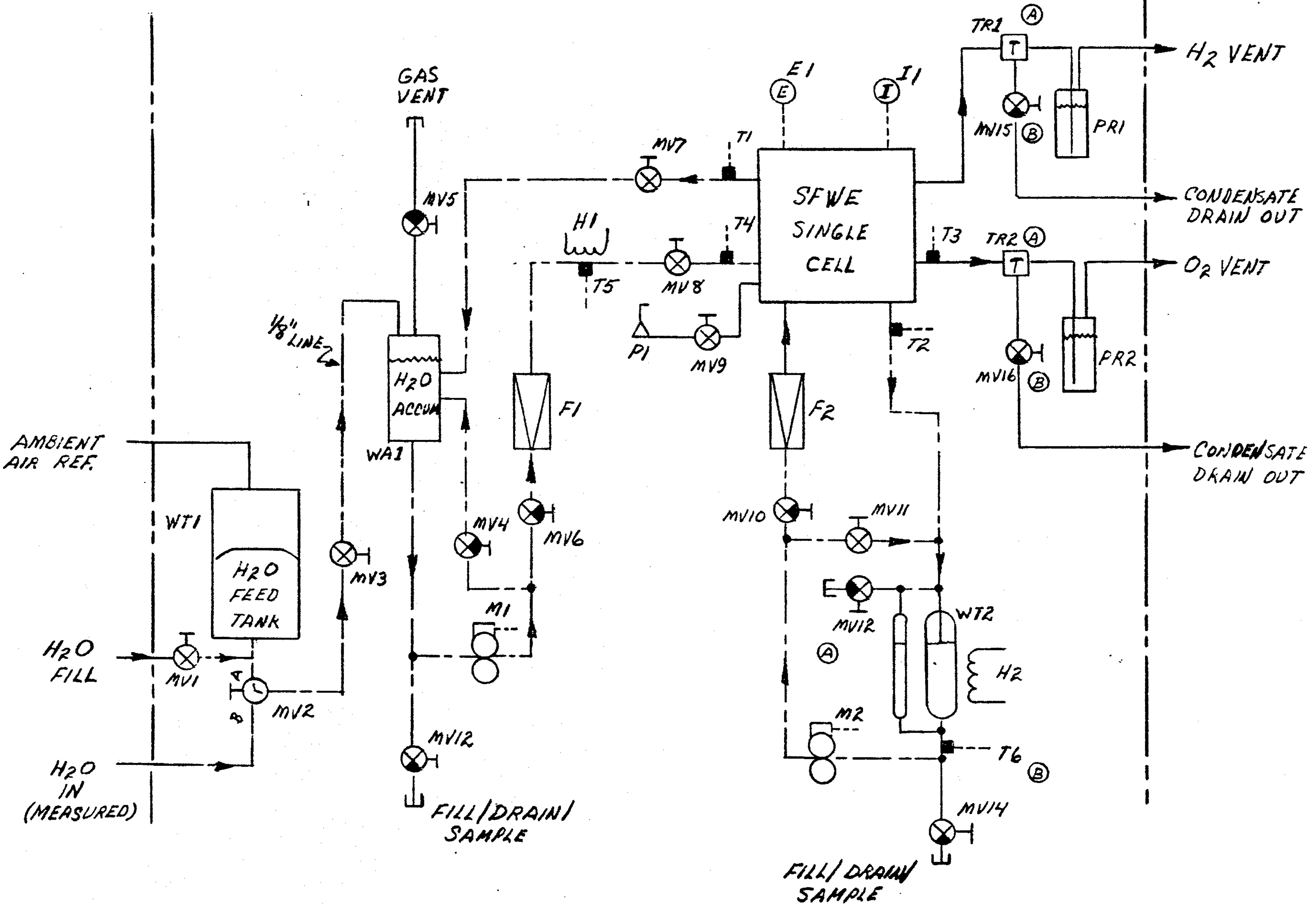

FIGURE 29 KOH ELIMINATION TEST STAND SCHEMATIC

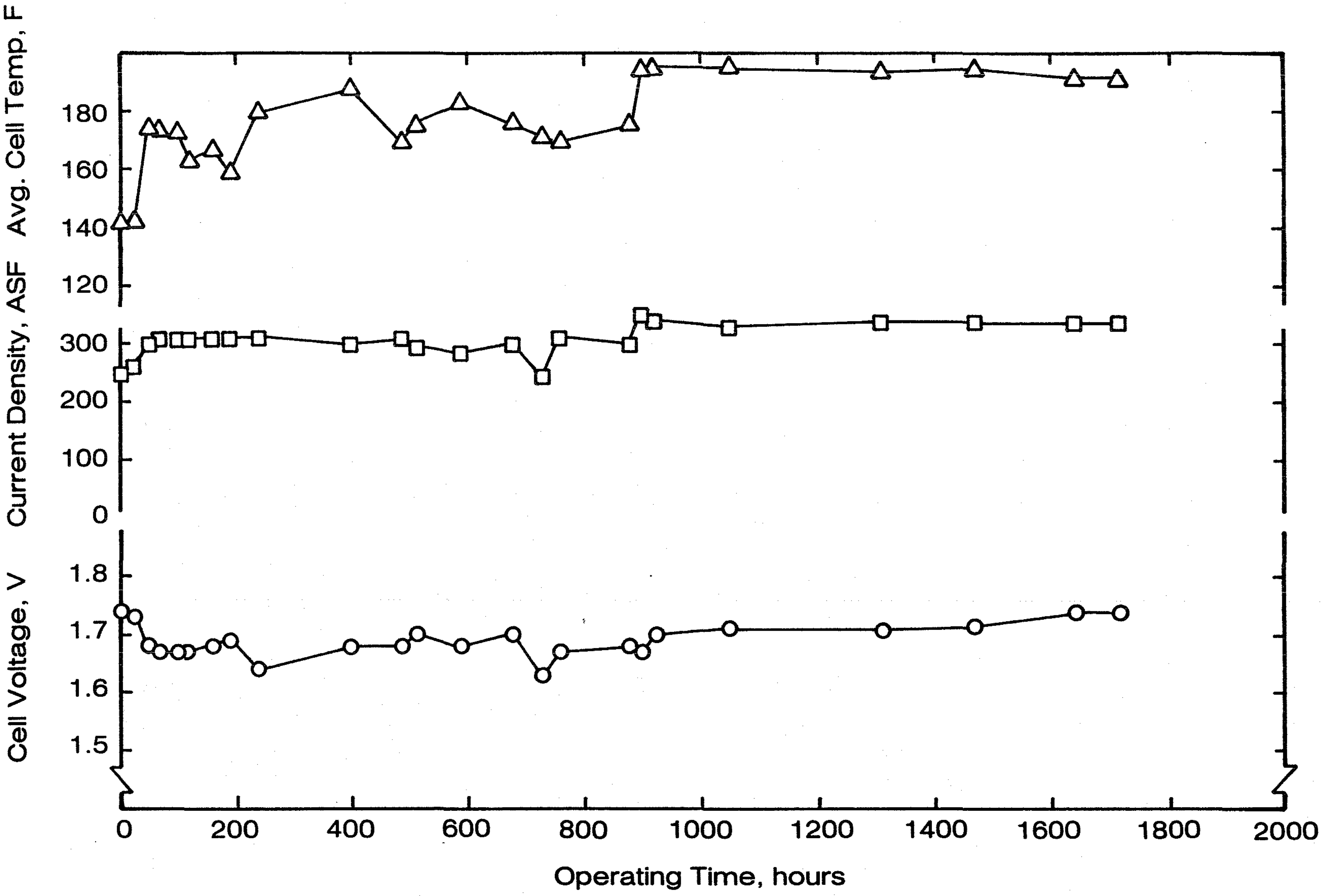

FIGURE 30 RESULTS OF TEFLON MEMBRANE-TYPE KOH ELIMINATION CELL TEST

test effort. The KEC performed like the corresponding baseline cell. The rate of KOH back diffusion into the water feed compartment was calculated to be approximately 7.4×10^{-7} gram-moles of KOH per hour. From this data it can be estimated that approximately 1,000 days would be required for the cell electrolyte concentration to decrease from 25% KOH to 20% KOH. This represents approximately a 10 fold increase in KEC operational longevity.

