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ALKALINE STATIC FEED ELECTROLYZER BASED OXYGEN GENERATION SYSTEM

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FINAL REPORT

by

L.D. Noble, A.J. Kovach, F.A. Fortunato, F. H. Schubert and D.J. Grigger

October, 1988

Prepared Under Contract NAS9-17602

by

Life Systems, Inc.
Cleveland, OH 44122

for

LYNDON B. JOHNSON SPACE CENTER
National Aeronautics and Space Administration

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. in Cleveland, Ohio under Contract NAS9-17602, during the period of April, 1986 through October, 1988. The Program Managers were Franz H. Schubert and Dr. Fred A. Fortunato. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Jeff H. Birkel	Control and Monitor Instrumentation Software Design
Steve Czernec	Test Support Accessories Assembly
David N. Case	Control and Monitor Instrumentation Hardware Assembly
B. J. Chang, Ph.D.	System Analysis and Test Support Accessories Design
James Chu	Mechanical Component Design and Material Evaluation
Robert W. Ellacott	Module and Component Assembly
Fred A. Fortunato, Ph.D.	Program Management
David J. Grigger	Material Testing and Evaluation
Jeff R. Hanck	Electrode Fabrication
Dennis B. Heppner, Ph.D.	Signal Conditioning
Don W. Johnson	Control and Monitor Instrumentation Fabrication
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Eugene P. Koszenski	Product Assurance and Electrode Fabrication
Jim M. Khoury	Control and Monitor Instrumentation Hardware Design
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Larry D. Noble	System Testing and Analysis
Dave W. Novak	0.093 m^2 (1.0 ft^2) Module Designs
Dorothy A. Ruschak	Contract Administration
Franz H. Schubert	Program Management
Dennis S. Szulinski	Module and Component Assembly
Dan C. Walter	Mechanical Component Design
Robert C. Werner	Mechanical Component Design
Lowell E. Wolfe	Cell Core Fabrication and Analytical Instrumentation

The contract's Technical Monitors were Michael Le, Patrice Miller, Irene M. Hackler, Albert F. Behrend and Nickolas J. Lance of the Lyndon B. Johnson Space Center, Houston, TX.

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LIST OF ACRONYMS

AGE	Static Age Life
C/M I	Control/Monitor Instrumentation
CORR	Corrosion Resistance
DC	Direct Current
ECLSS	Environmental Control/Life Support System
ESS	Energy Storage System
FCA	Fluids Control Assembly
FCF	Fluids Charging Fixture
FLAM	Flammability
GC	Gas Chromatograph
GOX	Compatibility with Gaseous Oxygen
LoH_2	Compatibility with Low Pressure Gaseous Hydrogen
MSA	Mine Safety Appliance
NASA	National Aeronautics and Space Administration
PCA	Pressure Control Assembly
PDU	Performance Display Unit
RFC	Regenerative Fuel Cell
RFCS	Regenerative Fuel Cell System
RFCSB	Regenerative Fuel Cell System Breadboard
RRS	Reactant Recharge System
SCC	Stress Corrosion Cracking
SFE	Static Feed Electrolyzer
SFWE	Static Feed Water Electrolysis
SFWEM	Static Feed Water Electrolysis Module
SSCB	Space Station Control Board
SSP	Space Station Prototype
TCA	Thermal Control Assembly
3-FPC	Three-Fluids Pressure Controller
TOX	Toxicity/Offgassing
TR	Technical Report
TSA	Test Support Accessories
TVS	Thermal Vacuum Stability
WES	Water Electrolysis System
WSA	Water Supply Assembly
WS-3	Three-person Water Electrolysis Subsystem

SUMMARY

In preparation for the future deployment of the Space Station, a research and development program was established to demonstrate integrated operation of an alkaline Water Electrolysis System and a fuel cell as an energy storage device. The program's scope was revised when the Space Station Control Board changed the energy storage baseline for the Space Station. The new scope was aimed at the development of an alkaline Static Feed Electrolyzer for use in an Environmental Control/Life Support System as an oxygen generation system. As a result, the program was divided into two phases.

The Phase I effort was directed at the development of the Static Feed Electrolyzer for application in a Regenerative Fuel Cell System. During this phase, the program emphasized incorporation of the Regenerative Fuel Cell System design requirements into the Static Feed Electrolyzer electrochemical module design and the mechanical components design. The mechanical components included a Pressure Control Assembly, a Water Supply Assembly and a Thermal Control Assembly. These designs were completed through manufacturing drawing during Phase I.

The Phase II effort was directed at advancing the alkaline Static Feed Electrolyzer for an oxygen generation system. This development was aimed at extending the Static Feed Electrolyzer database in areas which may be encountered from initial fabrication through transportation, storage, launch and eventual Space Station startup. During this Phase, the Program emphasized three major areas: materials evaluation, electrochemical module scaling and performance repeatability and Static Feed Electrolyzer operational definition and characterization.

The materials evaluation consisted of a complete metallic and nonmetallic acceptability review for the electrolysis cells, module and mechanical components. Alternative materials were also identified for some applications to allow for flexibility of design.

The electrochemical module scaling and performance repeatability evaluations consisted of testing tasks aimed at improving electrolyzer operation and performance predictability. This testing encompassed product gas purity, the use of recombiners for product gas purification, electrolyte charging, system depressurization and the development of a fluids charging fixture.

The Static Feed Electrolyzer operational definition and characterization evaluation consisted of design and testing tasks aimed at characterizing components and operational regions and optimizing performance and reliability. The tasks included development of a unitized feed core and cell core test apparatus, multi-cell module testing (up to 24 cells), alternative system pressurization and depressurization techniques and mechanical component designs.

ACCOMPLISHMENTS

Key program accomplishments included:

Phase I

- Performed systematic assessment of requirements for a Static Feed Electrolyzer (SFE) system for a Space Station Prototype (SSP) of a Regenerative Fuel Cell System (RFCS)
- Reviewed SFE module design requirements and incorporated resulting improvements into a 46-cell, 10 kW final design using 0.093 m^2 (1.0 ft^2) cells.
- Completed final design for a Pressure Control Assembly (PCA).
- Completed final design for a Water Supply Assembly (WSA).
- Completed final design for a Thermal Control Assembly (TCA).

Phase II

- Completed a compatibility review for SFE metallic and nonmetallic materials.
- Determined that product gas purity was unaffected when the multi-cell stack size was increased to 24 cells.
- Evaluated recombiners for possible product gas purification to reduce the levels of hydrogen (H_2)-in-oxygen (O_2) and O_2-in-H_2 found in the electrolysis product gases (no recombiners were needed).
- Developed and implemented an electrolyte charging management practice utilizing Electrolyte Management Fixtures that ensured uniform electrolyte concentrations from cell to cell and from charge to charge resulting in repeatability of cell and module performance.
- Established and verified a method of SFE module depressurization eliminating any adverse effects of residual dissolved gases in the feed water compartment.
- Designed and fabricated a Fluids Charging Fixture (FCF) that allowed predictable and controlled charging of the feedwater circulation loop.
- Scaled-up and tested the SFE multi-cell module and test equipment to incorporate a 24-cell (from 12-cell) module and characterized through testing its performance as function of pertinent operating parameters, special emphasis was placed on product gas purity.
- Increased system efficiency and flexibility by evaluating and defining SFE thermal control concepts using cell current to ramp module/subsystem operating temperatures without the use of a startup heater.

- Eliminated the need of a pressure regulator motor and its controls by use of a slave pressure regulator to maintain H_2 to O_2 differential pressure.

- Eliminated the need for an expendable and increased system flexibility by establishing a pressurization control technique without using nitrogen (N_2) and reducing the overall time required for pressurization.

- Improved SFE mechanical component (PCA, Fluids Control Assembly (FCA) and TCA) designs to achieve increased reliability and safety and lower maintenance time.

INTRODUCTION

Under Contract NAS9-16659, a Regenerative Fuel Cell System Breadboard (RFCSB) was developed to demonstrate integrated operation of an alkaline Water Electrolysis System (WES) and fuel cell subsystem as an energy storage device. As part of this program, design work was also initiated to upgrade the components of the WES to meet the requirements of a Space Station Prototype (SSP) of an RFCS. A decision by the Space Station Control Board changed the energy storage baseline for the Space Station from the RFCS. As a result of this decision, the remainder of contract NAS9-17602 was redirected to enhance the database for Environmental Control/Life Support System (ECLSS) electrolyzer requirements.

Background

Key aspects of the alkaline SFE 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.[1,2,3] 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 dissociated into its component elements by supplying electrons to a negatively charged electrode (cathode) and removing electrons from a positively charged electrode (anode). The half-cell reactions are as follows for water electrolysis cells using an alkaline electrolyte:

At the cathode:

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

(1,2,3) References are at the end of this report.

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 an Static Feed Water Electrolysis (SFWE) cell. As electrical power is supplied to the electrodes, water is electrolyzed from the cell matrix increasing the concentration gradient between the electrolyte in the water feed cavity and the fluid 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:

1. No moving parts are required since the water feed mechanism is entirely passive 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, reliability and long life.

Subsystem Concept

The basic cells are combined into an electrochemical module with supporting mechanical components and microprocessor based controls to form the subsystem. The mechanical portion of the subsystem consists principally of four components: an electrochemical module, a TCA, an FCA and a PCA. The TCA, FCA and PCA are special components developed by Life Systems for use with an SFE. The module consists of a series of individual electrochemical cells stacked fluidically in parallel and connected electrically in series. Oxygen and H_2 are generated in the module from water supplied by the water supply tank.

The TCA supplies a constant flow of controlled, variable temperature liquid feed water to the module. The FCA controls fluids (gas and liquid) into and out of the SFE subsystem. The PCA (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., startups and shutdowns).

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

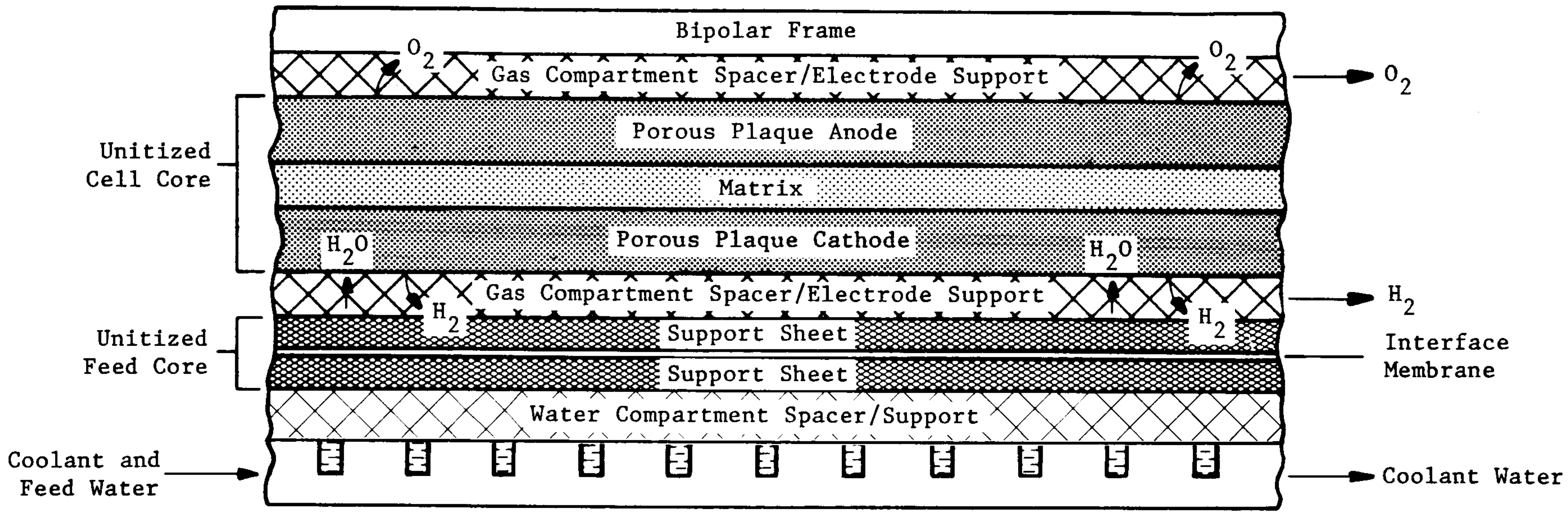

FIGURE 1 SCHEMATIC OF CURRENT STATIC FEED ELECTROLYSIS CELL ASSEMBLY

Program Objectives

The objectives of Phase I of this program were to:

1. To develop an alkaline WES for integration into a Regenerative Fuel Cell (RFC) SSP having as the nominal design point a capacity of supplying reactants for a 10 kW fuel cell output.

2. To approach, within funding constraints, space qualification capability. Thus, reliability, redundancy, autonomy, maintainability, volume, weight and flight environments were considered a significant part of this effort.

The goals of Phase I of this program were to:

1. Continued reduction of the weight, volume, power, heat rejection and complexity (although reliability and minimizing the need for maintainability were of more importance than weight reduction).

2. Technology advancement of the integrated mechanical components for the SFE portion of the RFCS to achieve an equal maturity development level for all components.

3. Characterization and endurance testing of the SFE.

The objectives of Phase II of this program were to:

1. Define acceptable materials compatible with SFE operation (2,413 kPa (350 psia) maximum O_2 and H_2 pressure at 355 K (180 F)).

2. Evaluate effects of module scale-up on subsystem design and operation.

3. Characterize SFE cell performance using the newly developed three-compartment (no separate coolant compartment) cell technology.

4. Define operational aspects of the SFE for Space Station ECLSS requirements and applications.

The goals of Phase II of the program were to:

1. Eliminate problems identified during RFCSB testing.[4]

2. Generate scientific and engineering data to increase the SFE database to allow optimized designs for further applications, e.g., Space Station needs and beyond.

Report Organization

The remaining sections of this report summarize the results according to the efforts in each phase.

Phase I - Design and Development of an alkaline-based SFE for an SSP RFC.

Phase II - Development of an alkaline-based SFE O_2 generation system.

These sections are followed by Conclusions and Recommendations based upon the work completed under this program.

DESIGN AND DEVELOPMENT AN ALKALINE SFE FOR SPACE STATION PROTOTYPE REGENERATIVE FUEL CELL - PHASE I

Phase I of this program provided for the design of an alkaline SFE for the SSP RFCS. The Phase I efforts focused on designing SFE components compatible with up to 10 kW nominal fuel cell output. Designs were completed for a 10 kW SFE module consisting of forty-six (46) 0.093 m^2 (1.0 ft^2) cells, a PCA, a WSA and a TCA. The designs emphasized long life high reliability motors and pumps and use of applications compatible materials having high manufacturability. This report summarizes the scale-up activities and incorporation of innovative features into the SFE for an RFCS starting with the results of the development activities completed under Contract NAS9-16659 as reported in Reference (4).

Static Feed Electrolysis Requirements

The system level requirements of the SFE for a Space Station RFC were assessed and are summarized in Table 1. A mechanical schematic with sensors was finalized, as shown in Figure 2. Detailed mass and energy balances, as well as projected end of life electrochemical performances were calculated. To enhance operating life and to improve operational flexibility of the SFE, several features were evaluated and incorporated into the electrochemical module design. These features included a unitized feed core with a gas permeable membrane, three-compartment cell operation, modifications to prevent stray electrolysis and redundant O-rings. It was determined that 40,000-hour life and capacity equivalent to 10 kW fuel cell output for all accessory components were mandatory to meet the requirement specifications for the Space Station Energy Storage System (ESS).

The capacity of the ancillary components was increased to 30 kW level from the reference design by adjusting TCA motor speed and gear size, WSA accumulator size or a combination of these items without changes in the basic design of the ancillary components.

Static Feed Electrolysis Module Design Requirements

The primary requirements for the SFE module design were reliability and operability. To ensure good electrochemical performance and long operating life, Life Systems' high performance super anodes and cathodes were incorporated as baseline electrodes. An alkaline electrolyte was used and retained in the baseline matrix. The original four compartment (O_2, H_2, water feed and coolant) cell design was retained as a conservative measure since only limited three compartment cell operation experience was available.

TABLE 1 DESIGN SPECIFICATIONS OF 0.093m^2 (1.0 ft^2) 46-CELL WATER ELECTROLYSIS MODULE FOR 10 kW SSP RFC

Water Feed, kg/h (lb/hr)	
Nominal	2.31 (5.09)
Range	1.55 - 6.18 (3.41 - 13.63)
H_2 Generation Rate, kg/h (lb/hr)	
Nominal	0.26 (0.57)
Range	0.17 - 0.69 (0.38 - 1.53)
O_2 Generation Rate, kg/h (lb/hr)	
Nominal	2.05 (4.52)
Range	1.37 - 5.48 (3.03 - 12.1)
Power Consumed, kW	
Nominal	10.5
Range	3.36 - 18.63
Heat Rejection, W (Btu/hr)	
Nominal	276 (943)
Range	-115 - 1,381 (-393 - 4,712)
Module Voltage (Max), VDC	75
Current Density, mA/cm^2 (ASF)	
Nominal	161.4 (150)
Range	53.8 - 269 (50 - 250)
Cell Voltage, V	
Nominal	1.52
Module Temperature, K (F)	
Nominal	355 (180)
Range	344 - 361 (160 - 190)
Operating Pressure, kPa (psia)	
Nominal	2,171 (315)
Range	0 - 2,205 (0 - 320)
Cycle Time, min	
Charge Time	58
Discharge Time	36

continued-

Table 1 - continued

PRODUCT GASES (H_2 AND O_2)	
Purity, % (excluding water vapor)	>99.9
Water Feed	
Source	Alkaline Fuel Cell or Deionized Water
Dissolved H_2 (max), %	0.0006 (by Wt.)
Environment	
Capable of running in zero-g and 1-g	
No. of Cells	
Range	46 to 133
Operating Mode	Continuous or Cyclic
Shelf Life, yr	Indefinite
Operating Life, hr	40,000 (goal)
Physical Characteristics	
Weight, kg (lb)	131.8 (290)
Volume, m^3 (ft^3)	0.1846 (6.52)
Basic Configuration, cm (in)	42.4 x 52.1 x 83.6 (16.7 x 20.5 x 32.9)
Electrochemical Active Area, m^2 (ft^2)	0.092 (1.0)

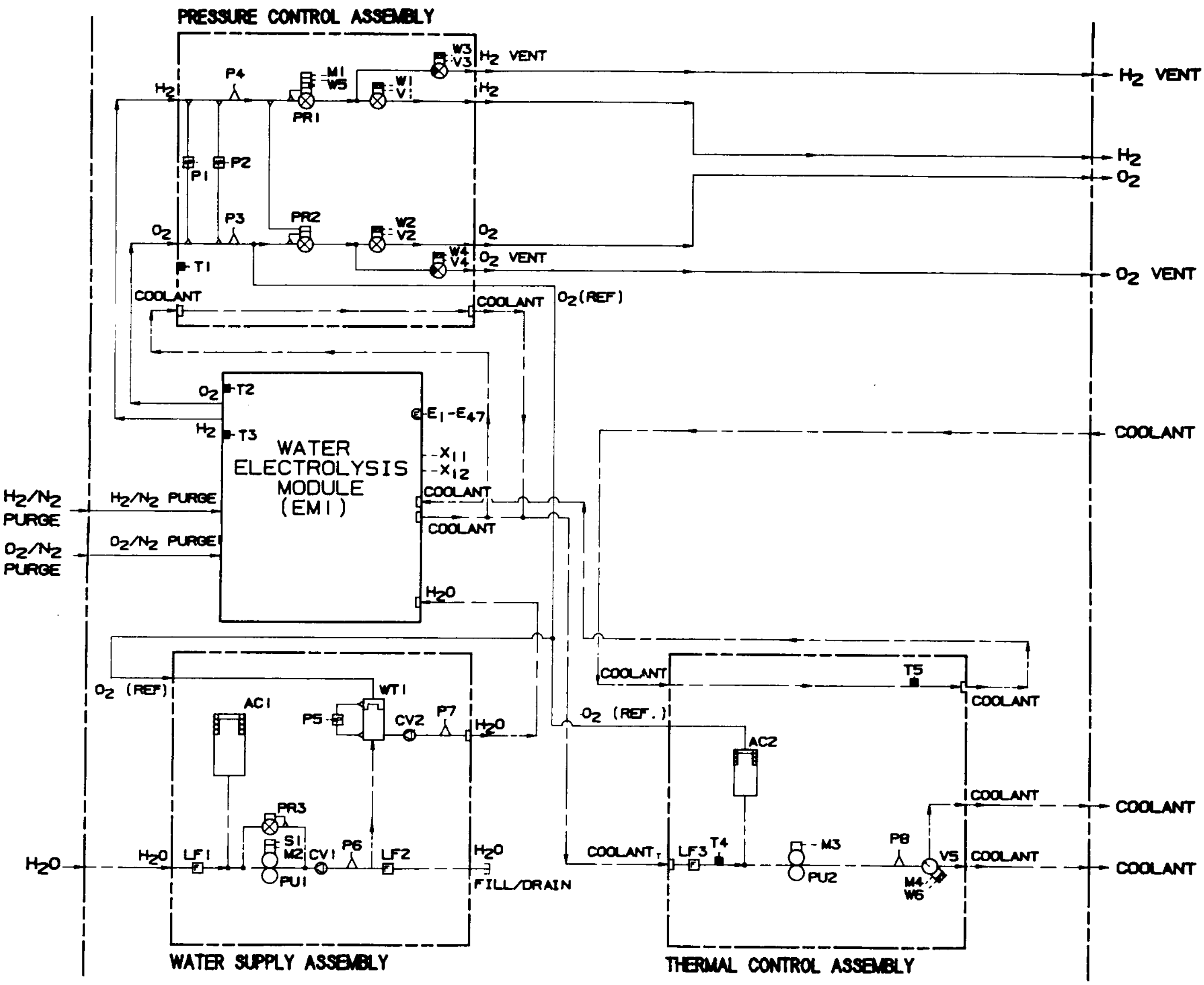

FIGURE 2 SFE MECHANICAL SCHEMATIC WITH SENSORS FOR RFCS-SSP

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An extensive search and evaluation of new cell frame materials was conducted. The purpose of this search and evaluation was to identify alternatives to the baseline polysulfone cell frame. The materials evaluated included polyphenylene sulfide (PPS), polyarylsulfone (PAS), polyetheretherketone (PEEK), polyimide and polyethersulfone (PES). Although PPS and PEEK appeared to be viable candidates, it was determined that for the projected operating pressure of 2,172 kPa (315 psia) for the RFC, polysulfone remained the most desirable and was an acceptable material in terms of O_2 compatibility. Therefore, it was retained in the final module design.