Further tests were performed under an Internal Research and Development (IRAD) program on a KEC that had no asbestos feed matrix but only a porous membrane. Further reductions in the KOH back diffusion rate were observed. Estimated operating lifetimes exceed 5 years.

Conclusions and Recommendations

It appears that the SFWE cell without KOH in the water feed compartment can operate without significant loss of performance. The rate of KOH back diffusion into the water feed compartment has been minimized to the point where a practical KEC operation is feasible.

The results to date are very encouraging. There are areas which need further investigation and development, however. The KEC's tested in this technology program operate with two liquid streams: a feed water stream and a coolant stream. Continuation of this technical effort should include the demonstration of the elimination of the separate coolant compartment of the cell using the feed water as a coolant. Additional testing should also be done to demonstrate scale-up from a single cell to a multicell module configuration and to identify conditions for operating the KEC module.

PRODUCT ASSURANCE

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractural performance, including design, purchasing, fabrication and testing. The product assurance program included Quality Assurance, Reliability, Maintainability and Safety functions. Quality Assurance was necessary to ensure reproducibility of the WS-1 design and configuration during subsequent development. Reliability was included to ensure that test equipment and test data gathering and recording were basic factors in the development of WS-1 reliability and long life. Maintainability was included to identify parameters for "hands-off" operation as well as routine and nonroutine maintenance requirements. Safety was included to ensure that no system component characteristic would be dangerous to personnel or equipment during testing.

Quality Assurance

The Quality Assurance activities performed during the fabrication and assembly of the WS-1 were included to ensure that no defective components or parts were incorporated into the test hardware. These activities consisted of: performing receiving inspections of all vendor supplied parts, including preparation of required documentation; ensuring that assembly techniques specified in design drawings were complied with and were consistent with the developmental nature and scope of the program; ensuring that configuration control was provided by monitoring the drawing and change control procedures; and monitoring the testing of the WS-1. These activities were successfully complete.

As part of the Quality Assurance function, Life Systems' Quality Assurance Plan was upgraded to ensure that the procedures and controls described therein were compatible with the WS-1 hardware development program. The elements of this plan were used to search for any design, engineering or quality weaknesses and to provide appropriate corrective action, if required. No weaknesses were identified.

Reliability

Reliability personnel participated in the program to ensure (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 designs was performed to determine the calibration requirements for testing. Appropriate components were calibrated during assembly and after installation.

A test procedure was established to ensure that all critical parameters would be properly monitored and that the testing would conform to the programs' Quality Assurance and Safety procedures. All WS-1 testing required that a test plan be completed and reviewed.

Maintainability

A Maintainability function was carried out during the design and testing phases of the program. During the design phase the emphasis was placed on configuring the module hardware and test stand components for accessibility if unscheduled maintenance were to be required; during the testing phase the emphasis was placed upon maintaining a log of scheduled and unscheduled maintainance, as well as preparation of a log which detailed operational problems and their sources, the corrective action and the time required to correct a failure or problem.

During the design phase a Shutdown Avoidance Analysis was also performed in order to identify the methods by which a WS-1 shutdown could be avoided during the test program. The objective was to identify preventive shutdown measures so as to increase the amount of test data obtained per test dollar and ensure that a shutdown caused by an out-of-tolerance parameter would not damage any WS-1 components. A review of the results of the analysis is as follows:

1. The SFWEM, all ancillary components, the TSA and the Control/Monitor Instrumentation package hardware and software were checked out and debugged prior to being integrated into the WS-1 subsystem.