Pressure Control Assembly Design

The PCA was designed to control and sense the O_2 and H_2 generation pressure and pressure differential and to provide reference pressure to the water storage tank in the WSA and coolant accumulator in the TCA. In addition, the PCA switched reactant flows between the reactant storage tanks and vacuum vent. The PCA design was based on the Three-Fluids Pressure Controller (3-FPC) used in the RFCSB. The major improvements over the 3-FPC include incorporation of dual redundant metallurgical seals between O_2 and H_2, elimination of two motors and one pressure regulator, upgraded design of the valve plunger, plunger cap and pilot, as well as incorporation of the passive cooling/heating concept into the design. The PCA mechanical schematic is shown in Figure 3.

To reduce weight and volume, the PCA was repackaged. Repackaging involved the relocation of two solenoid latching valves. As a result, the final PCA design has the H_2 vent valve and shutoff valve on one side of the slave regulator and O_2 valves on the other side. An index pin was added to each valve to prevent assembly errors. The electrical interface was simplified by internally routing all sensor wires to a control connector. No wiring can be seen from outside the PCA. In addition, an effort was made to reduce the weight of the manifold plate. It includes relocation of sensors, contour cutting and milling of extra metal, as well as an internal conduit for all wiring. Total weight savings was estimated at five pounds. An isometric view of the PCA is shown in Figure 4.

Water Supply Assembly Design

The WSA was designed to provide for storage of fuel cell produced water at or below fuel cell operating pressure, to transfer fuel cell produced water from low pressure to high pressure, to provide for storage of a portion of the product water at the electrolysis operating pressure and to supply water to the electrolysis module to make up for that electrolyzed. A two-stage positive displacement pump was employed to ensure long life (>80,000 hours). A brushless rare earth magnet direct current (DC) motor with minimum life of 150,000 hours was selected to drive the water supply pump. The WSA capacity was verified to be compatible with an up to 20 kW fuel cell output. A mechanical schematic of the WSA is shown in Figure 5 and an isometric view of the WSA is shown in Figure 6.

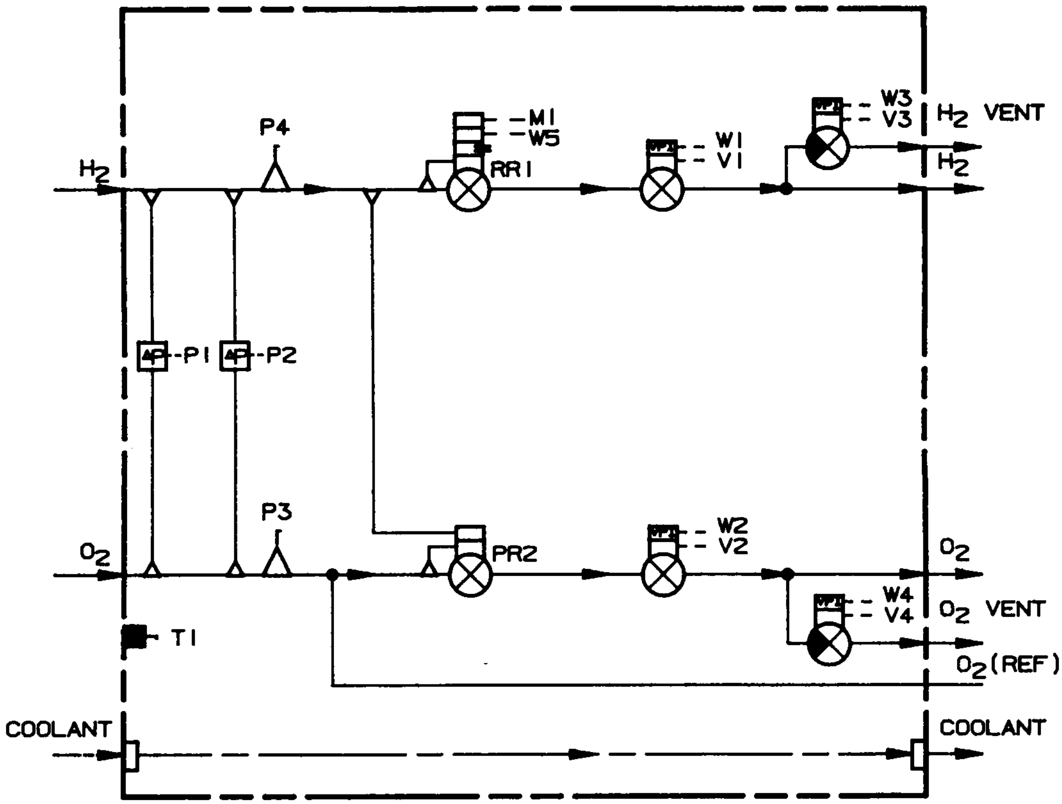


FIGURE 3 PRESSURE CONTROL ASSEMBLY MECHANICAL SCHEMATIC WITH SENSORS (SSP)

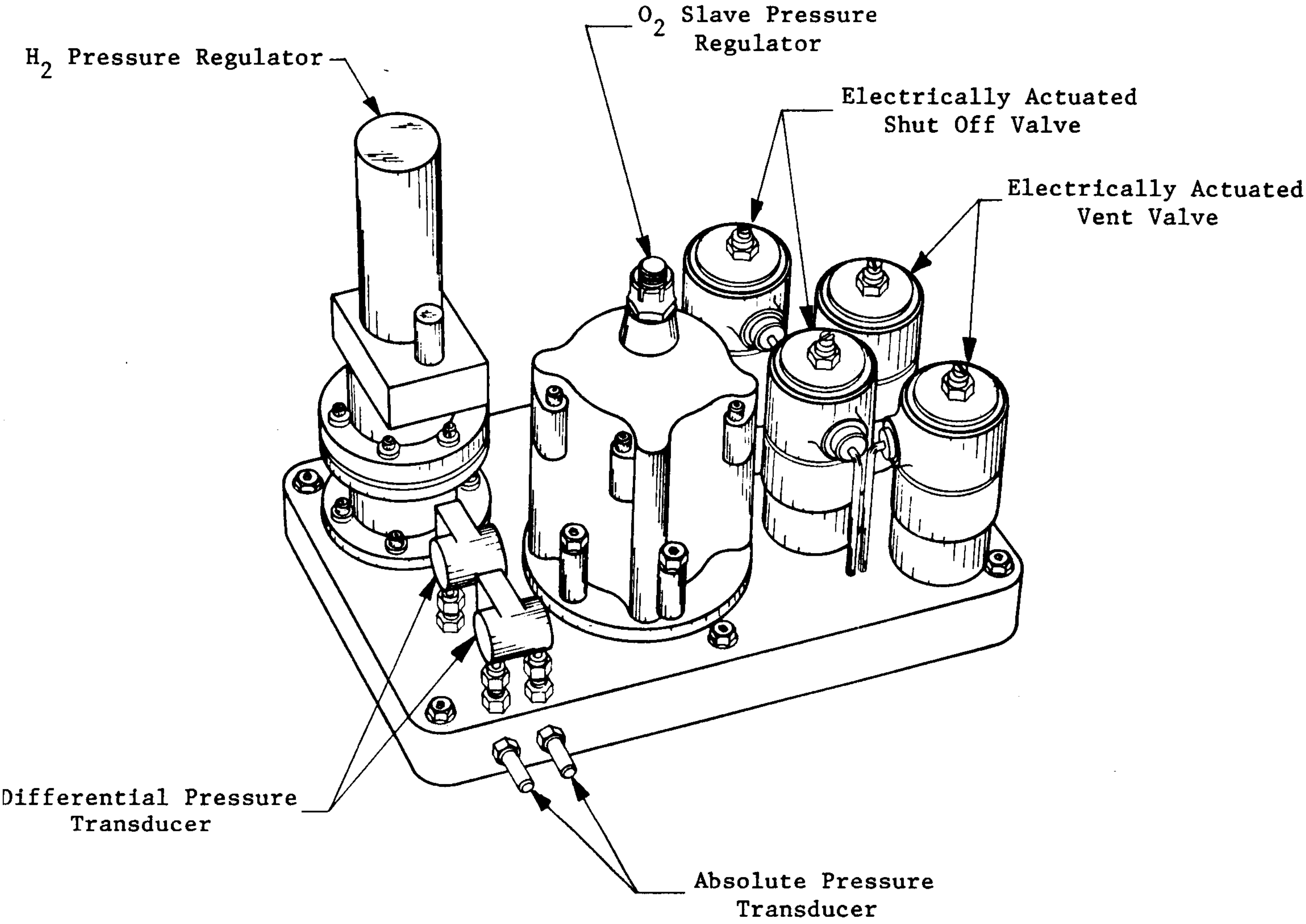


FIGURE 4 PRESSURE CONTROL ASSEMBLY RFCS-SSP, ISOMETRIC VIEW

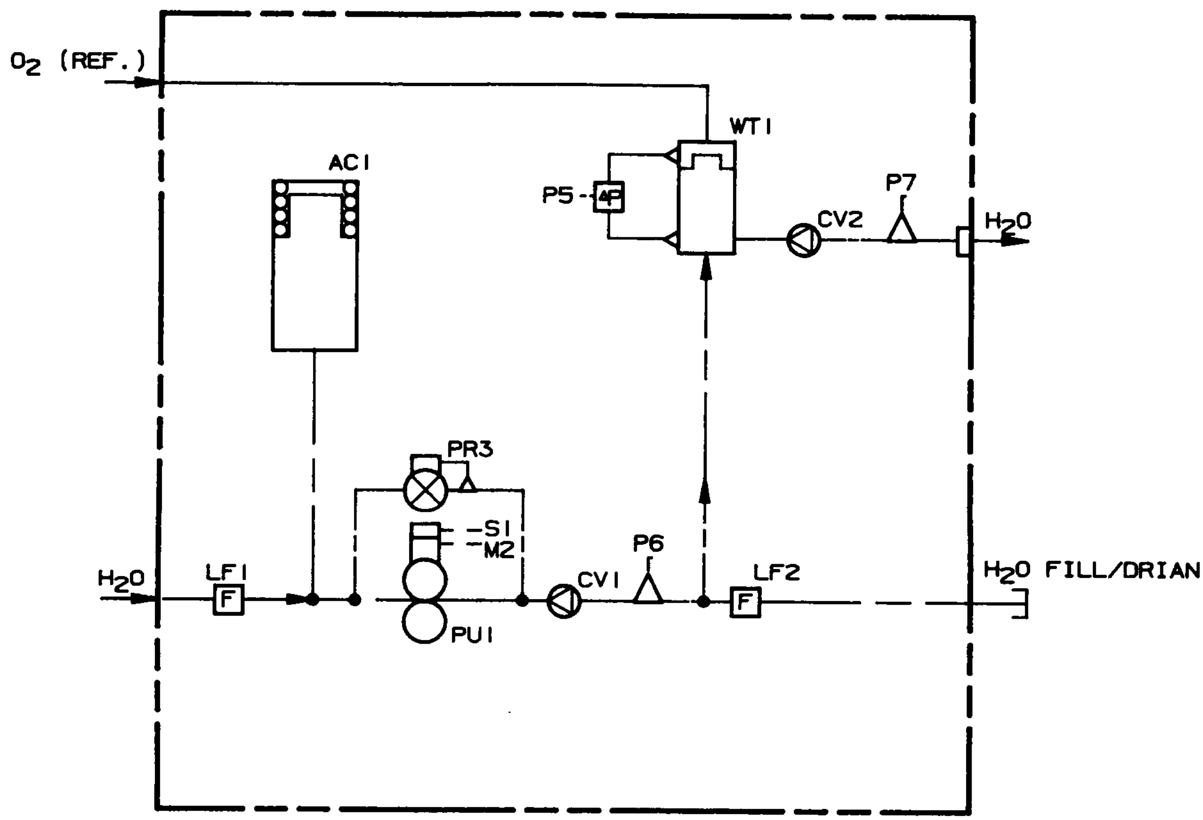


FIGURE 5 WATER SUPPLY ASSEMBLY MECHANICAL SCHEMATIC WITH SENSORS (SSP)

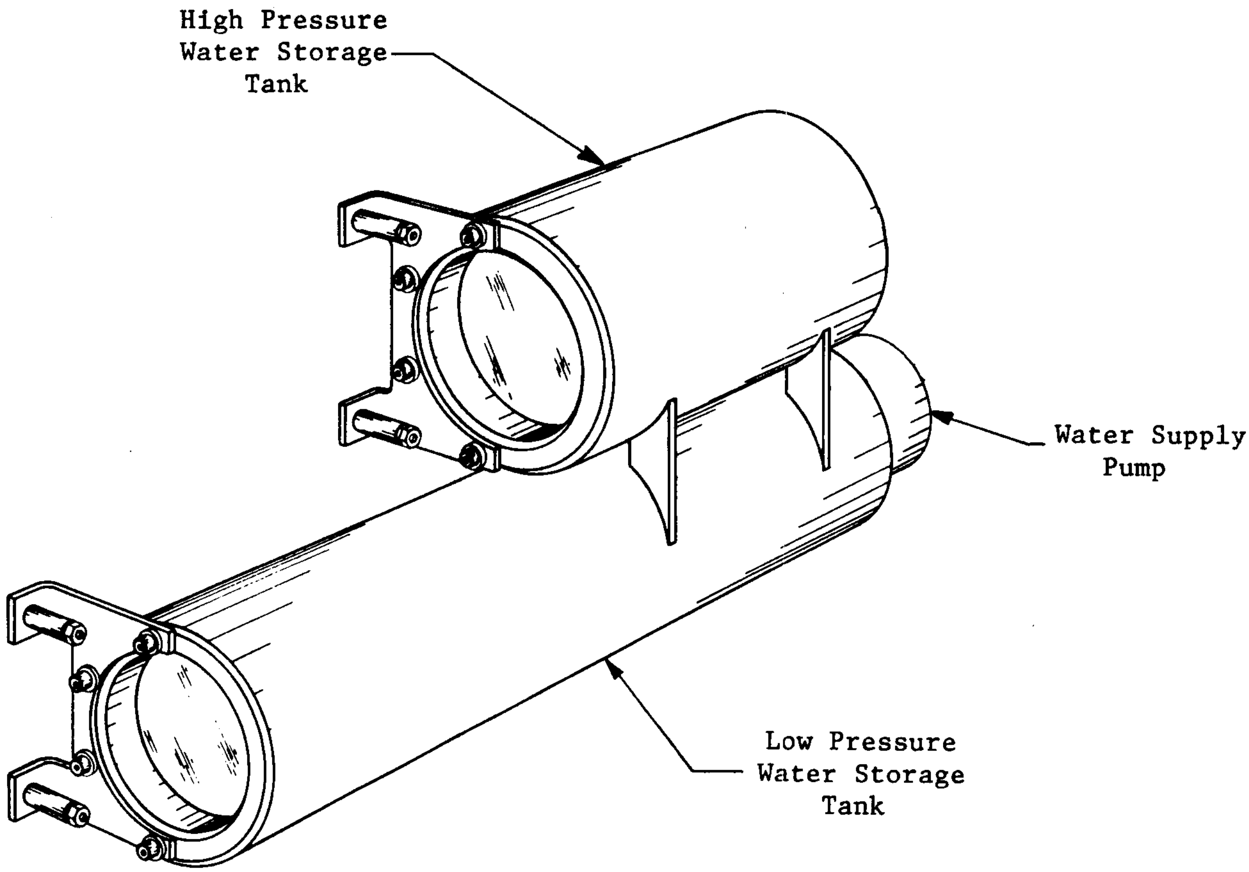


FIGURE 6 WATER SUPPLY ASSEMBLY FOR RFCS-SSP, ISOMETRIC VIEW

Thermal Control Assembly Design

The TCA was designed to control a constant coolant flow rate to the electrolysis module, to control electrolysis module coolant inlet temperature and to accommodate coolant volumetric changes. A mechanical schematic of the TCA is shown in Figure 7 and an isometric of the TCA is shown in Figure 8. A positive displacement gear pump operating at 1,200 rpm was used to improve reliability. Two versions of TCA motor designs were completed. The "wet motor" version has the motor submerged in the coolant being pumped. It was intended to be used in conjunction with the four-compartment cell design. The dry motor design has the motor isolated from the working fluid by the separation cup of the magnetic coupling and could be used with a three-compartment cell design, i.e., a cell where the water feed compartment fluid is used both as the coolant as well as the feed water source. The torque of the motor was transmitted to the pump through the magnetic coupling instead of a direct drive splined coupling used in the wet motor design. The dry motor design is illustrated in Figure 9. A detailed design of the TCA with a dry motor has also been completed and verified. The entire drawing package, including the magnetic coupling, has been fully checked. The coolant pump motor is the same high reliability design as in the WSA with a minimum life of 150,000 hours.

The proposed packaging for a 10 kW SFE for RFCS-SPP including PCA, WSA and TCA is shown in Figure 10.

DEVELOPMENT OF ALKALINE BASED SFE O_2 GENERATION SYSTEM - PHASE II

Phase II of this program provided for advanced development of the alkaline-based SFE for use in an O_2 generation system operating at 2,413 kPa (350 psia) or less. This development provided a means for enhancing and extending the existing SFE database into regions from fabrication to Space Station startup. The development effort was targeted into three areas: (1) materials, (2) module scaling and performance repeatability, and (3) SFE definition and characterization. These areas are discussed in detail in subsequent sections.

Material Acceptability Review

The materials that had been baselined at the initiation of the Phase II activities for use in the alkaline SFE based O_2 generation system were studied to determine if they will meet manned space flight requirements for metallic and nonmetallic materials. At the start, a list of baseline materials was established. These materials were then studied for their acceptability not only to the NASA requirements but also for their chemical compatibility with the alkaline electrolyte. Provisions were included in the program for those candidate materials which would require special testing or manufacturability evaluation.

As the evaluation progressed, an interim list of metallic and nonmetallic materials was prepared which included the NASA usage evaluation values. Certain materials which were originally baselined were replaced with candidate materials that were felt to be better for the SFE application.

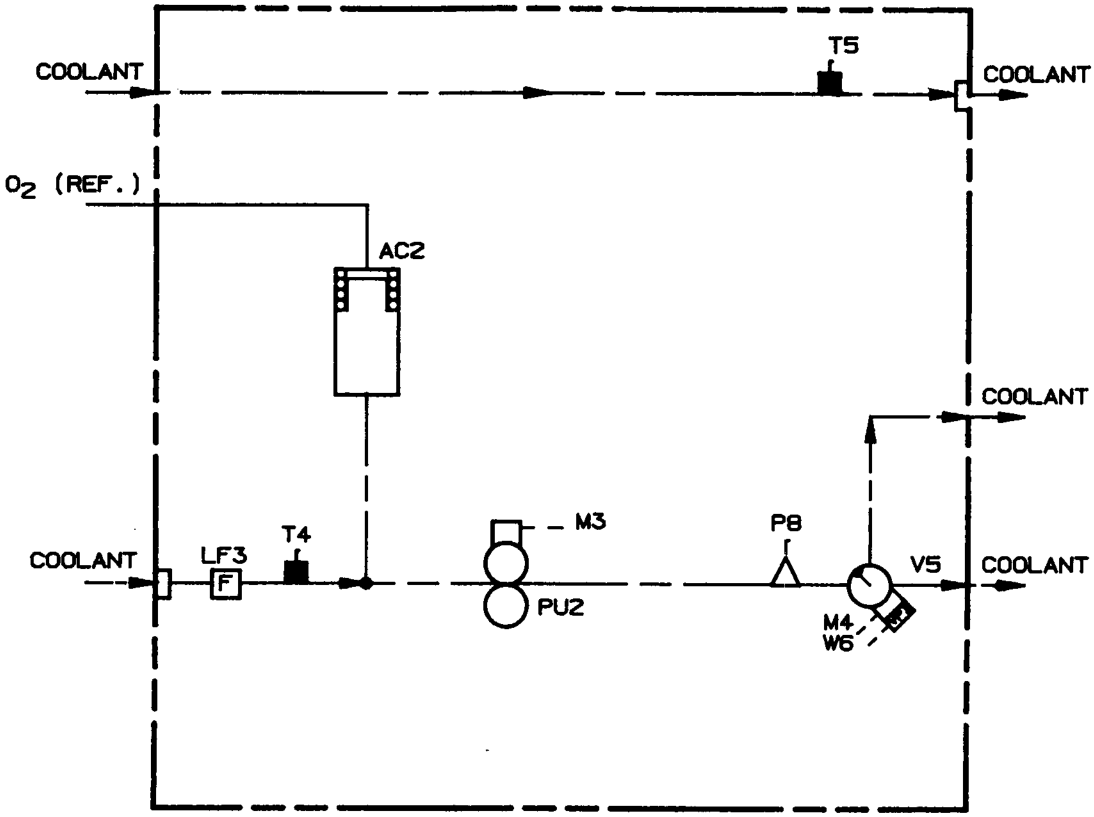


FIGURE 7 THERMAL CONTROL ASSEMBLY MECHANICAL SCHEMATIC WITH SENSORS (SSP)

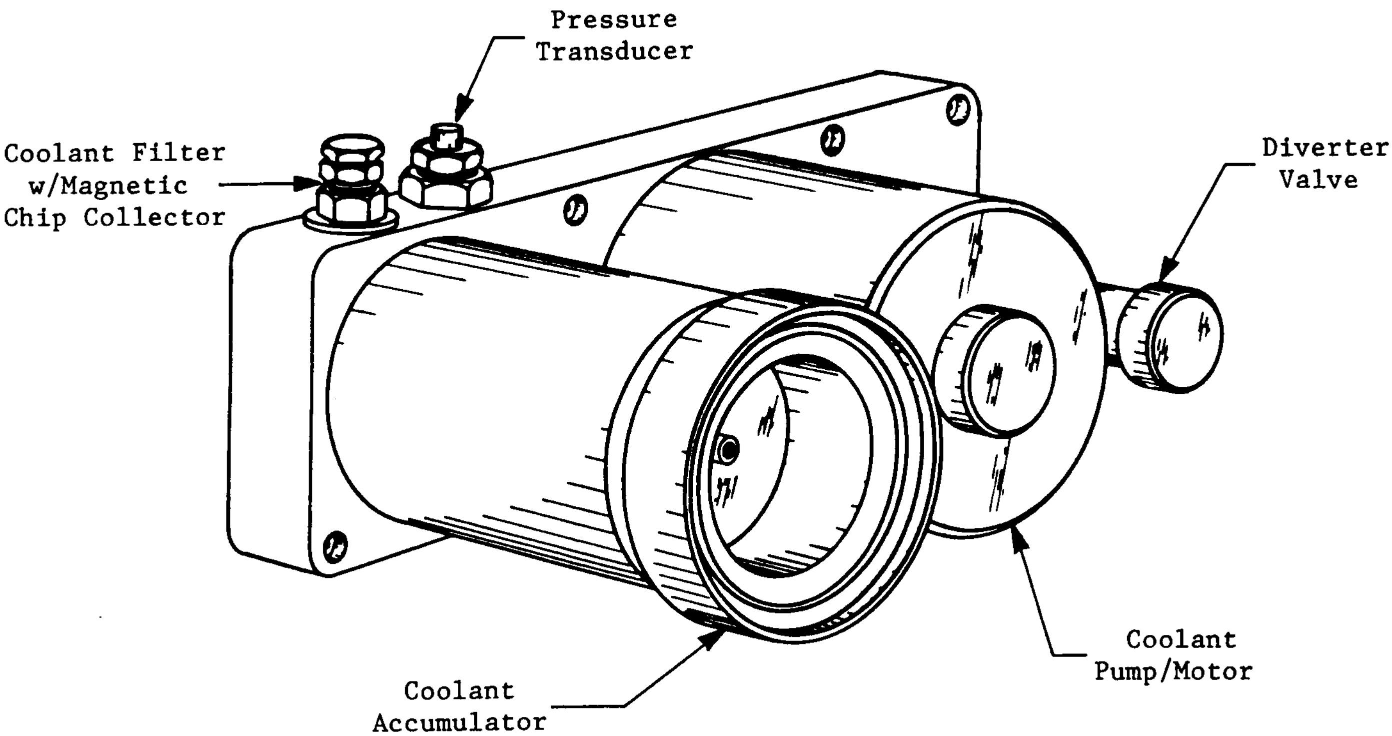


FIGURE 8 THERMAL CONTROL ASSEMBLY FOR RFCS-SSP, ISOMETRIC VIEW

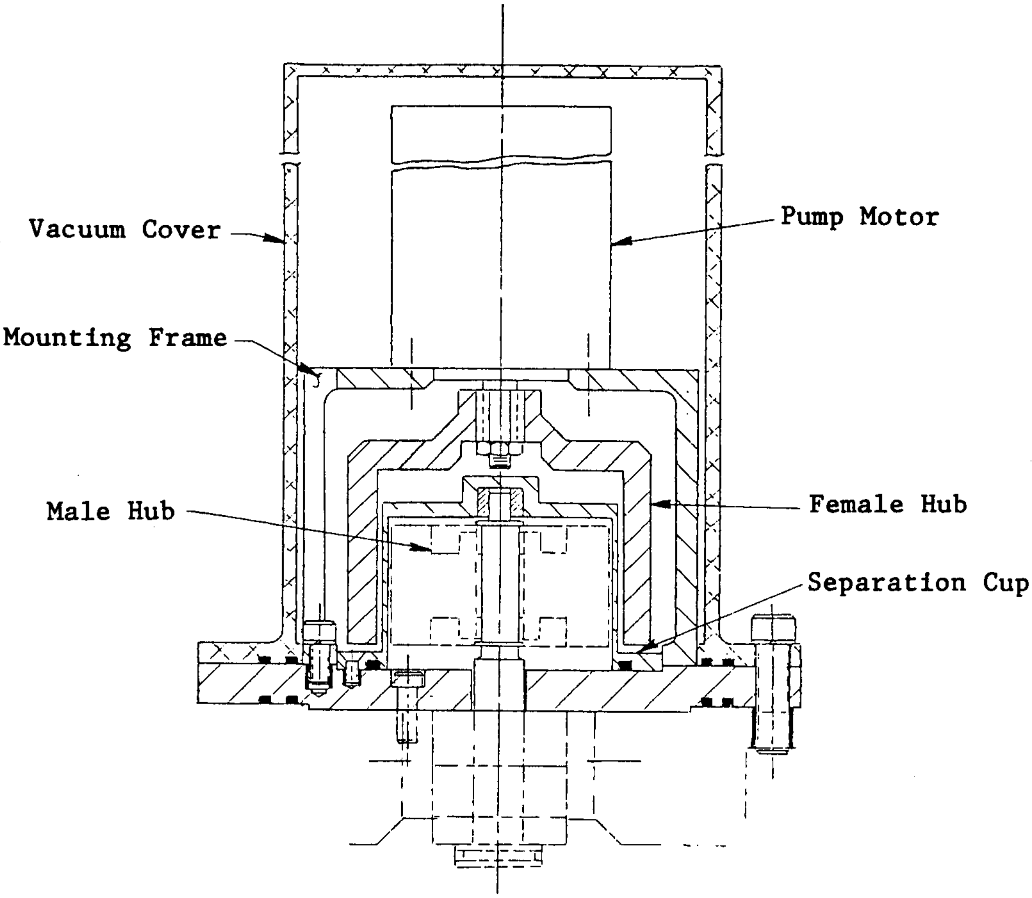
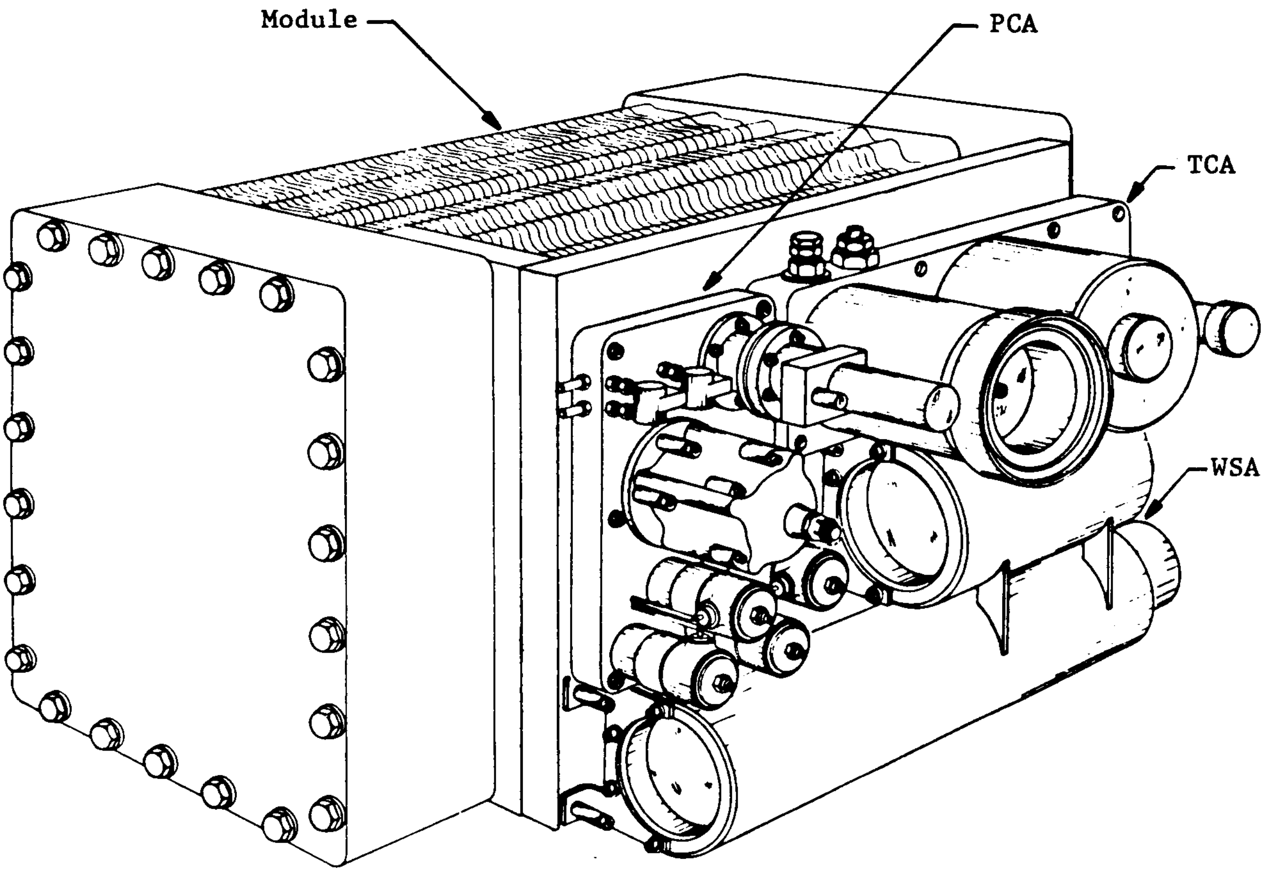


FIGURE 9 COOLANT PUMP/MOTOR/MAGNETIC DRIVE FOR RFC SSP



Key Characteristics

Reactant Generation Rate, kg/hr (lb/hr):	2.3 (5.1)
Operating Pressure, kPa (psia) :	2,172 (315)
Weight, kg (lb) :	132 (290)
Volume, m^3 (ft^3) :	0.18 (6.5)
Projected Life, hr :	>40,000

FIGURE 10 PROPOSED PACKAGING FOR 10 kW STATIC FEED ELECTROLYZER FOR RFC-SPACE STATION PROTOTYPE

Sequence of Material Evaluation

In order to determine if the materials pass applications requirements, a sequence of reviewing the materials in the alkaline SFE system was established and refined. The final sequence is depicted in Figure 11, SFE Materials Evaluation Process Flow Chart.

The second step was to establish compatibility requirements for the SFE. In order to appreciate the broad applicability of an SFE to the Space Station, multiple uses and their operating requirements were identified and are listed in Table 2. The requirements for this program (Phase II) are shown under the ECLSS column on Table 2. All materials were, however, evaluated for a pressure of 2,413 kPa (350 psia), hence, a margin of safety is included for the ECLSS applications.

The overall evaluation of a material proceeded as follows. The first step in the sequence was to list and document the requirements and acceptance criteria for space application. Table 3, Requirements and Acceptance Criteria for SFE Materials for Space Application, details the parameter/characteristic, requirement and acceptance criteria that resulted. This table is followed by Table 4 and Table 5 which complete the identification of the criteria and the reference documents and specifications. They are entitled "Criteria of Material Selection for Alkaline Static Feed Electrolyzer Based O_2 Generation System" and "Documents and Specifications Used for Evaluating and Selecting Metallic and Nonmetallic Materials for Alkaline Static Feed Electrolyzer (SFE) Based Oxygen Generation System."

The evaluation process involved the preparation of a list of parts and materials of construction for these parts, as well as the contact fluid and the operating conditions. The part thickness is important in comparing the operating conditions and the NASA test data. Each part and material usage is evaluated using the MSFC-HDBK 527 Rev. E data. If that material had been tested with a piece of comparable thickness and had passed, the rating is indicated on the list. These ratings and their meanings are summarized in Table 6. This table also specifically indicates the value hierarchy for each materials evaluation criteria.

If a material had been tested and passed the various testing criteria, additional data was located where available to determine the appropriate compatibility with H_2 and 35% KOH. If data was not sufficient, then additional test or use data was obtained. The end result of the total evaluation sequence is a list of alkaline SFE system materials which are being recommended for use aboard manned space systems. A summary of the recommended baseline SFE metallic and nonmetallic materials for the ECLSS application is given in Table 7.

Alternative Metallic and Nonmetallic Materials

As a result of the program activities, alternatives that showed promise were also identified. These materials are also shown in Table 7. A final metallic and nonmetallic material list was prepared and submitted.

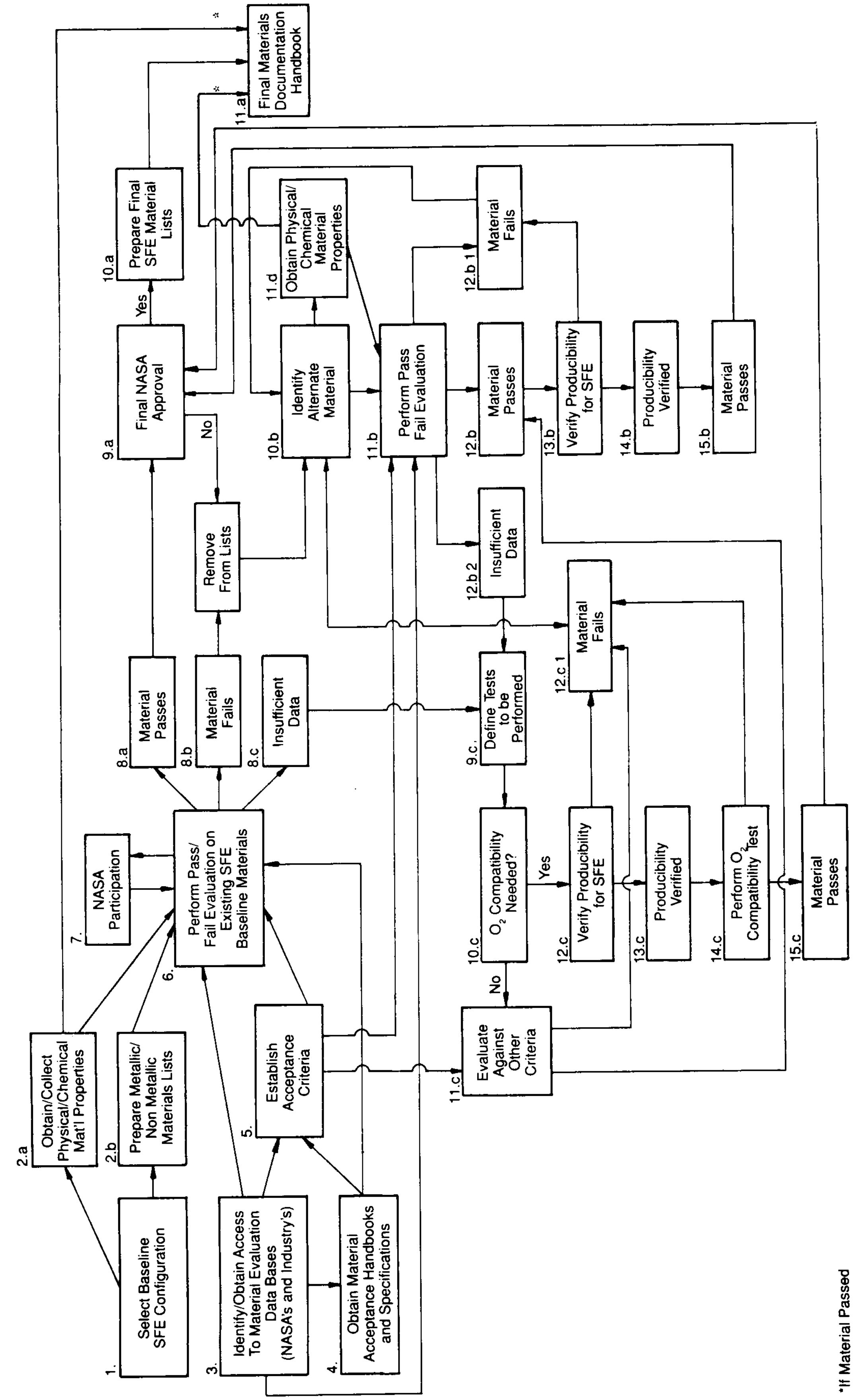


FIGURE 11 SFE MATERIALS EVALUATION PROCESS FLOW CHART

*If Material Passed

TABLE 2 SFE MATERIAL COMPATIBILITY REQUIREMENTS

(English Units)

	Space Station Application			
	ECLSS	Power	Propulsion	EVA
Exposure to GOX				
Pressure (Max), psia	200	350	3,000	6,000
Temperature (Max), F	180	180	180	180
Dew Point (Max), F	180	180	180	180
Dew Point (Min), F	20	20	20	20
Flow Velocity (Max), ft/sec	0.88	3.90	0.36	0.01
Gas Purity, % O_2 Max	100	100	100	100
Aqueous Solution,[(a)] Type/% by wt	KOH/40	KOH/40	KOH/40	KOH/40
Duration (Operating), yr	10	10	10	10
Duration (Storage), yr	N/A	N/A	N/A	N/A
Exposure to H_2 (Gaseous)				
Pressure (Max), psia	200	350	3,000	$\leq$50
Temperature (Max), F	180	180	180	180
Dew Point (Max), F	180	180	180	180
Dew Point (Min), F	20	20	20	20
Flow Velocity (Max), ft/sec	1.75	7.89	0.72	0.52
Gas Purity, % O_2 Max	100	100	100	100
Aqueous Solution,[(a)] Type/% by wt	KOH/40	KOH/40	KOH/40	KOH/40
Duration (Operating), yr	10	10	10	10
Duration (Storage), yr	N/A	N/A	N/A	N/A
Exposure to Aqueous Solutions				
Type	KOH	KOH	KOH	KOH
Concentration (Min), %	0[(b)]	0	0	0
Concentration (Max), %	40	40	40	40
Pressure (Max), psia	200	350	3,000	6,000
Temperature (Max), F	180	180	180	180
Dissolved Gases, Type/Part Press, psia	H_2/200	H_2/350	H_2/3,000	H_2/6,000
Duration (Operational), yr	10	10	10	10
Duration (Storage), yr	Indef.	Indef.	Indef.	Indef.
Exposure to N_2 (Gaseous)				
Pressure (max), psia	220	385	3,300	6,500
Temperature (Max), F	100	100	100	100
Temperature (Min), F	30	30	30	30
Dew Point (Max), F	-50	-50	-50	-50
Gas Purity, %	99.99	99.99	99.99	99.99
Duration (Operating), Days	10[(c)]	N/A	N/A	10[(c)]
Duration (Storage), yr	Indef.	Indef.	Indef.	Indef.
Exposure to Liquid Coolant				
Type	N/A	FC-40	Water	Water
Pressure (Max), psia	N/A	350	3,000	6,000
Temperature (Max), F	N/A	220	200	200

(a) Co-Exposure.
(b) Meaning Pure Water.
(c) Estimate.

Table 2 - continued

(SI Units)

	Space Station Application			
	ECLSS	Power	Propulsion	EVA
Exposure to GOX				
Pressure (Max), kPa	1,379	2,413	20,685	41,370
Temperature (Max), K	356	356	356	356
Dew Point (Max), K	356	356	356	356
Dew Point (Min), K	267	267	267	267
Flow Velocity (Max), m/sec	0.27	1.19	0.11	0.003
Gas Purity, % O_2 Max	100	100	100	100
Aqueous Solution,[a] Type/% by wt	KOH/40	KOH/40	KOH/40	KOH/40
Duration (Operating), yr	10	10	10	10
Duration (Storage), yr	N/A	N/A	N/A	N/A
Exposure to H_2 (Gaseous)				
Pressure (Max), kPa	1,379	2,413	20,685	$\leq$345
Temperature (Max), K	356	356	356	356
Dew Point (Max), K	356	356	356	356
Dew Point (Min), K	267	267	267	267
Flow Velocity (Max), m/sec	0.53	2.40	0.22	0.16
Gas Purity, % O_2 Max	100	100	100	100
Aqueous Solution,[a] Type/% by wt	KOH/40	KOH/40	KOH/40	KOH/40
Duration (Operating), yr	10	10	10	10
Duration (Storage), yr	N/A	N/A	N/A	N/A
Exposure to Aqueous Solutions				
Type	KOH	KOH	KOH	KOH
Concentration (Min), %	0[c]	0	0	0
Concentration (Max), %	40	40	40	40
Pressure (Max), kPa	1,379	2,413	20,685	41,370
Temperature (Max), K	356	356	356	356
Dissolved Gases, Type/Part Press, kPa	H_2/1,379	H_2/2,413	H_2/20,685	H_2/41,370
Duration (Operational), yr	10	10	10	10
Duration (Storage), yr	Indef.	Indef.	Indef.	Indef.
Exposure to N_2 (Gaseous)				
Pressure (max), kPa	1,517	2,655	22,754	44,818
Temperature (Max), K	311	311	311	311
Temperature (Min), K	272	272	272	272
Dew Point (Max), K	228	228	228	228
Gas Purity, %	99.99	99.99	99.99	99.99
Duration (Operating), Days	10	N/A	N/A	10
Duration (Storage), yr	Indef.	Indef.	Indef.	Indef.
Exposure to Liquid Coolant				
Type	N/A	FC-40	Water	Water
Pressure (Max), kPa	N/A	2,413	20,685	41,370
Temperature (Max), K	N/A	378	367	367

(a) Co-Exposure.
(b) Meaning Pure Water.
(c) Estimate.

TABLE 3 REQUIREMENTS AND ACCEPTANCE CRITERIA FOR SFE MATERIALS FOR SPACE APPLICATION

Parameter/Characteristic	Requirement	Acceptance Criteria[a]		
		Type A[b]	Type D[c]	Type H
Flammability, Odor and Offgassing	Operational for conditions defined in Table 2	Materials must pass or have passed tests 1, 4, 5, 6, 7 or 10 and 16	Materials must pass or have passed tests 1, 4 and 13 part 2 and 14	Materials must pass or have passed tests 1, 4 and 5
Life				
Operational	10 years	Can be achieved through periodic inspection, maintenance and replacement		
Storage	Indefinite			
Corrosion	Operational for conditions defined in Table 2	Less than 0.5 μV/hr increase in cell voltage over operating/storage life		
Producibility				
Metallic	(d)	Producible to specified design tolerances per Manufacturing Drawings		
Nonmetallic	(e)	Producible to specified design tolerances per Manufacturing Drawings		
Permeability	No permeation for for conditions defined in Table 2 that result in unsafe or intolerable conditions	1. Resulting in less than 2,500 ppm product gas impurities 2. Resulting in no free gases in liquid coolant (for separate coolant compartment only)		

(a) Material type and tests as defined in NHB 8060.1B, i.e., Type A materials are exposed to crew bay environment (e.g., SFE for ECLSS and possibly EVA), Type D materials contact high pressure (>25 psia) gaseous O_2 (e.g., all SFE's) while Type H materials are located in unpressurized portions of spacecraft (e.g., SFE for propulsion and Regen fuel cells).
(b) Only Group I materials allowed (per NHB 8060.1B).
(c) Batch testing required until capability of material to meet acceptance per NHB 8060.1B is established.
(d) Producible by standard machining practices including welding, brazing and stamping.
(e) Producible by standard machining practices including injection molding, modeling, bonding and stamping.