2. All parameter level setpoints were checked out to ensure that the level warning lights operated by simulating inputs at the sensor level and verifying these inputs using the C/M I.

3. All sensors were calibrated.

4. Current transitions were entirely automatic to avoid human error as may be caused by manual operations.

A Limited Life Items Analysis was also performed. With the exception of the feed water conditioning cartridge, all components were determined to have a minimum life of five years. This cartridge is an accessory which is part of the water conditioning hardware designed to primarily remove dissolved CO_2 from the feed water. The cartridge is designed for 180 days useful operation, but has the capability of being recharged when removed from the spacecraft.

During the testing phase of the program, Life Systems' Failure Reporting Procedure was implemented. This procedure establishes the requirements for reporting, investigating and correcting a product operational failure. The purpose of the document is to enable Life Systems to monitor those product problems which relate to operation of the WS-1 design, together with the analysis and corrective action taken against each problem, and to assist in assuring that the final corrective action achieves maximum effectiveness.

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.

Safety Design Criteria for the WS-1 were prepared as part of the safety program. A review of the major items addressed and actions implemented is given below.

1. Although metallic and nonmetallic material control was not required contractually, all materials were subjected to informal evaluation during design and manufacturing phases of the WS-1. Before being incorporated into the WS-1, nonmetallics were evaluated for their compatibility with an atmosphere of 24% O_2/76% N_2 at 101 kPa (14.7 psia) total pressure and for compatibility with any corrosive media to which the nonmetallic might be exposed. Metallic materials were evaluated with regard to corrosion resistance and strength criteria. The following metallic materials were not included in the design of the WS-1: brass, cadmium, magnesium, mercury and zinc.

2. Human Engineering considerations were given to both operation and maintenance of the WS-1. All known possibilities of human error were eliminated, with primary emphasis being given to possible accidental activation of subsystem components or of the subsystem itself. Where feasible, fluid line end fittings or connections were used with dimensions or configurations that would not permit incorrect installation of a fluid line.

3. The use of toxic fluids or materials that could produce hazards was not permitted.

4. Electrical design considerations included the following:

   a. Electrical equipment presenting a shock hazard was covered with a protective guard.

b. Switches were mounted or protected so that they could not be inadvertantly actuated, and the position of a switch was identified in order to make the position obvious to the operator.
c. Where practical, the "hot" (live) electrical connectors were designed to be the female socket.
d. Where protective coating or sheathing was added to wire bundles, the wire bundles were designed to have the ability to withstand anticipated handling and operating deformations without wire damage.
e. A supplementary shutdown concept was used to disable subsystem power in the event that the C/M I primary system failed to do so (when selected critical parameters exceed preset levels).

5. Sharp edges and corners were eliminated or were adequately covered with a protective cushion in order to prevent injuries. Care was taken to prevent sharp edges from being exposed during maintenance.

6. Since surface temperatures of some portions of the WS-1 were within the range of 294 - 355K (70-180 F), items that might be leaned on, brushed against or held up to ten seconds were insulated so that the surface temperatures would not fall outside the range of 289-322 K (60-120 F).

7. The only hazardous fluids contained in the WS-1 are H_2 and KOH. Care was taken to ensure that proper servicing and maintenance techniques were followed to minimize the introduction of these materials into the cabin atmosphere.

   a. All H_2 and KOH components and lines in the WS-1 were pressure leak tested to two times operating pressures.
   b. During the design of the WS-1 care was taken to avoid stagnant areas where H_2 gas could accumulate, should a leak develop.
   c. All H_2 and KOH lines and components were purged with N_2 prior to starting up and after shutting down the subsystem and prior to performing any maintenance activity.