TABLE 4 CRITERIA OF MATERIAL SELECTION FOR ALKALINE STATIC FEED ELECTROLYZER BASED O_2 GENERATION SYSTEM

	Criteria of Selection[a]				
		Non-metallic Material			
Item	Metallic Material	Plastics	Elastomer	Adhesive	Lubricant/ Inert Fluid
General Selection	1, 4, 7, 8	1, 4, 7, 8, 13	1, 4, 7, 8	1, 4, 7, 8	1, 4, 7, 8
Corrosion Control	-	-	-	-	-
Stress Corrosion	6	-	-	-	-
Structural Strength	5	13	-	-	-
O_2 Compatibility	1, 2, 10, 11	1, 2, 10, 11	1, 2, 10, 11	1, 2, 10, 11	1, 2, 10, 11
Offgassing	-	2, 3	2, 3	2, 3	2
Fluid Compatibility	-	2	2	2	2
Flammability	-	2	2	2	2
Bonding	-	9	-	9	-
Odor	-	2	2	2	2
Toxicity	4, 7, 8	-	-	-	-

(a) Numbers refer to specified documents in Table 5.

TABLE 5 DOCUMENTS AND SPECIFICATIONS USED FOR EVALUATING AND SELECTING METALLIC AND NONMETALLIC MATERIALS FOR ALKALINE STATIC FEED ELECTROLYZER (SFE) BASED OXYGEN GENERATION SYSTEM

	Document No.	Document Title
1.	MSFC-HDBK-527/ JSC 09604 Rev. E	Materials Selection List for Space Hardware Systems
2.	NHB 8060.1B	Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments that Support Combustion, with Errata
3.	SP-R-0022A	Vacuum Stability Requirements of Polymeric Materials for Spacecraft Applications
4.	SE-R-0006A	NASA-JSC Requirements for Materials and Processes
5.	MSFC-SPEC-250A	Protective Finishes for Space Vehicles, Structures and Associated Flight Equipment
6.	MSFC-SPEC-522A	Design Criteria for Controlling Stress Corrosion Cracking
7.	MSFC-STD-506B	Materials and Processes Control
8.	JSC 30233	Space Station Requirements for Materials and Processes
9.	MSFC-SPEC-445	Requirements for Adhesive Bonding, Process, and Inspection
10.	JSC-20810	JSC Handbook of Material Test Data
11.	NASA Ref. 1113	Design Guide for High Pressure Oxygen Systems
12.	MIL-HDBK-5E	Strength of Metal Aircraft Elements
13.	MIL-HDBK-17B	Plastics for Flight Vehicles

TABLE 6 MATERIALS EVALUATION CRITERIA SUMMARY

Rating Description	Materials Evaluation Criteria[a]							
	FLAM	TOX	TVS	AGE	SCC	CORR	GOX	LoH_2[b]
Highest Level	A	K	A	A	A	A	A	A
Second Level	B	A	B[c]	B	B[c,d]	B[e]	B[c,d]	
Third Level	C	B[f]	C[c]		C[c,d]		C[c,d]	
Untested	U[c]	U	U[c]		U[c]	U[c]	U[c]	
Fails Test (outside criteria)	X[c]	X[c]	X[c]			X[c]	X[c]	
Special Testing	S	S	S[c]				S[c]	
Insufficient Data	I	I	I[c]				I	
Other[g]		V[c]			N		Z[c,d]	

(a) FLAM - Flammability, TOX - Toxicity/Offgassing, TVS - Thermal Vacuum Stability, AGE - Static Age Life, SCC - Stress Corrosion Cracking (Susceptibility), CORR - Corrosion Resistance, GOX - Compatibility with Gaseous Oxygen, LoH_2 - Compatibility with Low Pressure Gaseous Hydrogen.
(b) Metallic materials only
(c) Requires Material Usage Agreement
(d) Requires batch testing
(e) Performs at A level if coated
(f) Performs at K or A level if specially cured.
(g) V = fourth level
N = not applicable
Z = further testing required

TABLE 7 SUMMARY OF RECOMMENDED BASELINE AND ALTERNATIVE SFE METALLIC AND NONMETALLIC MATERIALS FOR ECLSS APPLICATION

Part	Original Baseline	Recommended Baseline	Alternate (If Applicable)
Metallic Materials			
Accumulator Tank	347 Stainless Steel	316L Stainless Steel	Haynes 188
Accumulator Bellows	Inconel 718	316L Stainless Steel	Haynes 188
PCA Valve Stem	Inconel 718	Haynes 188	(a)
FCA Valve Body	TI-GAL-4V Titanium	316L Stainless Steel	Haynes 188
Nonmetallic Materials			
Cell Frames	Polysulfone P-1700	Polysulfone P-1700	Polyetheretherketone
Fluids Insulation Plate	30% Glass Filled Polysulfone	Polyethersulfone	Polyetheretherketone
Structural Insulation Plate	30% Glass Filled Polysulfone	Polyethersulfone	Polyetheretherketone
Plug Adhesive	Methylene Chloride	Scotchweld Epoxy	(a)
O-Ring Seal - Cell Core	Ethylene Propylene Rubber	Perfluoroelastomer	(a)
O-Ring Seal - Outer Cell Frame	Ethylene Propylene Rubber	Perfluoroelastomer	(a)
Unitized Feed Core	Epoxy Prepreg	Scotchweld	(a)
Polysulfone Bonding Agent	Scotchweld	Scotchweld	(a)
Cell Core Frame	Epoxy Prepreg	Aclar	Scotchweld
O-Ring Lube Grease	Krytox 240 AC	Braycote 601	(a)
Cover - Current Collector	Polysulfone P-1700	Aclar	Scotchweld
Hydrogen Purge Port Tabs	Polysulfone P-1700	Eliminated From Design	N/A
Interface Plate	30% Glass Filled Polysulfone	Polyethersulfone	Polyetheretherketone
FCA O-Ring Seals	Ethylene Propylene Rubber	Perfluoroelastomer	(a)
PCA Diaphragm	Epichlorohydrin Copolymer	316L Stainless Steel	(a)
Coolant Pump Bearing	Glass Filled Graphite Filled Teflon	Polyetheretherketone	(a)
Magnetic Drive Bearing	Glass Filled Graphite Filled Teflon	Polyetheretherketone	(a)

(a) None identified.

Electrochemical Module Scaling and Performance Repeatability Evaluations

The electrochemical module scaling and performance repeatability evaluations consisted of testing tasks directed at improving and/or quantifying electrolyzer operation and performance. This testing encompassed product gas purity, an investigation of evaluating recombiners for product gas purification, electrolyte charging of the module, system pressurization and depressurization and the development of a single-cell evaluation and fluids charging fixture. These areas are discussed below.

Product Gas Purity

Product gas purity (i.e., H_2-in-O_2 and O_2-in-H_2) of the SFE was studied to determine the level, if any, source(s) and the influence of operating parameters on impurity levels. To assist in this evaluation, gas purity data from prior tests was collected and used to supplement data from this task. Of primary interest was to evaluate the probability of stray electrolysis being a source, or partial source of product gas impurities. Although unlikely with the current baseline design, this phenomenon was at one time suspected to cause the low levels of H_2-in-O_2 (2,000 to 4,000 ppm, range) and O_2-in-H_2 (10 to 50 ppm, range) observed.

Four gas analyzers were used to measure product gas purity. A Mine Safety Appliance (MSA) H_2 Series 510 Gas Analyzer was selected to measure H_2-in-O_2 to 400 ppm. Two Westinghouse gas analyzers, the Westinghouse O_2 6N and the Westinghouse Thermor Gas Analyzers were chosen to measure O_2-in-H_2 and H_2-in-O_2, respectively, to 40 ppm. The fourth unit was a Hewlett Packard 5890A Gas Chromatograph (GC) capable of measuring both H_2-in-O_2 and O_2-in-H_2 to 1 ppm.

Life Systems evaluated its existing water electrolysis database and test equipment to determine availability of data and hardware for product gas purity testing. Table 8 lists the test stands, subsystems and modules that were selected as candidates for data sources and/or generation to be used in the course of performing SFE product gas purity tests and analyses.

Gas purity testing was initiated with existing SFE hardware. This testing was conducted with current at baseline operating conditions. The gas purity analyzer utilized during this testing was the MSA analyzer. Initial test results were obtained with the Static Feed Electrolyzer (SFE-3) subsystem. This subsystem consists of a 12-cell, 0.023 m^2 (0.25 ft^2) module, an FCA, a PCA and a TCA. These results are shown in Table 9. Additional results were obtained with the WS-1 subsystem, which consists of a five-cell, 0.023 m^2 (0.25 ft^2) module, an FCA, a PCA and a TCA. These results are shown in Table 10. The MSA analyzer was first used since the more accurate gas chromatograph was not yet available. The values obtained appear higher than normal but the data was useful in establishing baseline conditions.

Parametric tests were conducted to investigate the effects of initial startup, current density, operating pressure, temperature and module stack size on product gas purity. These tests are discussed below.

TABLE 8 SUMMARY OF SFE HARDWARE/DATA SOURCES FOR PRODUCT GAS PURITY EVALUATION

Test Article	Module No.	Cell/Module Description	No. of Cells	Cell Area Size, m^2 (ft^2)
TS 127	127	Module with original design unitized cell cores	6	0.0093 (0.10)
TS 127	129	Module with baseline design unitized cell cores	6	0.0093 (0.10)
TS 131	131	0.023 m^2 (0.25 ft^2) single-cell module with baseline cell core and feed core	1	0.023 (0.25)
WS-1	WS-1	0.023 m^2 (0.25 ft^2) module with baseline design unitized cell cores, feed cores	5	0.023 (0.25)
TS 127	WS-3	0.0093 m^2 (0.10 ft^2) module with pre-baseline design. Modified to eliminate gas contact with metal current collectors	17	0.0093 (0.10)
SFE-2	SFE-2	0.023 m^2 (0.25 ft^2) module with baseline design feed cores and cell cores	12	0.023 (0.25)
SFE-2	SFE-2	0.023 m^2 (0.25 ft^2) module with baseline design feed cores and cell cores	24	0.023 (0.25)
SFE-3	SFE-3	0.023 m^2 (0.25 ft^2) module with baseline design feed cores and cell cores	12	0.023 (0.25)

TABLE 9 SFE GAS ANALYSIS DATA - SFE-3

(12-Cell, 0.25 ft^2)

Sample No.	Test Unit	Pressure, kPa (psig)	Temperature, K (F)	Current Density, mA/cm^2 (ASF)	H_2 in O_2, ppm	Analyzer Type
1	SFE-3	2,068 (300)	333.9 (141.1)	131.3 (122)	4,400	MSA
2	SFE-3	2,068 (300)	333.9 (141.1)	131.3 (122)	5,200	MSA
3	SFE-3	2,068 (300)	331.5 (136.7)	131.3 (122)	5,200	MSA
4	SFE-3	2,068 (300)	333.3 (140.0)	131.3 (122)	4,400	MSA
5	SFE-3	2,068 (300)	332.7 (138.9)	131.3 (122)	4,400	MSA
6	SFE-3	2,068 (300)	330.7 (135.2)	131.3 (122)	5,600	MSA
7	SFE-3	2,068 (300)	331.1 (136.0)	131.3 (122)	5,600	MSA
8	SFE-3	2,068 (300)	328.4 (131.2)	131.3 (122)	5,200	MSA
9	SFE-3	2,068 (300)	328.4 (131.2)	131.3 (122)	3,600	MSA
10	SFE-3	2,068 (300)	329.5 (133.1)	131.3 (122)	3,600	MSA

TABLE 10 SFE GAS ANALYSIS DATA - WS-1

(5-Cell, 0.25 ft^2)

Sample No.	Test Unit	Pressure, kPa (psig)	Temperature, K (F)	Current Density, mA/cm^2 (ASF)	H_2 in O_2, ppm	Analyzer Type
1	WS-1	1,131 (164.1)	334.4 (142.0)	131.3 (122)	1,200	MSA
2	WS-1	1,131 (164.1)	334.4 (141.9)	131.3 (122)	1,200	MSA
3	WS-1	1,142 (165.7)	329.8 (133.7)	131.3 (122)	3,200	MSA
4	WS-1	1,140 (165.4)	329.6 (133.2)	131.3 (122)	2,400	MSA
5	WS-1	1,142 (165.6)	330.0 (134.0)	131.3 (122)	2,400	MSA

The Effects of Initial Startup on Product Gas Purity. Testing was initiated on the SFE-2 to evaluate "worst-case" operating conditions on product gas purity. The "worst-case" operating condition was defined as the conditions present during the initial startup and operation of an SFE module which has been freshly charged with electrolyte. Due to the electrolyte charging technique which was employed, an electrolyte film could remain within the gas manifolds of the module. Such a film could contribute to a higher product gas impurity level during the initial startup than in subsequent startups due to stray electrolysis. All modules would normally be pre-conditioned prior to system use to eliminate this film (through ambient pressure operation).

A test to prove this theory was conducted by starting up an unpreconditioned, freshly charged 12-cell module (in the SFE-2). The results of this test are shown in Figure 12. Performance shows that after ten minutes, with 26 A current applied to the module, the H_2-in-O_2 level is at its maximum value of 4,050 ppm. The H_2-in-O_2 level steadily falls from 4,050 ppm to 2,150 ppm over the next 90 minutes of operation with module current remaining stable at 30 A. The O_2-in-H_2 level is consistently low, in the 0 to 25 ppm range.

The SFE-2 was restarted after it sat unattended for a three-day period. The results of this second startup are shown in Figure 13. Performance shows that after ten minutes, with 30 A current applied to the module, the H_2-in-O_2 level is at its maximum value of 2,600 ppm. The H_2-in-O_2 level steadily falls from 2,600 ppm to 1,600 ppm over the next 50 minutes of operation with the module current remaining stable at 30 A. The O_2-in-H_2 level is consistently low, in the 0 to 10 ppm range.

The results for H_2-in-O_2 determinations for both tests are shown together in Figure 14. It is evident that the initial startup of a freshly charged module does in fact produce a higher H_2-in-O_2 impurity level than subsequent restarts. Also, the amount of time for H_2-in-O_2 levels to stabilize is longer in the initial startup than in the second startup. Therefore, the practice of module preconditioning, adopted several years back, is a correct procedure prior to module installation and use. This procedure will, therefore, be retained for all modules although a different charging technique (single cells) has been developed under this program (see section on Electrolyte Charging Management Practice, below) which should eliminate the chance of a film buildup.

The Effect of Current Density on Product Purity. Tests were conducted on the 12-cell module in the SFE-2 to measure H_2-in-O_2 levels as a function of five current densities. Each current density span was completed at three different temperature levels: 328 K (130 F), 333 K (140 F) and 339 K (150 F). The results from these tests were fitted to a curve and are shown in Figure 15. Two distinct trends are noticeable. First, product gas impurity levels decrease as current density is increased. This is due to dilution of the H_2 impurities by the greater volume of O_2 produced for increased current density. Second, the level of gas impurity increases slightly (~300 ppm) with increasing temperatures at constant current density. This can be ascribed to the increased gas permeation in the module at higher temperatures.

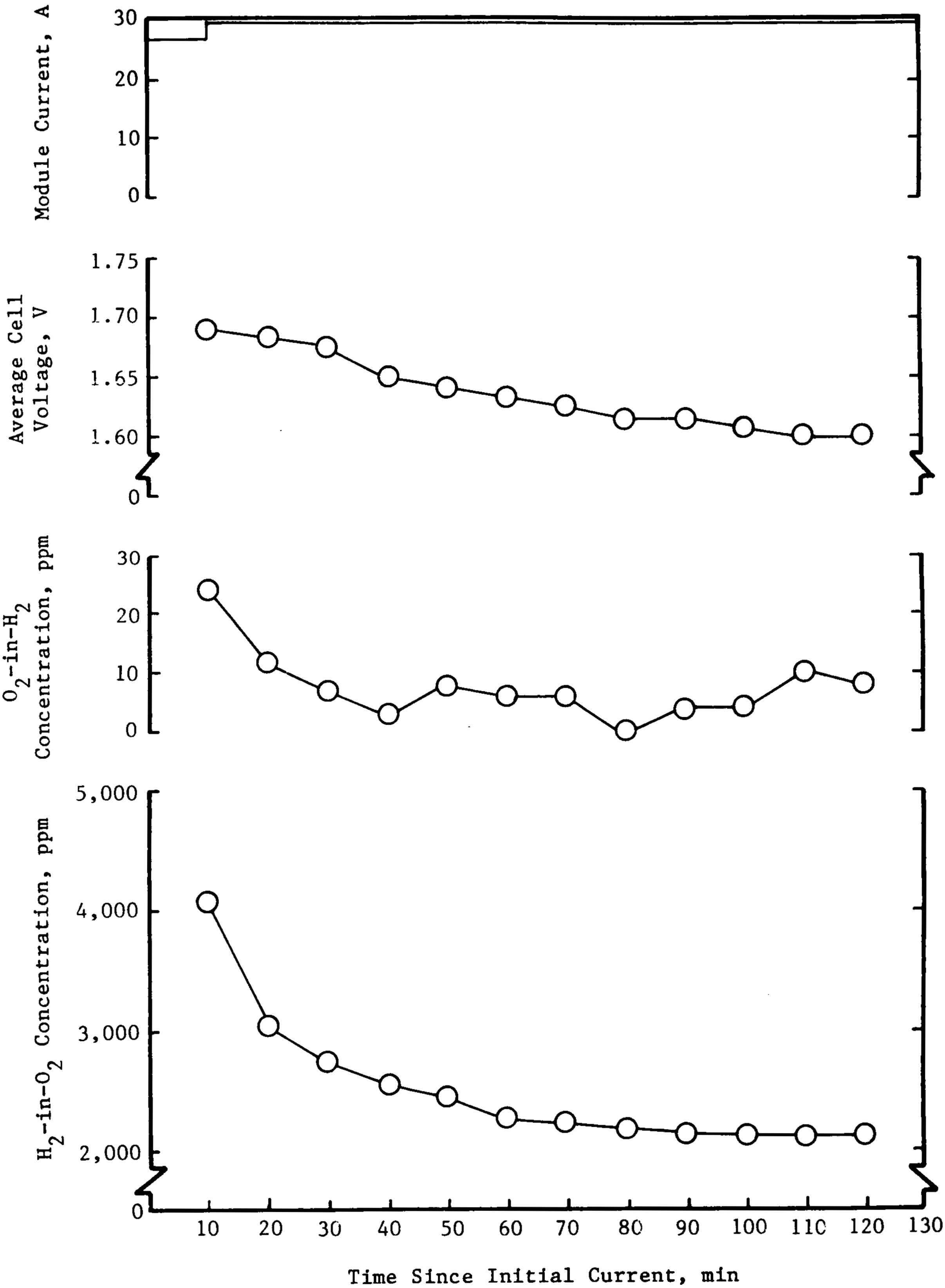


FIGURE 12 SFE-2 PERFORMANCE VERSUS TIME - INITIAL STARTUP

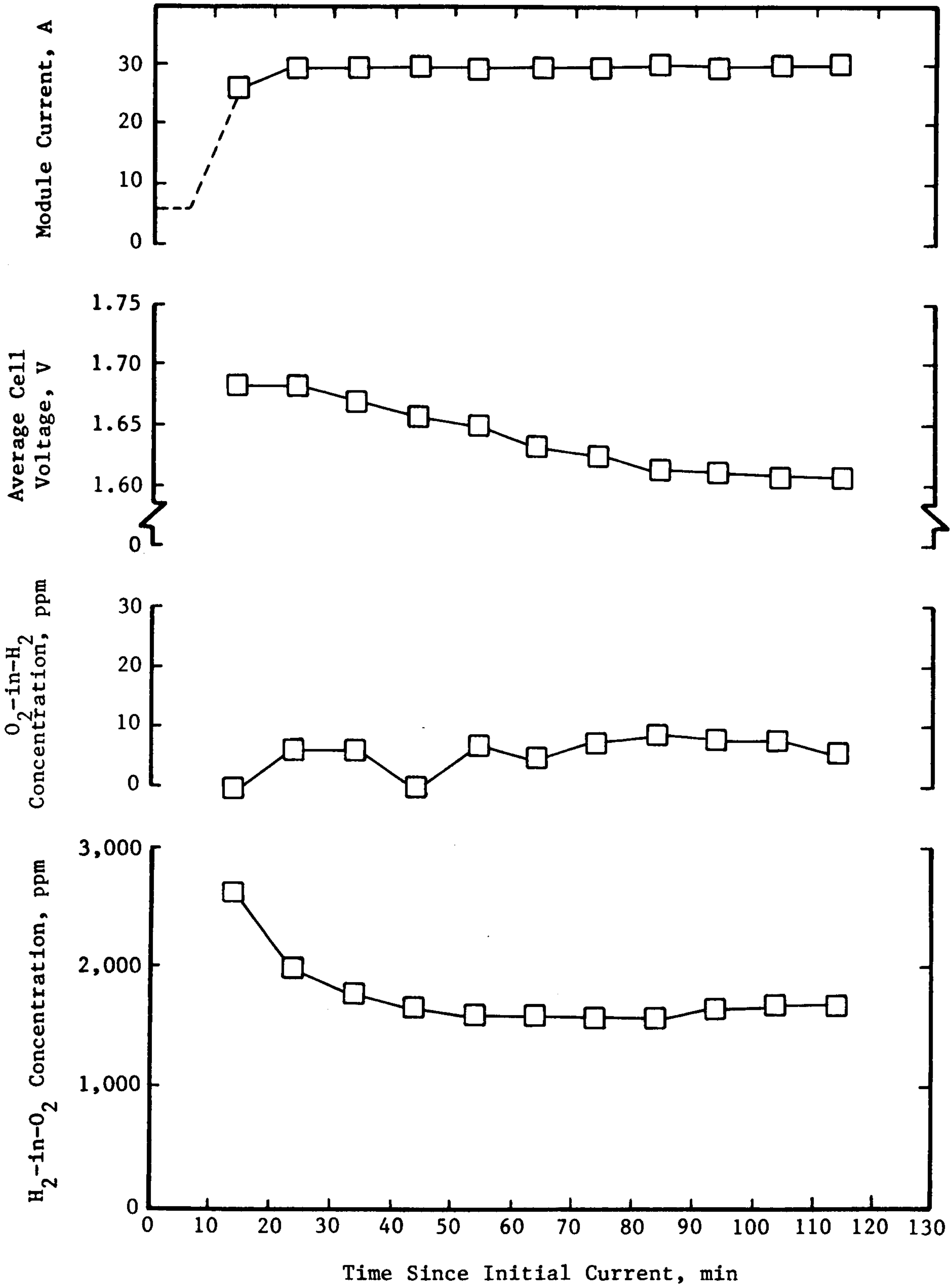


FIGURE 13 SFE-2 PERFORMANCE VERSUS TIME - SECOND STARTUP

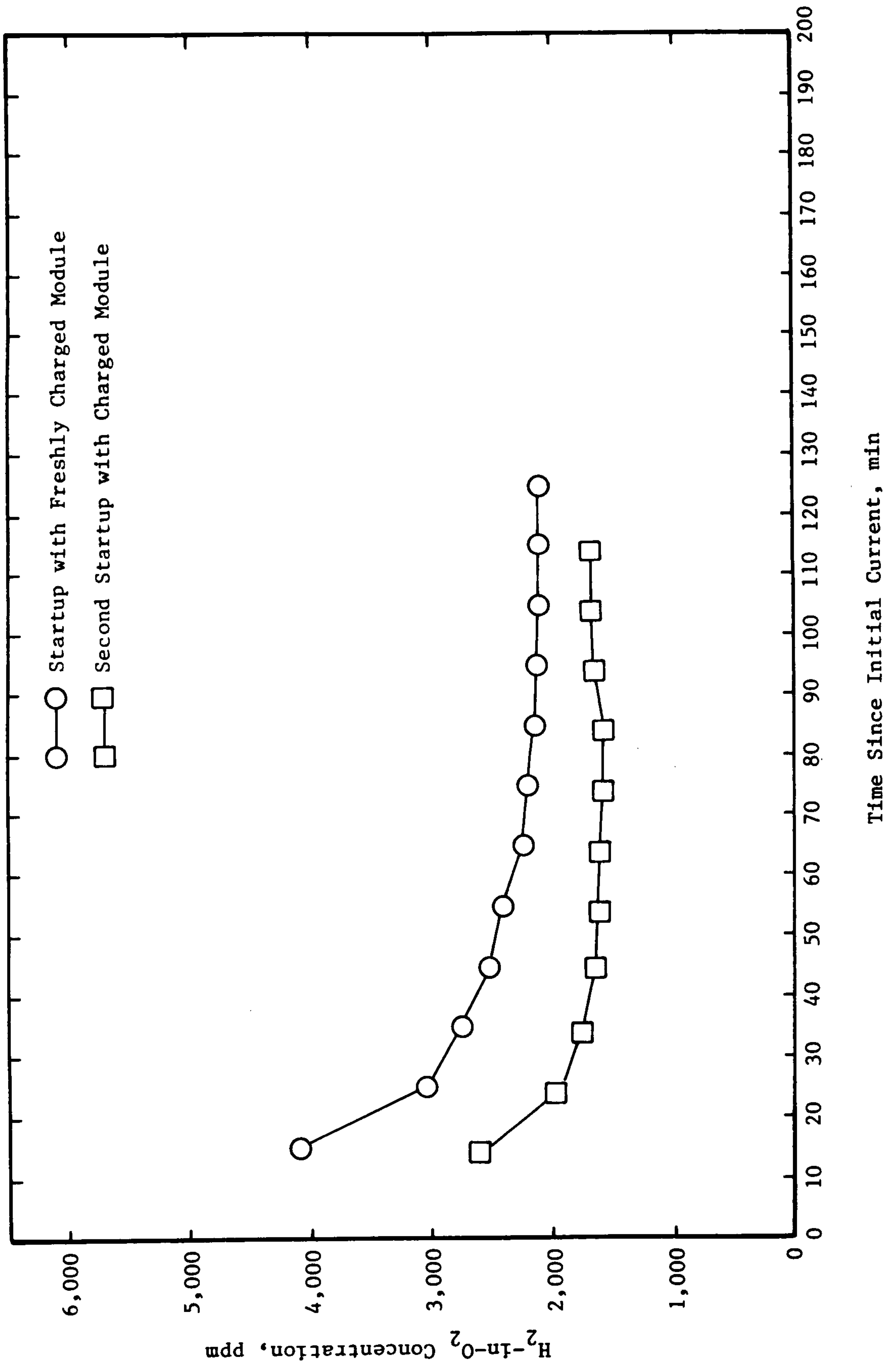


FIGURE 14 SFE-2 WORST-CASE OPERATING CONDITION - H_2-IN-O_2 CONCENTRATION VERSUS TIME

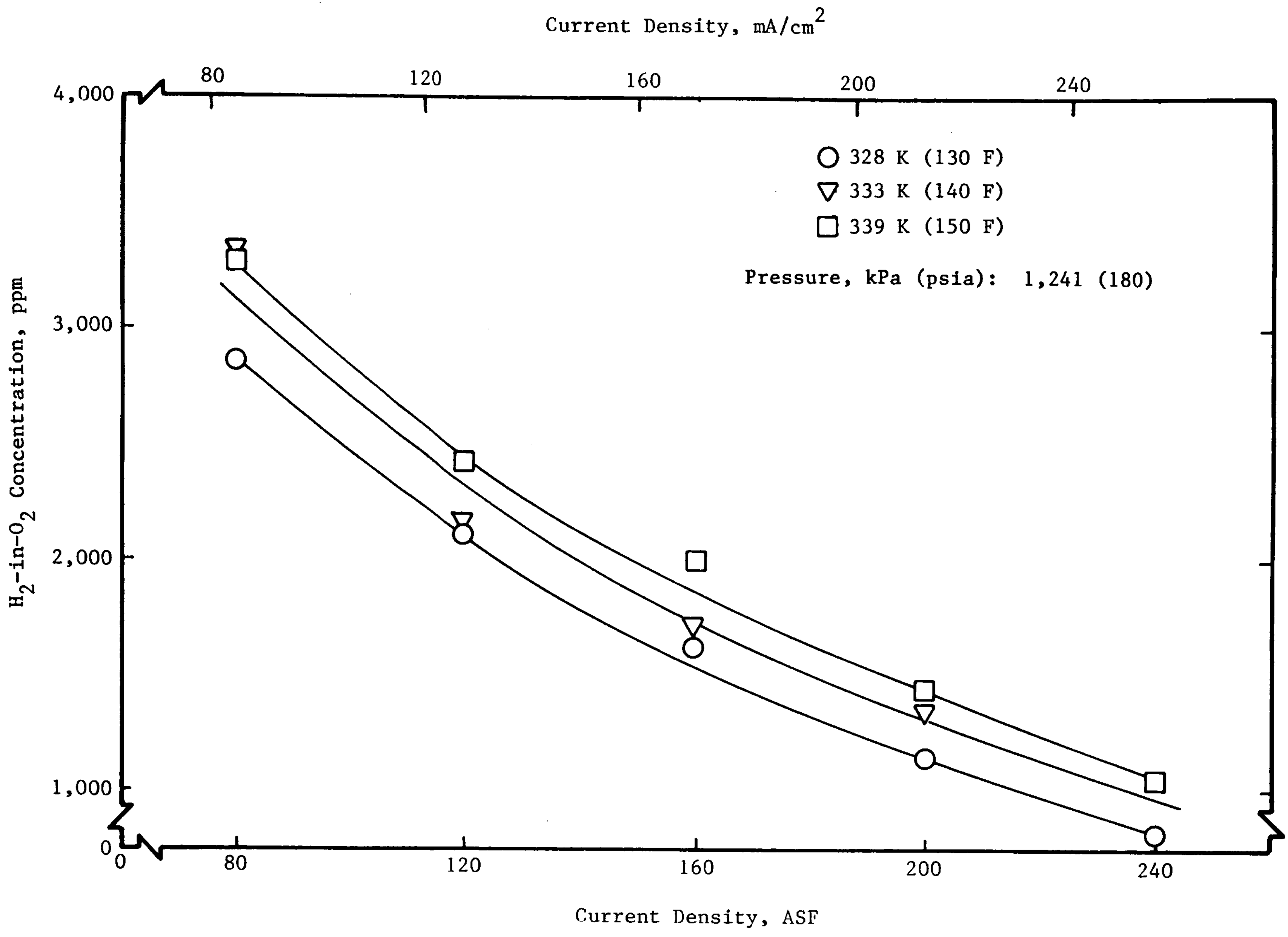


FIGURE 15 SFE-2 12-CELL H_2-IN-O_2 CONCENTRATION VERSUS CURRENT DENSITY

To further resolve the contribution of stray electrolysis, sample gas analyses on 0.0093 m^2 (0.1 ft^2) modules were conducted with and without current. The TS-127 module was chosen since it was of a 1972 construction which had been suspected to have stray electrolysis. These results could then be compared to those obtained with current baseline hardware. In order to conduct the tests, Test Stand 127 was modified to reduce the H_2 and O_2 "dead" volumes (i.e., traps, lines, etc.) and to include high pressure O_2 and H_2 sources. The gas analysis was performed using the in-line Westinghouse O_2 Thermor Analyzers for O_2-in-H_2 and H_2-in-O_2 determinations, respectively.

Using the modified test stand, a "reference baseline" (without current) contaminant level, expressed as μg-mole/min, was established for normal operating conditions: module temperature 338 K (149 F), module pressure 1,241 kPa (180 psia) and module pressure differential 13.8 kPa (2 psid). At these conditions, a baseline H_2-in-O_2 level of 16.9 μg-mole/min was determined.

This provides a measure of the contamination in the module due to mass transport (i.e., diffusion through or leaks around seals, etc.). This level of contaminant is not surprising since the module on TS-127 is of the 1972 vintage design and does not contain the latest cell improvements. The O_2-in-H_2 transport level was an order of magnitude lower than that for H_2-in-O_2.

After the "reference baseline" H_2 transport level was determined, testing with current was conducted. The results, shown in Figure 16, indicate that a level of stray electrolysis is present in the 1972 vintage module. This is indicated by the fact that the H_2 level in the O_2 outlet is: (1) greater than the baseline level, and (2) increased with current. The O_2-in-H_2 level dropped to zero when current was applied to the module, indicating that the small amount of "transport" O_2 that made it into the H_2 compartment was recombined at the electrode to form water.

A comparison test was then conducted with the current baseline hardware. During a current density span analysis on the 0.023 m^2 (0.25 ft^2) module of SFE-2, the H_2-in-O_2 and O_2-in-H_2 product gas impurities were monitored. The H_2-in-O_2 decreased with current density, attributable to dilution of the H_2 with increasing O_2 production. Correcting the ppm results for O_2 gas production, showed that the amount of H_2 transported was constant versus current, and indicates that stray electrolysis is only a minor, if any, factor in the SFE-2 hardware. The O_2-in-H_2 levels were again extremely low, indicating that mainly diffusion and not a counterpart production of O_2-in-H_2 due to stray electrolysis is the source.

Product Gas Purity as a Function of Pressure. Testing to determine SFE product gas purity as a function of system operating pressure was conducted at three pressure levels; 275.8 kPa (40 psia), 1,241 kPa (180 psia) and 2,172 kPa (315 psia). The SFE-2 was used for testing at 275.8 kPa (40 psia) and 1,241 kPa (180 psia), while the SFE-3 was used for testing at 1,241 kPa (180 psia) and at 2,172 kPa (315 psia).

The SFE-3 was operated at a baseline current of 30 A, an operating temperature of 336 K (145 F) and an operating pressure 2,172 kPa (315 psia) for 125 hours. Product gas purity measurements were obtained throughout the test. The average H_2-in-O_2 and O_2-in-H_2 levels were 1,087 ppm, and 15 ppm, respectively.

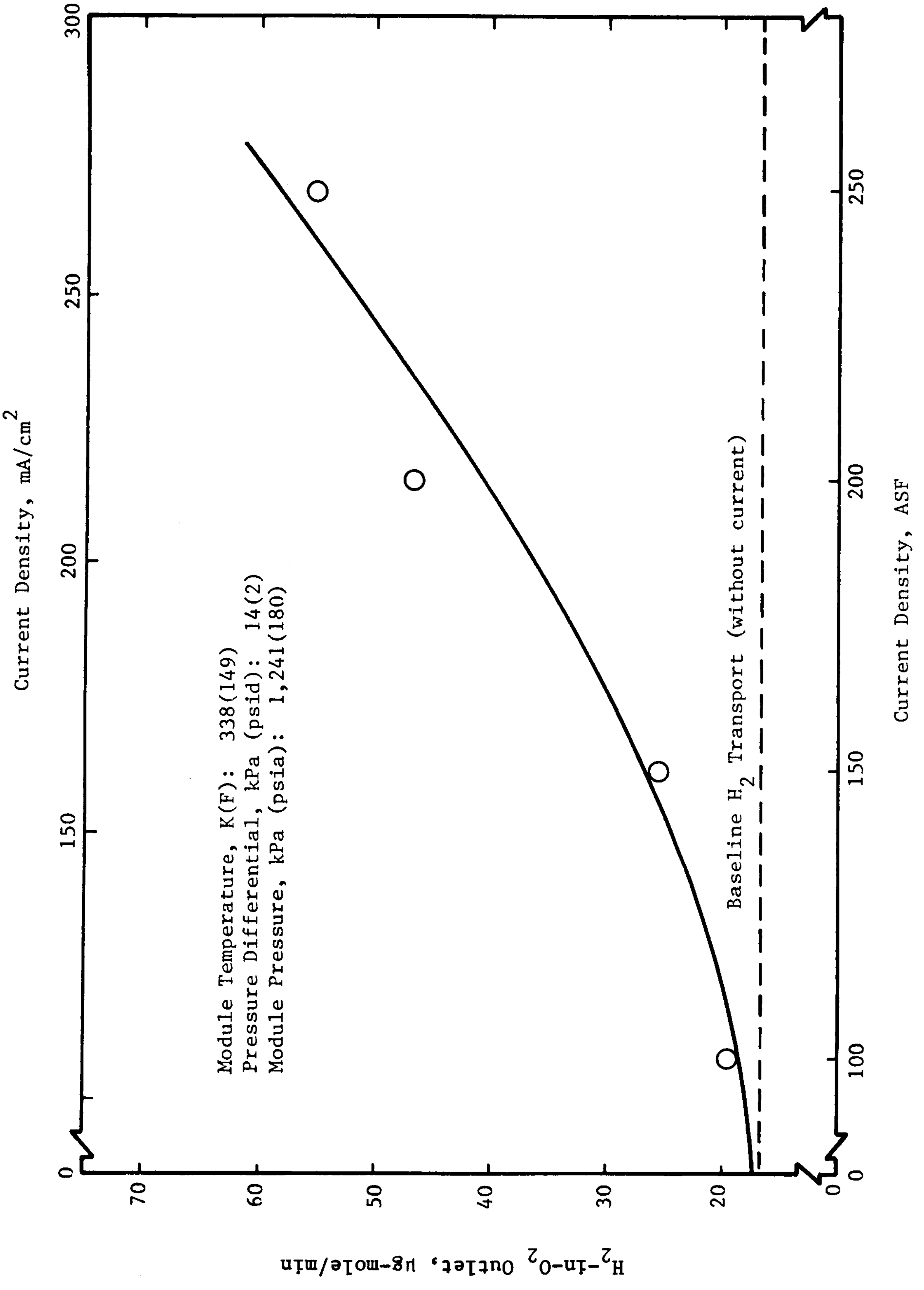


FIGURE 16 O_2-IN-O_2 OUTLET CONCENTRATION VERSUS CURRENT DENSITY FOR 0.0093 m^2 (0.1 ft^2) MODULE

The SFE-3 was then operated at a baseline current of 30 A, operating temperature of 336 K (145 F) and operating pressure of 1,241 kPa (180 psia) for 24 hours. Product gas purity measurements obtained throughout the test indicated average H_2-in-O_2 levels were 1,336 ppm with average O_2-in-H_2 levels of 19 ppm. The SFE-2 was initially operated at a baseline current of 30 A, operating temperature of 329 K (132 F) and operating pressure of 1,241 kPa (180 psia) for 48 hours. Product gas purity measurements were obtained throughout the test. Average H_2-in-O_2 levels were 1,046 ppm with average O_2-in-H_2 levels of 5 ppm. The SFE-2 was then operated at a baseline current of 30 A, operating temperature of 329 K (132 F) and operating pressure of 40 psia for six hours. Product gas purity measurements obtained throughout the test indicated average H_2-in-O_2 levels were 1,119 ppm with average O_2-in-H_2 levels of 12 ppm.

To evaluate impurities in the product gas streams due to permeation through the elastomeric parts of the cell (i.e., O-rings, seals, etc.), the lower pressure data was adjusted for the difference in operating temperature. The corrected results are shown in Table 11. Based on the data obtained from SFE-2 and SFE-3 testing, there is no significant effect of module pressure on product gas purity over the range tested.

Product Gas Purity as a Function of Temperature. Tests were conducted to measure the product gas purity as a function of temperature. The temperature in the SFE-2 was varied over the range of 328 to 336 K (130 to 145 F) at a constant current of 30 A. The H_2-in-O_2 level was monitored via the on-line gas chromatograph. As shown by the results plotted in Figure 17, there is an increase in product gas impurity level with increasing temperature. At 328 K (131 F), the H_2-in-O_2 level was 1,680 ppm. With temperatures increased to 336 K (145 F), the H_2-in-O_2 level increased to 2,285 ppm (an increase of 605 ppm). This increase in contamination is attributed to the change in gas diffusity through the module parts (O-rings, etc.) with increasing temperature. Using data contained in the Parker Co. O-Ring Handbook, an increase of almost 700 ppm for H_2-in-O_2 levels is estimated for H_2 diffusion through ethylene-propylene rubber, for a temperature increase from 328 to 339 K (130 to 150 F).

The Effects of Increasing the Module Size on Product Gas Purity. To determine the effects of increasing the module size on product gas purity, the 12-cell SFE-2 was operated at baseline conditions of 1,241 kPa (180 psia), 129 mA/cm^2 (120 ASF) and 329 K (132 F). The SFE-2 was then converted to 24-cells and operated under the same baseline conditions. The results are summarized in Table 12. These results show that doubling module size which will double the module voltage, hence driving "force" to electrical ground, will only marginally increase impurity levels. This is significant because it demonstrates that the primary source of impurities is gas permeation rather than stray electrolysis.

Evaluation of Recombiners for Product Gas Purification

The objective of this task was to evaluate (1) a commercially available H_2/O_2 recombiner and (2) an in-house recombiner design to reduce the already low levels of H_2-in-O_2 and O_2-in-H_2 to zero or near zero.

TABLE 11 SUMMARY OF SFE PRODUCT GAS IMPURITY VERSUS OPERATING PRESSURE PRACTICE

Unit	Pressure, kPa (psia)	Product Gas Impurity, ppm[a]	
		H_2-in-O_2	O_2-in-H_2
SFE-2	276 (40)	1,403	15
SFE-2	1,241 (180)	1,311	6
SFE-3	1,241 (180)	1,336	19
SFE-3	2,172 (315)	1,087	15

(a) Corrected to 145 F operation.

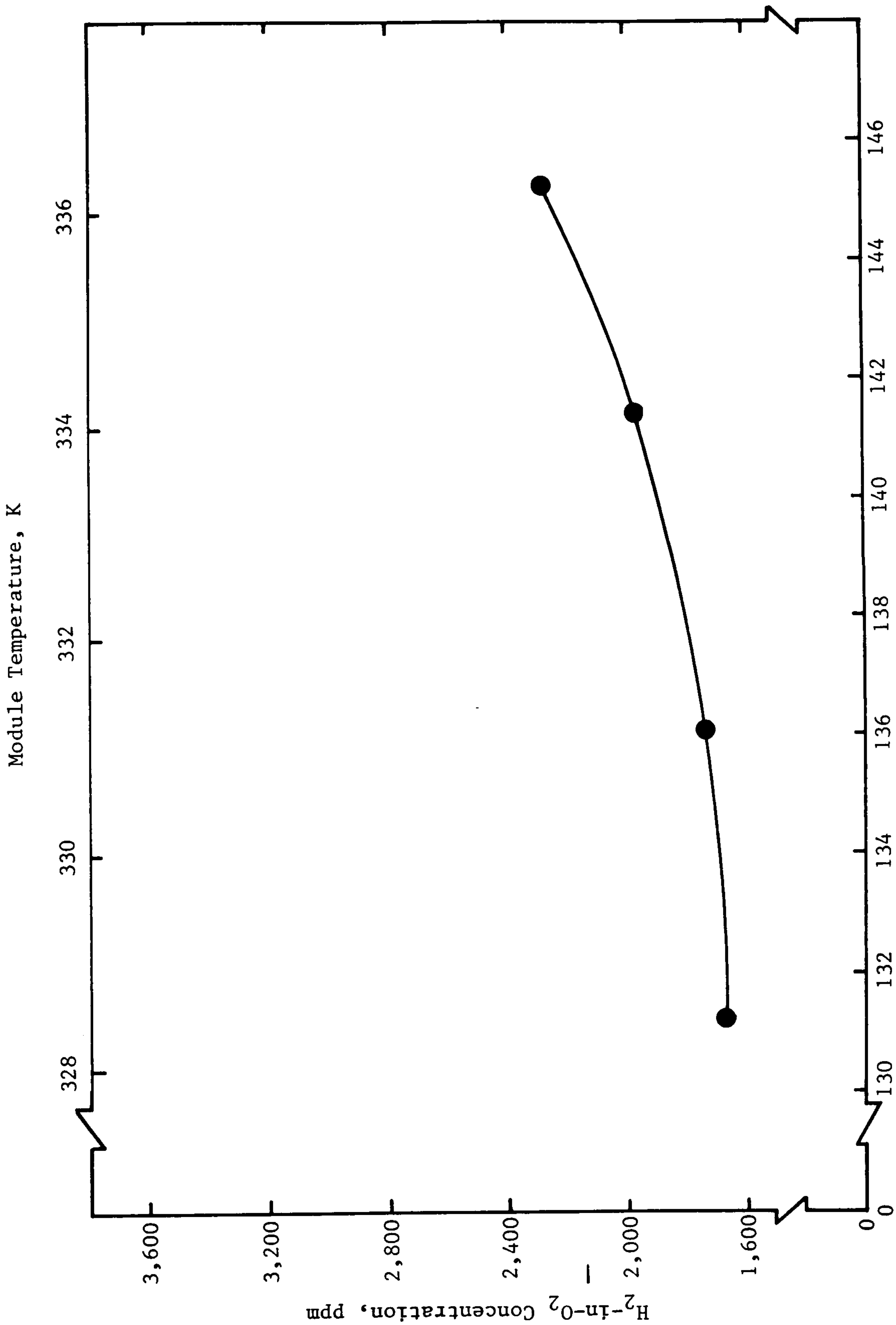


FIGURE 17 H_2-IN-O_2 CONCENTRATION VERSUS TEMPERATURE

TABLE 12 PRODUCT GAS PURITY AS A FUNCTION OF CELL STACK SIZE - SFE-2

No. Cells	Product Gas Impurity, ppm[(a)]	
	H_2-in-O_2	O_2-in-H_2
12	1,311	6
24	1,785	21

The commercial gas recombiner adapted with an auxiliary heating tape was tested on the O_2 product stream from both the SFE-2 (12-cell) and the WS-1 (5-cell) subsystems. The results are summarized in Table 13. Based on these results, a commercial recombiner could be used at nominal temperatures to remove the low levels of H_2 found in the electrolyzer product gas. As the O_2 production rate increases (12-cell versus 5-cell), slightly higher temperatures are required for complete removal of H_2. Increasing the pressure in the recombiner requires a higher temperature. Both of the results are consistent since the catalyst in the recombiner must be relatively dry (free from liquid water) to operate efficiently.