CONCLUSIONS

Based on the work completed the following conclusions are drawn:

1. The WS-1 OGS meets the O_2 requirements for one-person metabolic requirements, as designed. Previously demonstrated state-of-the art single cell performance was virtually duplicated at the modular level.

2. The evaluation of the module and the improvements identified and implemented during the evaluation program have established a firm basis for further OGS development based on the SFWE concept. Considering that this is the first time the components have ever been required to operate together as a self-contained subsystem, the degree of operational harmony achieved was excellent.

3. The improvements implemented on the 3-FPC, both in the inital design effort and during the WS-1 evaluation program, have resulted in an effective, integrated pressure controller for SFWE subsystems. It is anticipated that only minimal further changes will be required to achieve hardware maturity.

4. The improved cell frames functioned effectively in the WS-1 module.

5. The membrane concept used to allow elimination of electrolyte from the cell feed cavities is effective and is projected to provide in excess of three years of operation before the cell must be recharged due to KOH back-diffusion.

RECOMMENDATIONS

Based on the work completed the following recommendations are made.

1. Enhance the SFWE based OGS reliability and acceptability through additional endurance testing of the one-person capacity OGS (the WS-1) and its product gas/feedwater pressure controller (the 3-FPC). Specifically, an endurance test program should be conducted that extends the WS-1 testing beyond that accomplished under the current contract by 120 days. Also, the 3-FPC should be endurance tested for an additional 360 days.

2. The OGS should be simplified by grouping individual fluid handling components into a Fluid Control Assembly (FCA). This FCA should combine the on/off flow control, fluid flow restriction, water handling, and pressure measurement functions and all the functions needed to handle N_2 purge, N_2 pressurization and cyclic water tank filling.

3. Activities should be initiated to guarantee electrolysis cell performance reproducibility by development of unitized core/composite. cells, including the establishment of electrode fabrication specifications. Goals of the unitized core/composite cell development shall be to include improved concepts for current transfer between the cells in the module, increased differential pressure operating capabilities and isolation of the coolant cavity from the electrically conducting current collectors.

4. Scale-up the KOH elimination (from the water feed compartment) concept from the single cell to the multi-cell module level. Accomplish this by defining and incorporating both the demonstrated changes in cell configuration (evaluated via single cell testing) and other modifications required to eliminate the electrolyte from the electrolysis cell water feed compartments. It is recommended that a six-cell module be tested for a minimum of 30 days.

5. Perform an analysis to define the techniques that could minimize or eliminate the use on N_2 gas during the standby portion of the

cyclic operating mode, which simulates near earth orbit operation. Reduction or elimination of N_2 requirements would enhance the OGS acceptability for future space flight.

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16. Abstract

A one-person level Oxygen Generation Subsystem, called the WS-1, was developed. Production of the one-person oxygen metabolic requirements, 0.82 kg per day (1.81 lb per day) was demonstrated without the need for condenser/separators or electrolyte pumps. The size, weight and complexity of the remaining components was minimized by utilizing specially-developed integrated coolant and pressure control components. During 650 hours of shakedown, design verification and endurance testing, cell voltages averaged 1.62 V at 206 mA/cm^2 (191 ASF) and at average operating temperature as low as 326 K (128 F), virtually corresponding to the state-of-the art performance previously established for single cells at Life Systems. This high efficiency - and therefore, low waste heat generation - prevented maintenance of the 339 K (150 F) design temperature without supplemental heating. Cyclic operation (corresponding to low-earth orbit of a spacecraft) was demonstrated.

Improved water electrolysis cell frames were designed, new injection molds were fabricated and a series of new frames were molded. Both the module incorporated in the Oxygen Generation Subsystem and a spare were fabricated and assembled.

A modified Three-Fluid Pressure Controller was developed.
A Static Feed Water Electrolysis Cell that required no electrolyte in the static feed compartment has been developed and successfully evaluated.

17. Key Words (Suggested by Author(s))

Water electrolysis, oxygen generation
three fluid pressure controller

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