Testing of a Life Systems' built purifier was also conducted on the WS-1 subsystem. Using a catalyzed screen encased in a gas tight container, the H_2 level in the product O_2 was reduced from 4,800 to 3,200 ppm for ambient temperature operation. This result is comparable to the ambient temperature operation of the commercial recombiner with the Life Systems unit only 1/5 the size of the commercial unit. Although these recombiners can effectively reduce product gas impurities, they are not recommended since they constitute a potential ignition source.

Electrolyte Charging Management Practice

In order to insure individual cell performance uniformity, Life Systems evaluated and implemented an electrolyte charging management practice. To implement this practice, special test equipment was developed. This test equipment included a cell core charging fixture (see Figures 18 and 19), a delta pressure check fixture and a carbon dioxide (CO_2) free glove-box for final cell and module assembly. The electrolyte charging requirements are summarized below:

1. A single cell charge fixture will be utilized to complete the initial electrolyte charge of each unitized cell core.
2. The cell core will then be checked for O_2-to-H_2 delta pressure to 69 kPa (10 psid).
3. The single cell charge fixture will have provisions to pass 0 to 30 A through the cell core. When current is passed through the cell, the voltage of the cell core will be measured and if it falls within the acceptable performance band level, it will be accepted for final assembly into a cell frame and module.
4. After the cell core has been accepted it will be assembled into the cell frame.
5. The cell frame will then be placed in the delta pressure check fixture. In the fixture both the unitized feed core and the unitized cell core will be checked at 69 kPa (10 psid).
6. If the cell frame passes both delta pressure tests, it will then be incorporated into the module.
7. All of the above assembly and checkout tests will be conducted in a CO_2-free glove-box.

TABLE 13 RESULTS OF RECOMBINER EVALUATION (RESOURCE SYSTEMS, INC. MODEL RCP-10-2000-4)

Electrolyzer Unit	O_2 Production Rate, cm^3/min	Recombiner Temperature, K (F)	Recombiner Pressure kPa (psig)	Exposure Time, min	H_2-in-O_2 Product, ppm w/o Recombiner	H_2-in-O_2 Product, ppm w/Recombiner	Removal, %
SFE-2[a]	1,300	298 (76)	~6.9 (~1)	1,050	1,400	128	91
SFE-2	1,300	381 (226)	~6.9 (~1)	1,550	1,440	58	96
SFE-2	1,300	419 (295)	~6.9 (~1)	2,750	1,440	<40[c]	~100
WS-1[b]	600	396 (252)	~6.9 (~1)	5,795	5,080	<40[c]	~100
WS-1	600	449 (348)	1,138 (165)	1,475	6,860	<30[c]	~100

(a) A 12-cell module.
(b) A 5-cell module.
(c) Lower detectable limit of gas chromatograph.

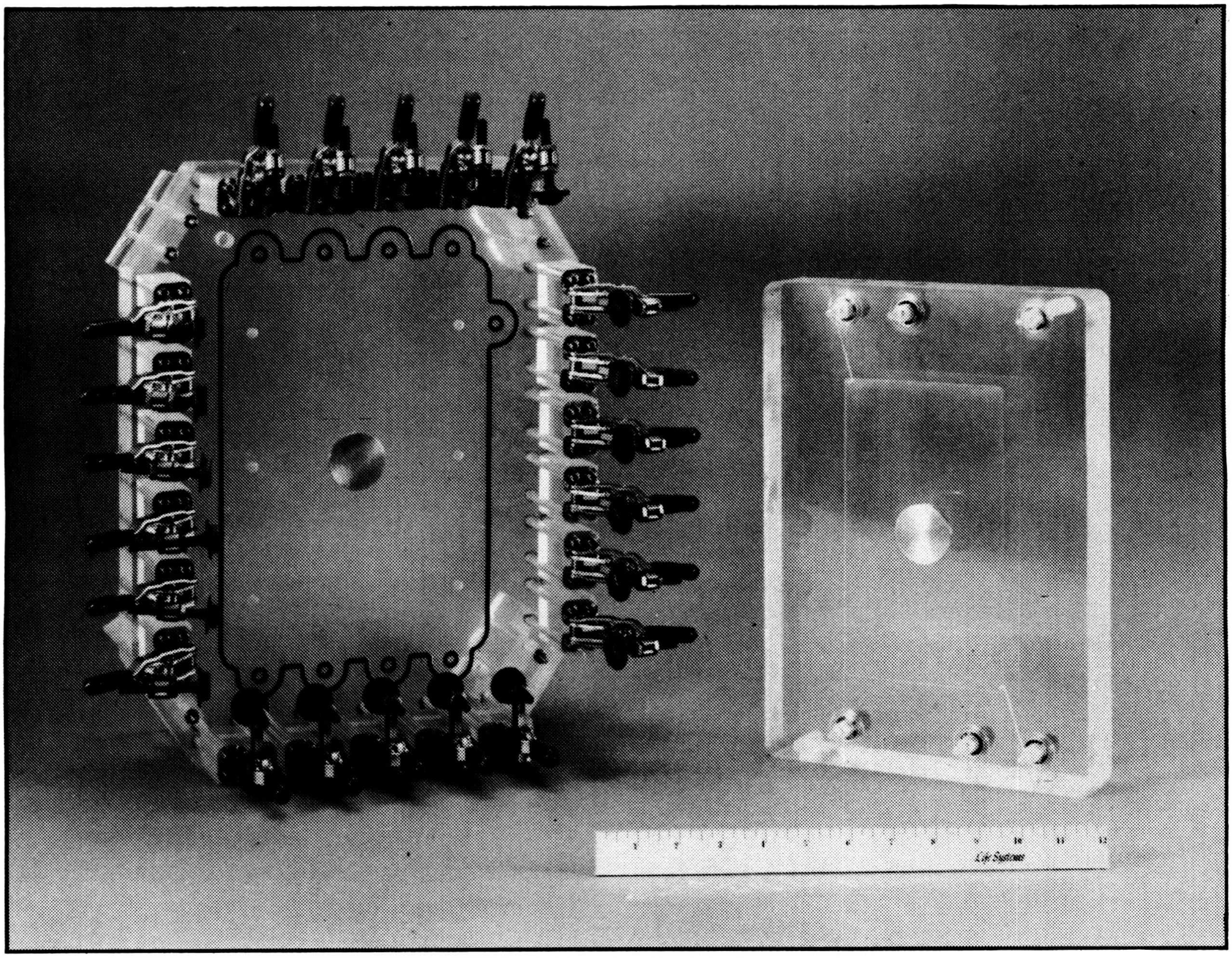


FIGURE 18 ELECTROLYTE MANAGEMENT CELL CORE CHARGING FIXTURE - UNASSEMBLED

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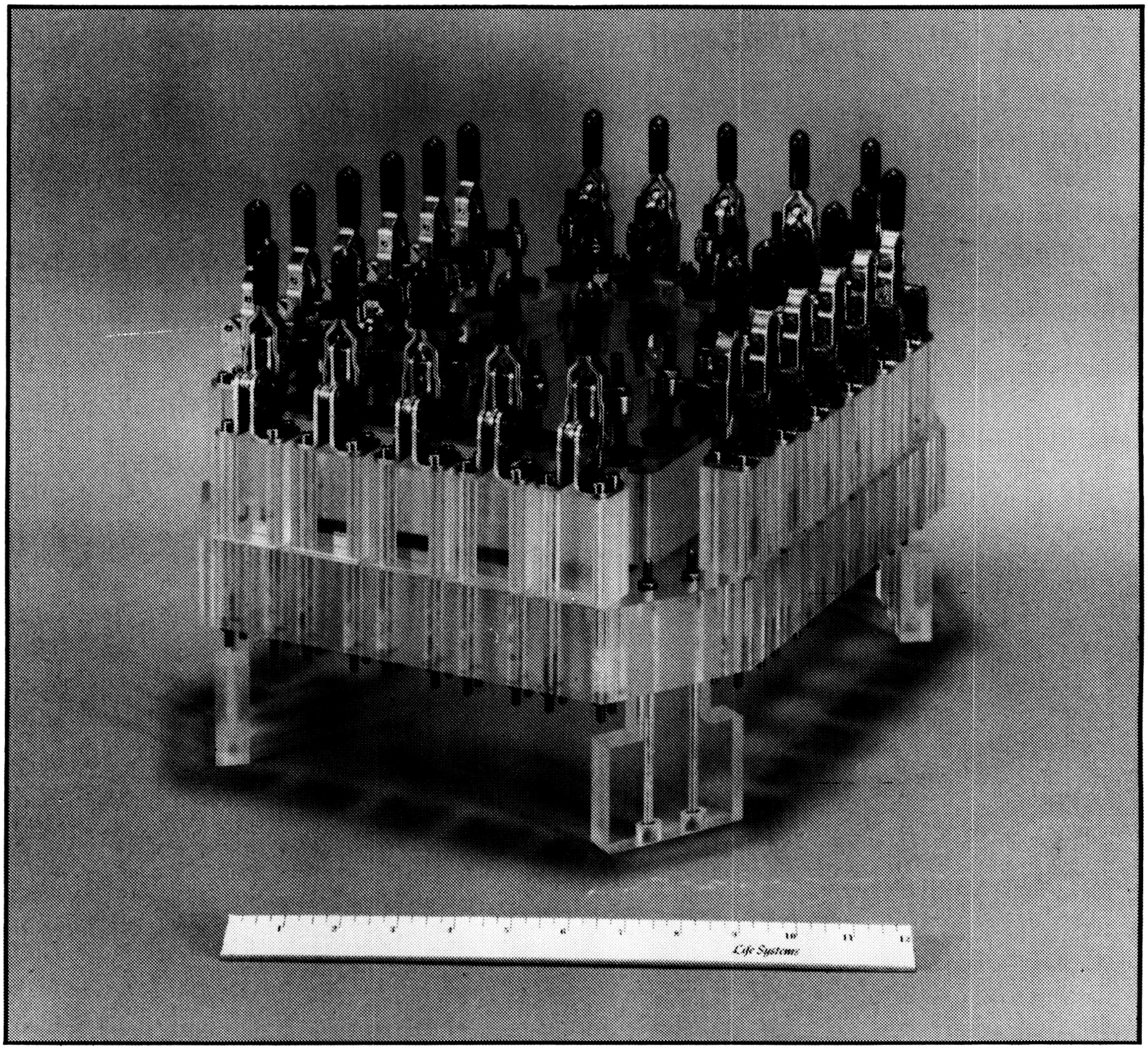

FIGURE 19 ELECTROLYTE MANAGEMENT CELL CORE CHARGING FIXTURE - ASSEMBLED

Cell cores were charged with electrolyte using the electrolyte management charging fixtures. The procedure consists of weighing the cell core dry, after electrolyte charging and after current (which induces electrolysis) has been applied. During the electrolysis phase of the procedure, the cell voltage is monitored.

Several electrolyte management tests were conducted to refine the procedures used and improve the results obtained. The series of tests identified fixture design improvements consisting of removal of rubber pads on the fixture clamps and replacement with hard plastic discs. This resulted in improved compression on the cell core. The tests with the modified fixture showed significant improvement in lowering the cell voltage.

Static Feed Electrolyzer Depressurization Improvements

In order to evaluate electrolyzer depressurization rates, tests were conducted to study the effects of dissolved gas in the SFE module water feed compartment. During the course of module operation, the feed water compartment fluid becomes saturated with dissolved H_2. Because this gas is in solution, it has no effect on the steady state water transport mechanism which transfers water from the water feed cavity to the electrode site. The dissolved H_2 gas can also pass back through the membrane from the water feed cavity into the H_2 cavity.

This dissolved gas can cause a pressure "hang up" as the module goes through the Normal-to-Shutdown-Transition when the module is depressurized. As the module pressure is decreased from 1,241 kPa (180 psia) to ambient, gas begins to come out of solution in the water feed cavity. If the gas contacts the water feed membrane, it simply passes through the membrane and exits through the H_2 cavity. However, the gas that does not come in contact with the water feed cavity can be partially trapped causing a residual pressure at shutdown.

Several methods were investigated to eliminate this pressure "hang up." The first method involved extending depressurization time to allow a larger quantity of gas a chance to come in contact with a water feed membrane and exit into the H_2 cavity. This technique consists of modifying the normal straight line depressurization to a straight line depressurization interrupted by three distinct plateaus or pauses in the depressurization. Based on tests, this cycle decreased the residual pressure in the water cavity from 103.4 to 138.0 kPa (15 to 20 psig) to 27.6 to 55.2 kPa (4 to 8 psig). This depressurization algorithm was incorporated into the software of the 12-cell SFE. This algorithm was implemented into the Normal to Shutdown mode transition. Figure 20 shows a typical depressurization of the SFE-2. Shown on the plot are P1 (H_2 system pressure) and P3 (water cavity pressure) versus operating time during the transition to Shutdown. Based upon the results of this test, the new depressurization cycle demonstrated that residual pressure in the water feed cavity had been reduced to within an acceptable pressure level.

Another method of eliminating residual gas pressure buildup from the water feed cavity was also investigated. This method relied on a volume reduction of water in the water feed cavity from the present volume of 30 cm^3 (1.8 in^3)

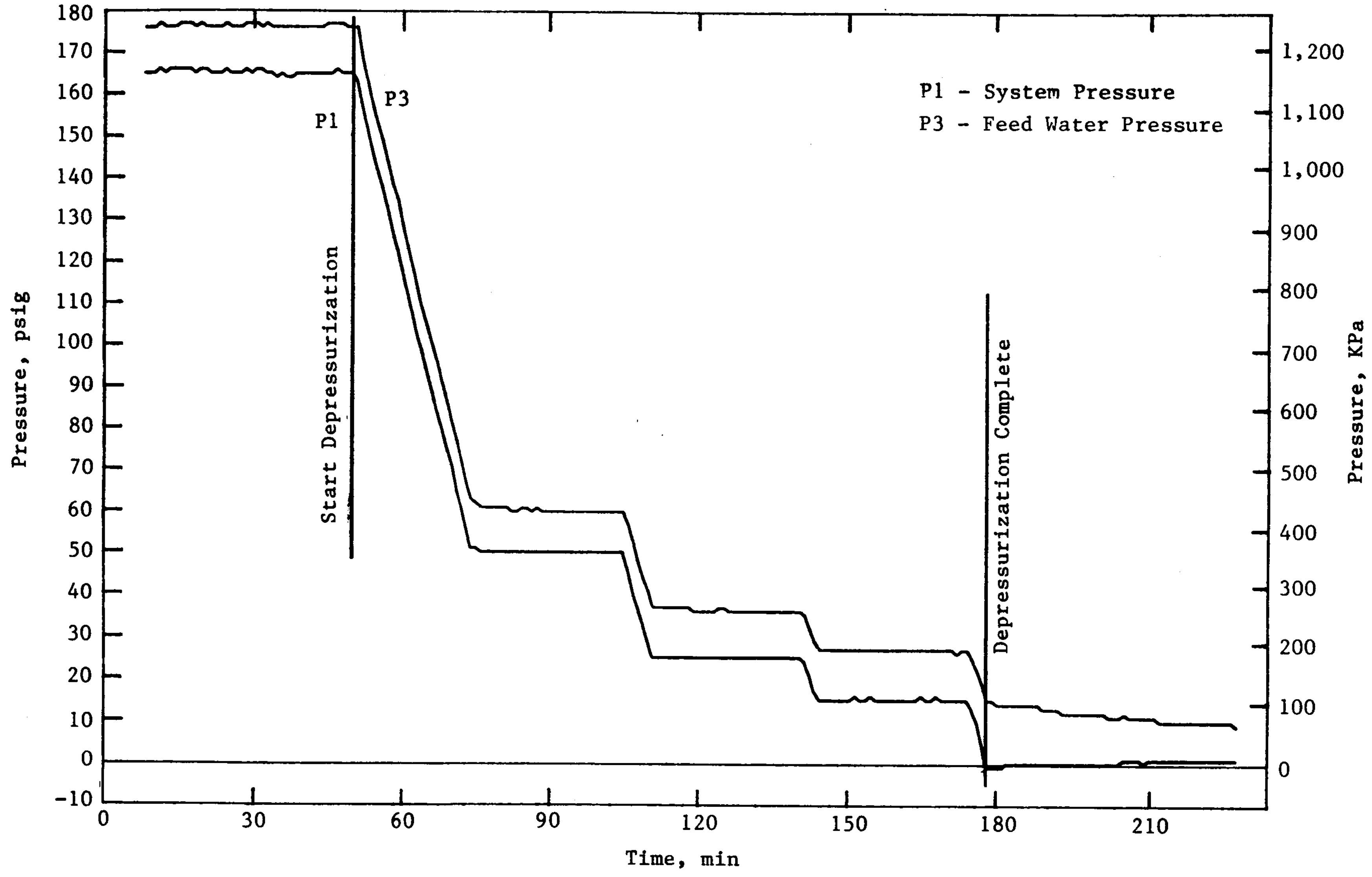

FIGURE 20 SFE-2 DEPRESSURIZATION CONTROL ALGORITHM IN NORMAL TO SHUTDOWN TRANSITION

to approximately 10 cm^3 (0.6 in^3). With this small volume of water in the water feed cavity, the gas liberated is significantly reduced. This method is compatible with the new baseline SFE configuration of not using an active thermal control technique. The fluid in the water feed compartment (at the low 10 cm^3 (0.6 in^3)) volume is always static in the cell hence all liquid is in contact with the gas permeable membrane (i.e., none exists in the plumbing, heat exchanger, etc.). Also, the shallowness of the cavity insures that dissolved gas bubbles stay in contact with the membrane and exits into the H_2 compartment.

Design and Fabrication of a Fluid Charging Fixture

In order to improve and simplify SFE fluid charging, the design and fabrication of a fixture was undertaken and completed. The design requirements of this fixture were as follows:

- Capability to use either water or 25% potassium hydroxide as the module fluid
- Fluid storage capability within the charge fixture of up to two liters
- Ability to vacuum evacuate the three types of compartments (O_2, H_2 and water) of the SFE module simultaneously
- Ability to back-fill the SFE circulation loop with fluid while maintaining vacuum on the H_2 and O_2 cavities of the module
- Use of a chemical bed to remove CO_2 from the repressurization air used in the fluid charging procedure

A mechanical schematic for the SFE fluid charging fixture is shown in Figure 21.

Static Feed Electrolyzer Definition and Characterization

The third major program task was directed at evaluating, through analyses and tests, the operating characteristics of the three-compartment cell based SFE. The objective was to further simplify the SFE's operation (from projected hardware procurement through on-orbit startup). Multi-cell module and system hardware as well as special test fixtures were developed to verify the simplified concepts.

In addition to optimizing SFE operation, the results of the analyses and testing were also used to design the integrated mechanical components that incorporated these specifications.

Unitized Cell Core and Feed Core Test Apparatus

To insure uniformity and integrity of unitized cell cores and feed cores, a special test apparatus was developed. The 0.023 m^2 (0.25 ft^2) cell size was used for the design of this test apparatus. The requirements of the unitized cell core and feed core test apparatus included: (1) one design for both the feed core and cell core with the use of different inserts to accommodate the different cores, (2) easy assembly, operation and disassembly of the test apparatus to ensure quick turnaround times and (3) visual inspection capability to identify a defective core.

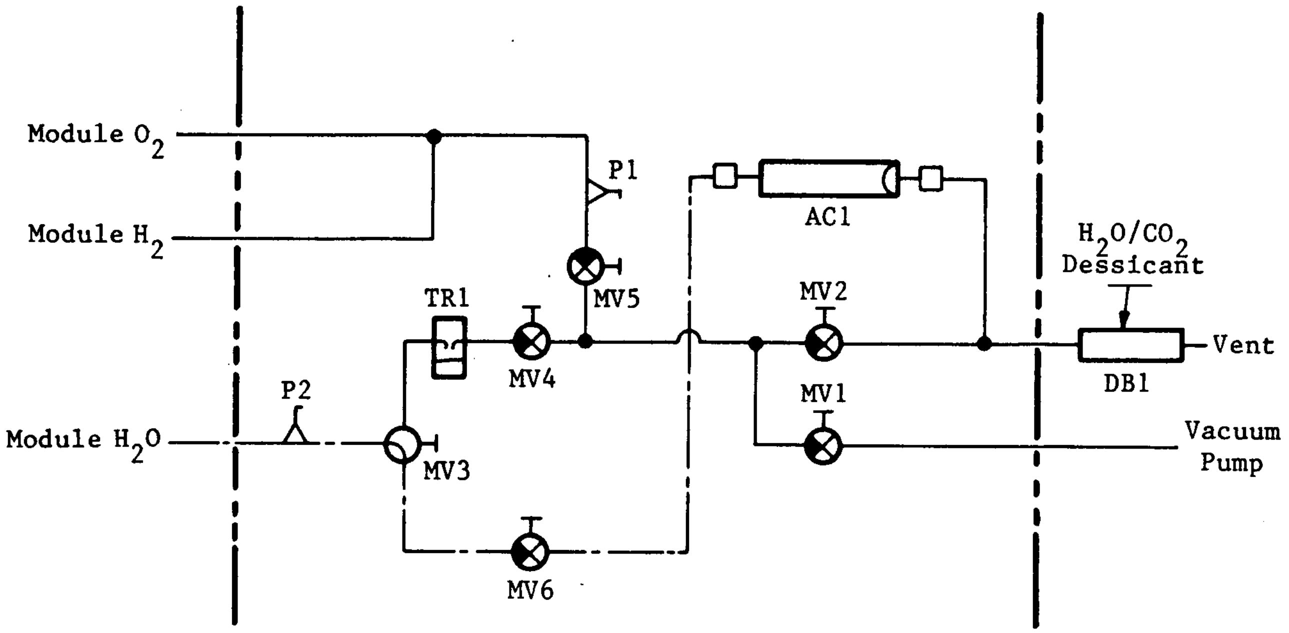

FIGURE 21 MECHANICAL SCHEMATIC OF SFE FLUID CHARGING FIXTURE

To meet these requirements, the lower plate and the upper plate of the apparatus were constructed of acrylic and polished for viewing clarity. Toggle clamps were utilized to facilitate easy assembly and disassembly. The apparatus and the location of the toggle clamps is shown in Figure 22. Cores were successfully tested for delta pressure and current carrying capabilities.

Multi-Cell Module and Test Equipment

The multi-cell test equipment used for this program included a 12 to 24-cell module used in a system designated "SFE-2"; a five-cell module based system, the WS-1; mechanical Test Support Accessories (TSA); a central power simulator; and a Performance Display Unit (PDU). A photograph of the SFE is shown in Figure 23. Initially the SFE-2 contained a 12-cell module. A contract modification provided for the number of cells to be increased to 24.

Multi-Cell Testing

Multi-cell testing was conducted to characterize and expand the operating regions of the new three-compartment 0.023 m^2 (0.25 ft^2) cell and to optimize system performance and reliability. The major operational concepts investigated included startup/shutdown, pure water static feed, thermal control with and without the TCA and/or heater, as well as alternate system pressure and differential pressure regulation techniques. These concepts are discussed below.

Startup/Shutdown Testing. The purpose of the startup/shutdown tests with the multi-cell SFE was to simulate shutdowns of various causes and durations and to demonstrate the flexibility of the SFE. Causes of shutdowns included several operator-induced alarm signals and power failures. Scheduled shutdown durations ranged from one-half to four days prior to restart. Thermal and pressure response characteristics besides typical performance aspects were investigated. Specifically, the following actions were completed.

1. After operating in the Normal mode for 215 hours, a transition to Shutdown was initiated via operator command. The SFE then remained in Shutdown for 30 minutes. A transition back to Normal mode was successfully completed without any effect on SFE operating performance.

2. After operating in Normal mode for 187 hours, a transition to Shutdown was initiated via operator command. The SFE remained in Shutdown for 30 minutes. A transition back to Normal mode was successfully completed without any effect on SFE operating performance.

3. After operating in Normal mode for 138 hours, the SFE was again deliberately sent to Shutdown mode. The SFE remained in Shutdown overnight (16 hours) prior to restart. The longer duration in Shutdown mode is important because the module completely cools to ambient temperature within this time period. Another transition back to Normal mode was successfully completed.

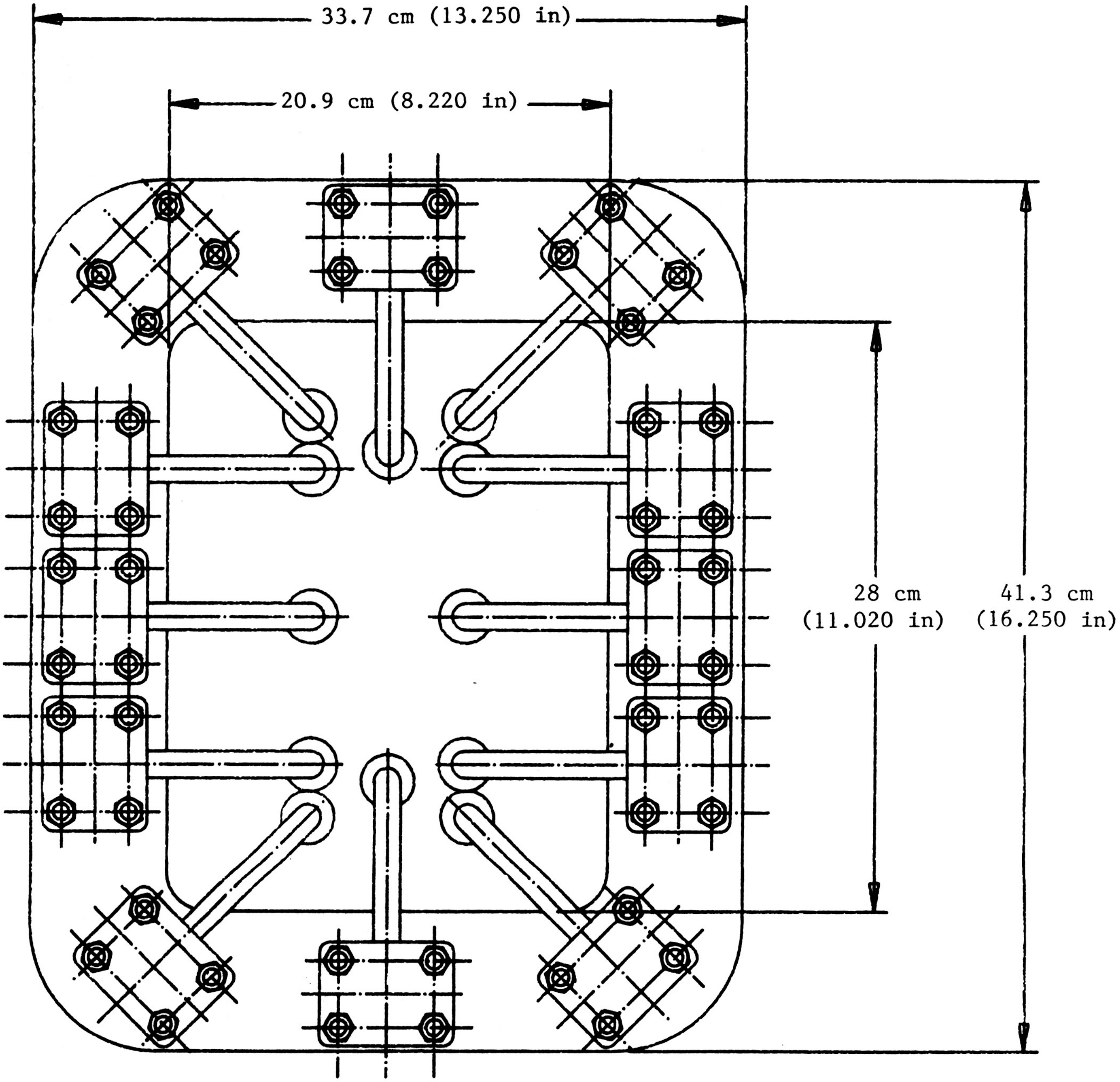

FIGURE 22 0.023 m^2 (0.25 ft^2) UNITIZED CELL CORE AND FEED CORE TEST APPARATUS

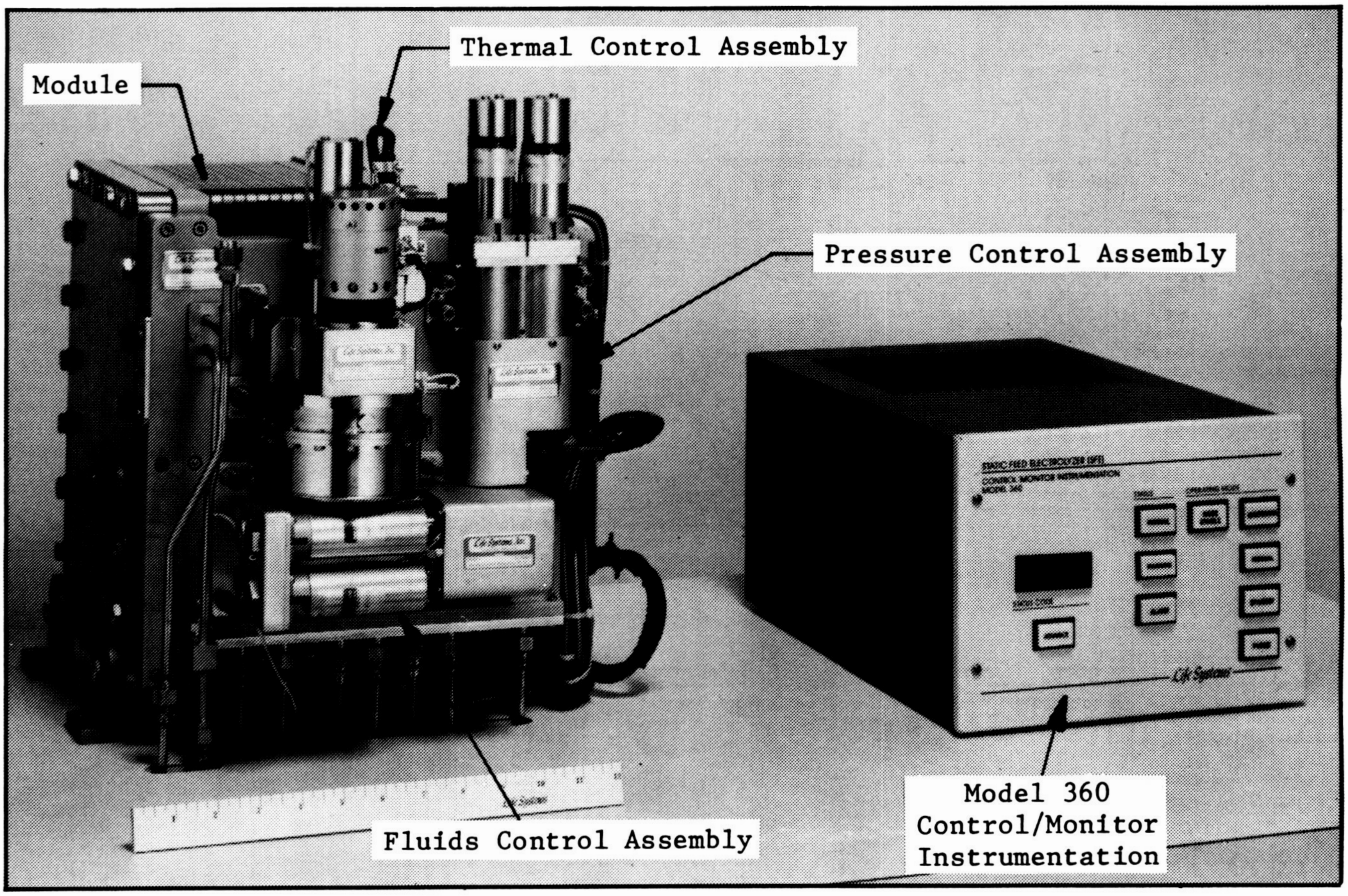

FIGURE 23 SFE-2 SUBSYSTEM HARDWARE

4. While operating in Normal mode, a building power failure was simulated by turning the SFE TSA "power" switch to "off." This action resulted in complete power removal from the SFE and the 360 C/M I. The function of the backup N_2 purge valves was checked out during this activity as the subsystem remained at pressure in the Unpowered mode for four hours. When power was reapplied, the subsystem completed the Unpowered to Shutdown mode transition. The SFE was then immediately restarted and the transition back to Normal mode was successfully completed.

5. After operating in Normal for 149 hours, the SFE was given the opportunity to remain in Shutdown mode for four days. The subsystem was successfully restarted after this time period with no resulting loss in performance.

Pure Water Static Feed Testing. An evaluation of the performance characteristics of the water feed membrane using a 0.023 m^2 (0.25 ft^2) single-cell module was initially proposed. Testing revealed that the water feed characteristics of the single-cell test stand (Life Systems' TS-131) did not duplicate the water feed characteristics of the SFE-2 subsystem. Thus, representative feed membrane evaluations were not possible with the single-cell module.

As a result, single-cell testing was eliminated and instead testing of the WS-1 subsystem was performed to characterize pure water noncirculating feed in the operation of a 5-cell, 0.023 m^2 (0.25 ft^2) module. The lack of feed water circulation provides for a totally passive and static control concept by using waste module heat to maintain module temperature. Total test time on the system in this configuration was 3,120 hours. Initial testing emphasized the optimization of the startup current algorithm to permit the module to warm up at a rate which maintains stable cell operation. Figure 24 depicts the initial WS-1 startup algorithm. After maintaining a constant current of 10 A on the module during system pressurization, module current is ramped up as a function of the cell temperature.

A second WS-1 startup control algorithm is depicted in Figure 25. After maintaining a constant current of 10 A on the module during system pressurization, module current is ramped up as a function of time. This algorithm removes the constraint of increasing current based on the cell temperature. Several subsequent startups were repeated using the algorithm and showed satisfactory results.

System Thermal Control Operating Concepts. In the original configuration, the SFE-2 utilized a 50 W cartridge heater embedded in the circulating feed water loop. The 50 W heater added heat to the circulating loop fluid warming the module to its operating temperature of 329 K (132 F). Extra heat was rejected through a heat exchanger and through losses in the plumbing.

It was desired to completely eliminate the need for the cartridge heater to conserve power. A test was conducted on the WS-1 to demonstrate that the external heat source can be eliminated. This test was also designed to prove the ability of the module to startup with a pure water static feed concept.

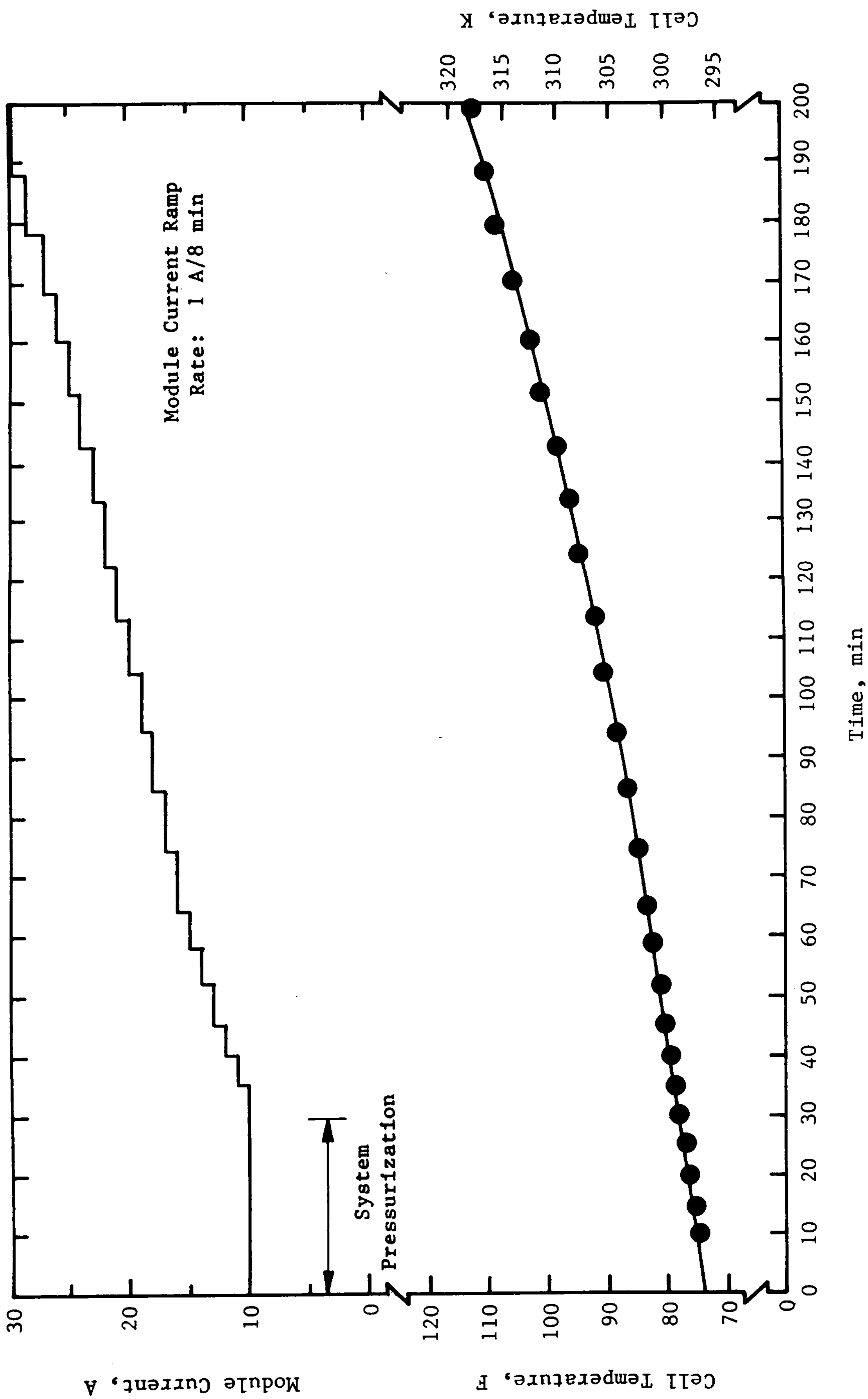

FIGURE 24 CELL TEMPERATURE AND MODULE CURRENT VERSUS TIME - WS-1 STARTUP ALGORITHM (FIRST)

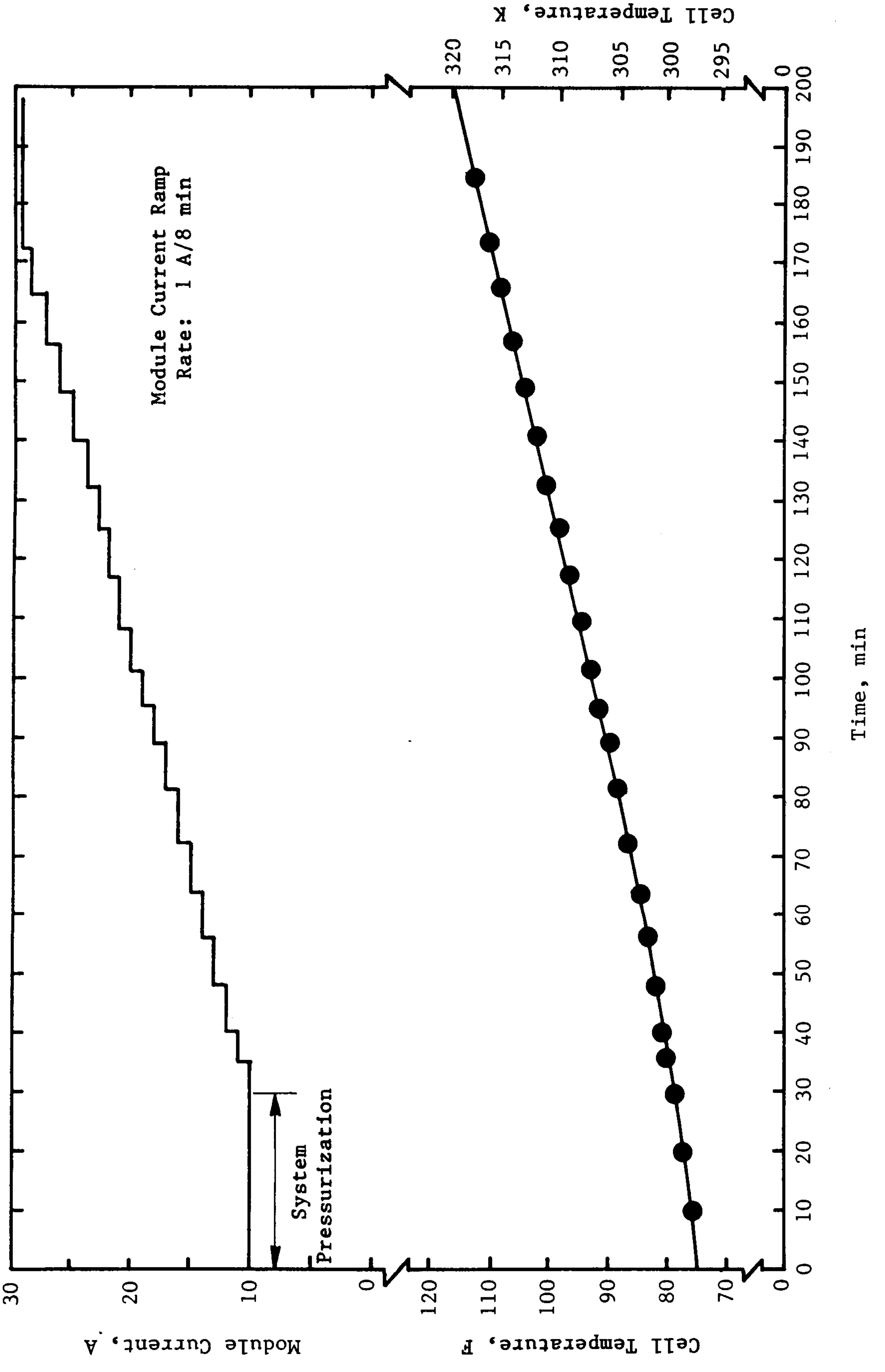

FIGURE 25 CELL TEMPERATURE AND MODULE CURRENT VERSUS TIME - WS-1 STARTUP ALGORITHM (SECOND)

The WS-1 test results are shown in Figure 26 for a typical Shutdown-to-Normal transition without water circulation and external heat. The average cell voltage steadily decreased as module temperature (due to the heat generated) increased. The WS-1 nominal average cell voltage leveled at approximately 1.63 V and continued to run for over 400 hours at that constant cell performance.

System Pressure Control Operating Concepts. In the original configuration, the PCA in SFE-2 contained two motor-driven regulators. To simplify system operation, increase reliability and decrease power consumption, elimination of one of the motors was investigated. It was proposed that the O_2 regulator be slaved to the system (H_2) pressure regulator. To accommodate the dynamic nature of pressure ramping during startup, the pressure control algorithm was modified to halt closing the system (H_2) regulator when the differential pressure sensor dropped below 6.89 kPa (1.0 psid) and continue when this pressure recovered to above 6.89 kPa (1.0 psid).

A test run of the above concept was conducted on the SFE-2 first without the module. The drive motor of the O_2 regulator was disabled to simulate a slave regulator. Sensor readings including system pressure and differential pressure were stored on a disk in the PDU of the SFE-2 TSA. This data is shown in Figures 27 and 28. It can be seen that during startup the differential pressure fluctuated between 13.8 kPa (2.0 psid) and 3.45 kPa (0.5 psid) and stabilized at 19.3 kPa (2.8 psid) after system pressure reached the desired operating level of 1,138 kPa (165 psig). These similar readings were smoother during depressurization. The test results confirmed that a slave regulator can be used in the PCA, thereby reducing by one the number of motors required and achieving the goal of overall simplification.

As a result, it was recommended that in the next generation PCA design, one motor can be eliminated and the "slave" regulator concept employed.

Alternative System Pressurization Technique Development

In an effort to simplify hardware design and operation, four alternative system pressurization control algorithms were tested. The purpose of this series of tests was to develop a pressurization and depressurization technique for the SFE-2 which reduces or eliminates the need for an external pressurization source such as N_2.

The four techniques were:

1. Self-pressurization and depressurization with flowing product gases
2. Pressurization and depressurization using "non-flowing" N_2
3. Pressurization and depressurization using "non-flowing" product gases
4. Modified self-pressurization and depressurization using flowing product gases

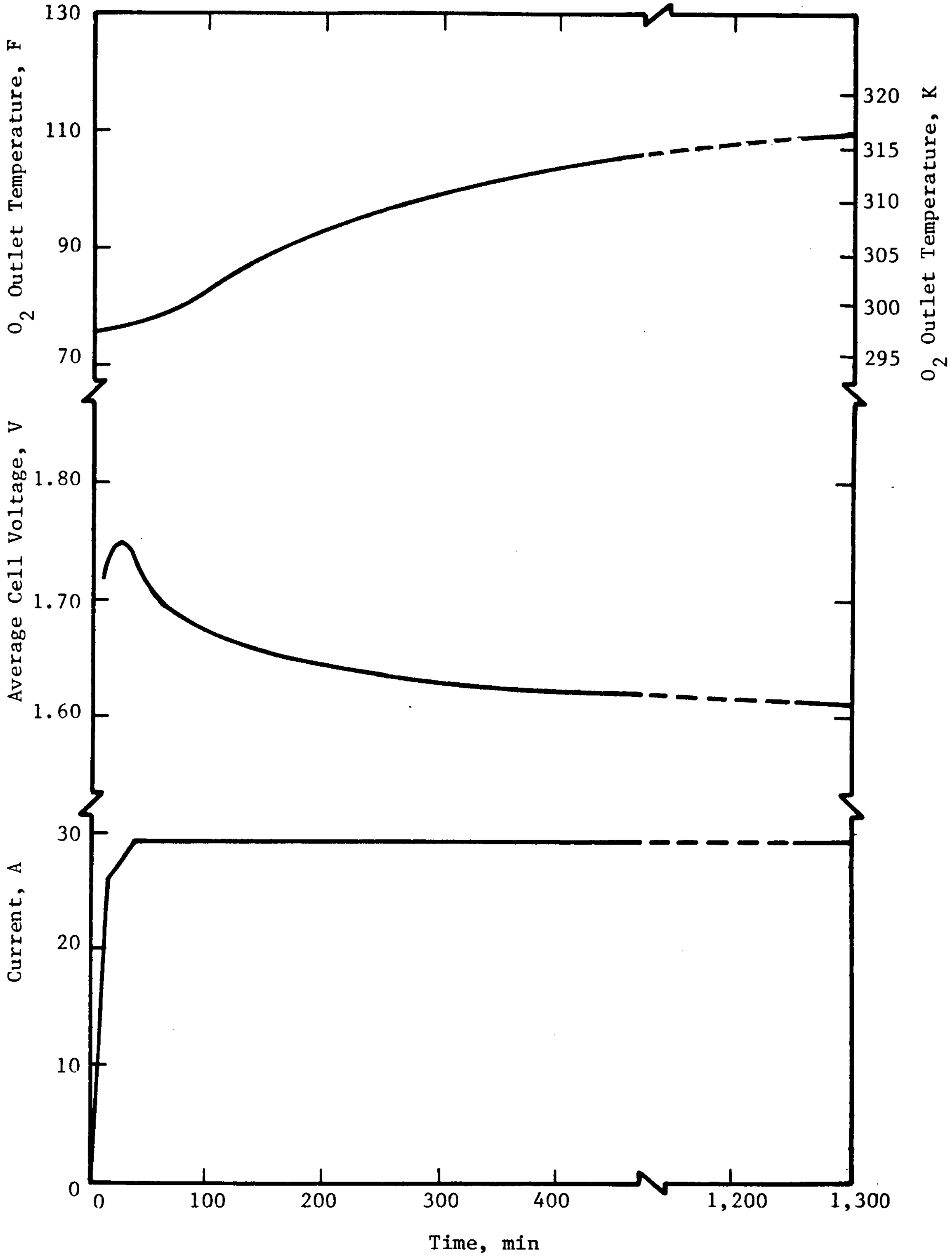

FIGURE 26 WS-1 SHUTDOWN TO NORMAL TRANSITION WITHOUT WATER CIRCULATION AND EXTERNAL HEAT

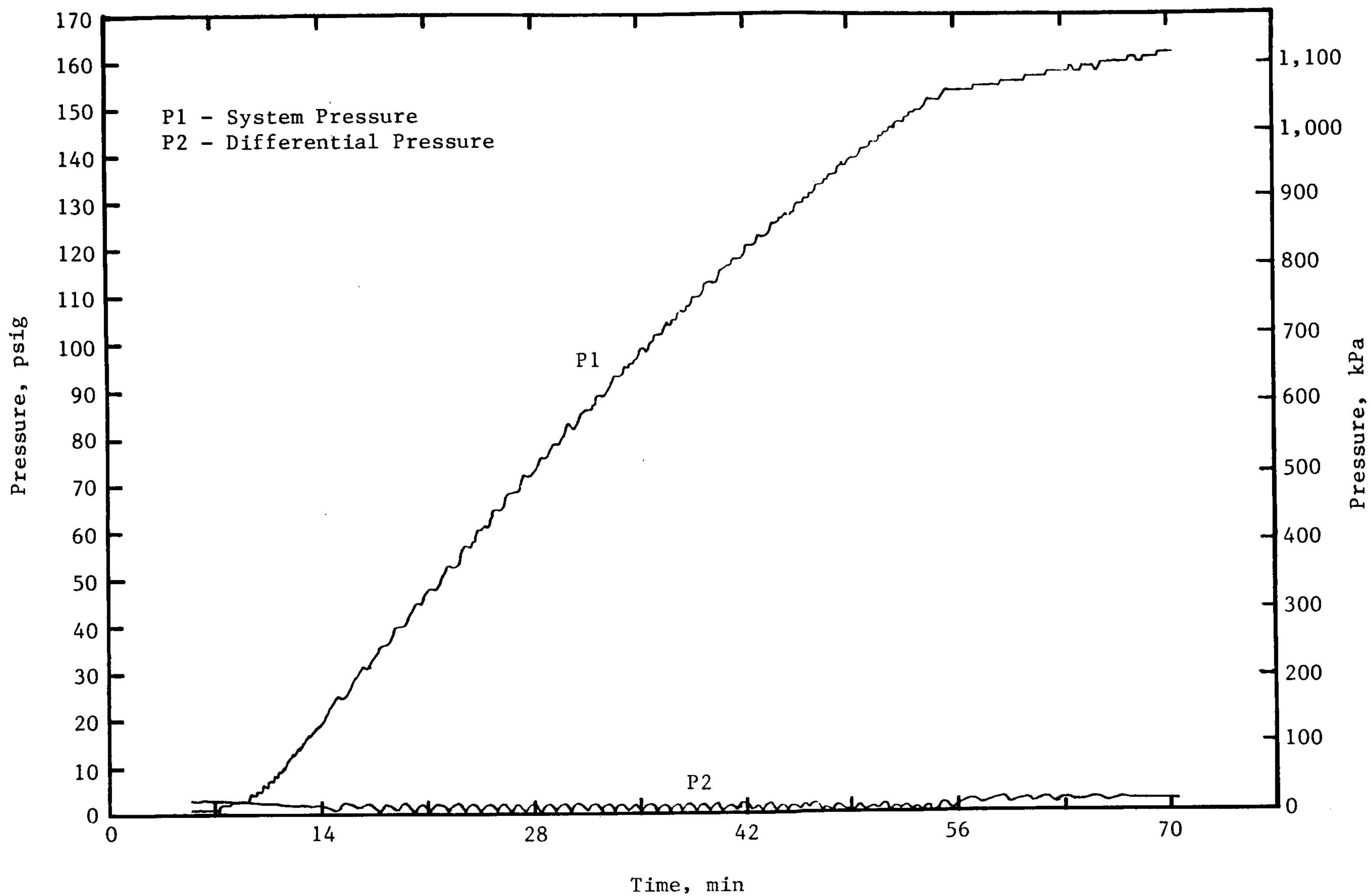

FIGURE 27 STARTUP PERFORMANCE OF PCA WITH SINGLE MOTOR

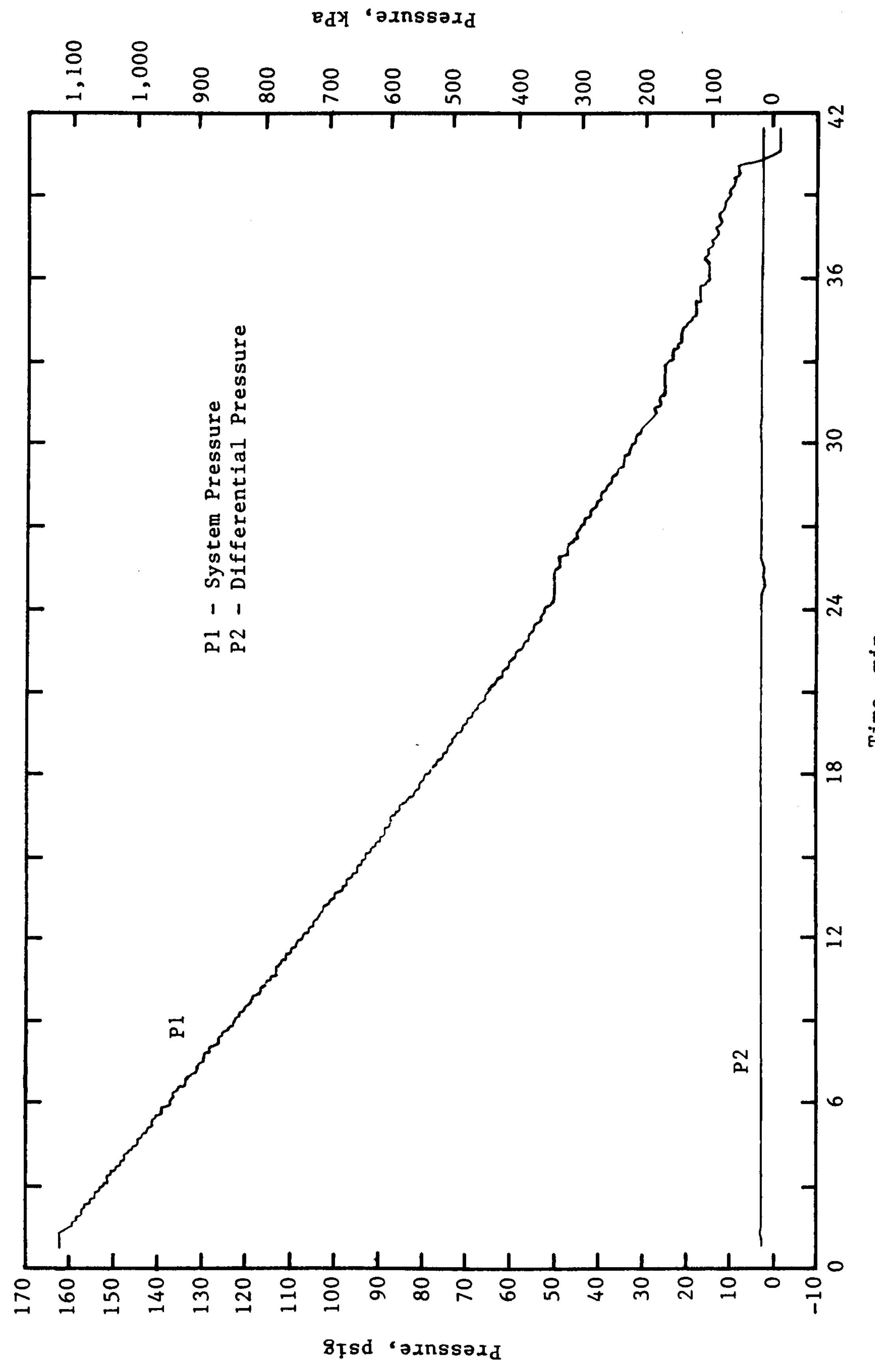

FIGURE 28 SHUTDOWN PERFORMANCE OF PCA WITH SINGLE MOTOR

Self-Pressurization with Flowing Product Gases. During the first test the ability of the SFE-2 module to self-pressurize on module generated flowing H_2 and O_2 was evaluated. The term "flowing" refers to the fact that the system pressure regulator (PR1) is initially in a fully open position and is gradually closed while product H_2 and O_2 is vented out of the subsystem. When the system pressure level enters its control band at 1,138 kPa (165 psig), PR1 stops closing and the SFE-2 enters the Normal mode at the baseline operating conditions of 1,138 kPa (165 psig), 30 A and 331 K (135 F). The pressurization and depressurization sequence is depicted graphically in Figure 29. This figure depicts the rate of pressurization as the H_2 system pressure (P1) increases linearly from ambient pressure to 1,034 kPa (150 psig) in approximately 45 minutes. The algorithm then slowly raises the pressure from 1,034 to 1,138 kPa (150 to 165 psig) over the next 20 minutes, using generated O_2 and H_2.

Following the pressurization cycle, the SFE-2 was run for several hours. Performance of the cells was within normal operating ranges. During a Normal-to-Shutdown transition, the module current was first lowered from 30 A to 8 A to provide a low level of product gas. This permitted the module pressure (P1) and feed water pressure (P3) to decrease properly. When the module pressure returned to ambient, the module current was turned off. The rate of system depressurization is faster using this algorithm compared to the baseline algorithm which incorporates the three "waits" to reduce the P1 to P3 differential pressure observed during baseline shutdown.

Non-Flowing N_2. The second alternative system pressurization control algorithm evaluated the ability of the SFE-2 to self-pressurize with non-flowing inert, N_2 gas. The term "non-flowing" refers to the fact that the system pressure regulator (PR1) is initially moved to a fully closed position as inert gas is introduced into the subsystem for pressurization. PR1 is only opened when the subsystem has reached the system pressure control band. All inert gas flowing into the subsystem on the H_2 side is used to increase system pressure (P1) and no inert gas is vented through the H_2 vent until the system pressure control band is reached. On the O_2 side a minimal amount of inert gas is vented through the O_2 vent during the pressurization as the differential pressure regulator (PR2) opens to maintain the O_2-to-H_2 differential pressure.

During the depressurization portion of the test, the depressurization algorithm was modified to minimize the amount of N_2 used. At the start of the Normal-to-Shutdown transition, the module current was turned off and the system pressure regulator immediately opened allowing the system pressure to decrease. No N_2 purge was introduced into the subsystem until the system pressure decreased to ambient pressure. At that time a ten minute N_2 purge was used to purge the O_2 and H_2 cavities of any remaining product gas.

The pressurization and depressurization sequence is depicted graphically in Figure 30. This figure shows the rate of pressurization as the H_2 pressure (P1) increases linearly from ambient pressure to 1,034 kPa (150 psig) in 15 minutes. The algorithm then raised the pressure from 1,034 to 1,138 kPa (150 to 165 psig) in 10 minutes using module generated O_2 and H_2. The figure also depicts the rate of depressurization as the H_2 pressure decreases linearly from 1,138 kPa (165 psig) to ambient in approximately 39 minutes.

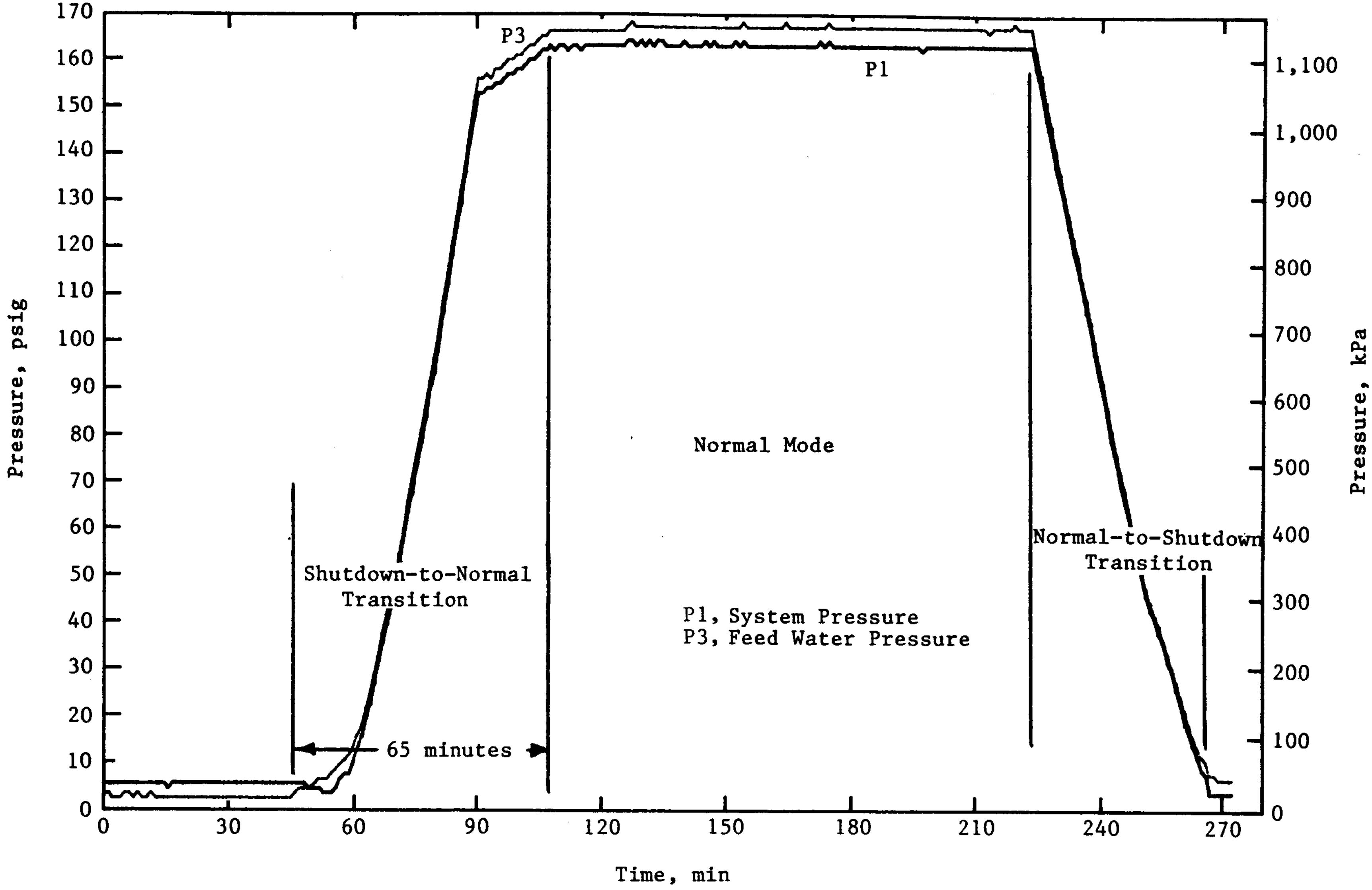

FIGURE 29 SFE FEED WATER PRESSURE AND SYSTEM PRESSURE VERSUS TIME: SELF-PRESSURIZATION (FLOWING O_2 AND H_2) ALGORITHM

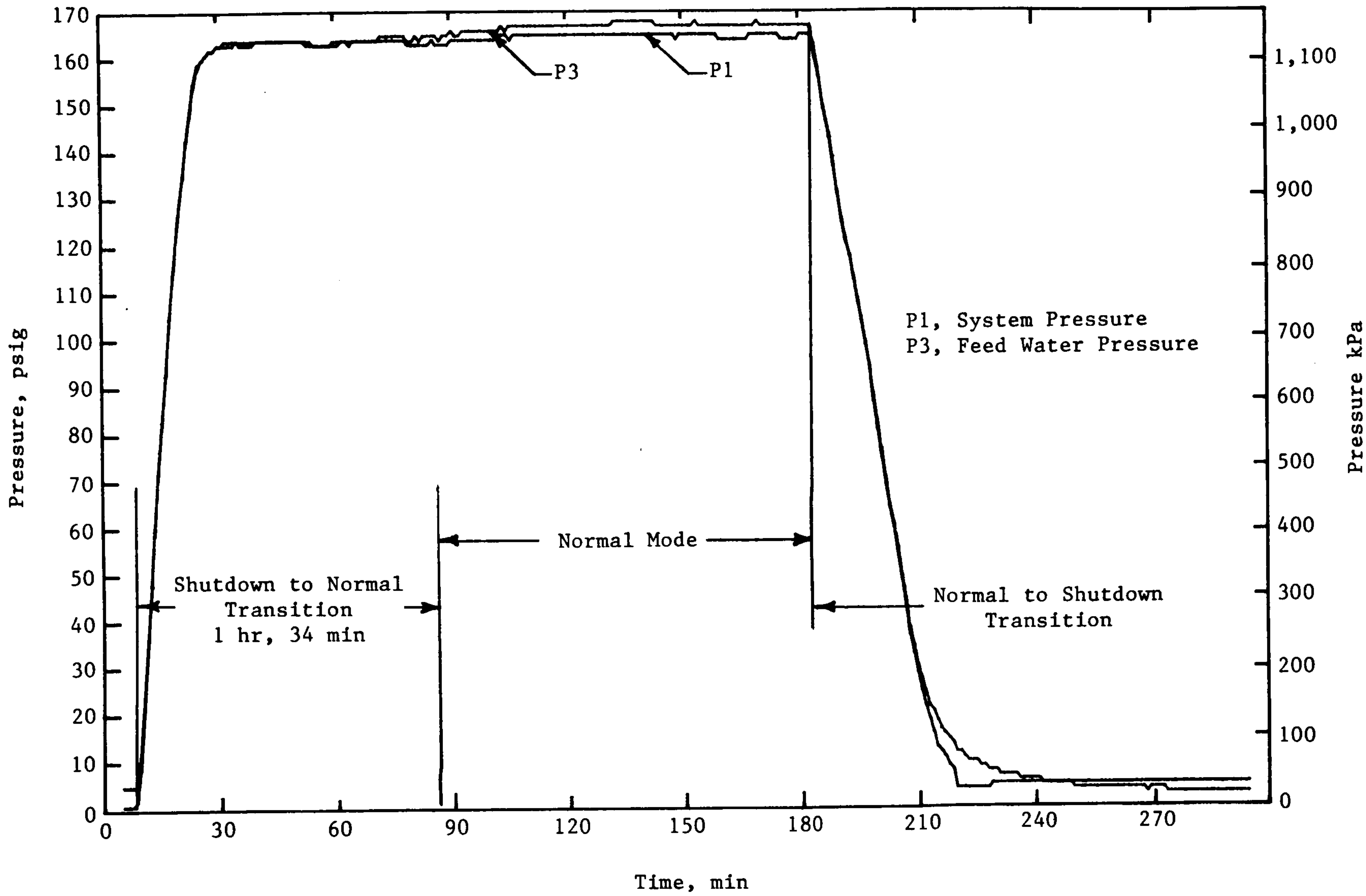

FIGURE 30 SFE FEED WATER PRESSURE AND SYSTEM PRESSURE VERSUS TIME: NONFLOWING INERT GAS PRESSURIZATION ALGORITHM

The non-flowing inert gas pressurization algorithm reduced the amount of inert gas by 70%.

Non-Flowing Product Gases. Testing of the third alternative pressurization algorithm was performed to verify the ability to startup with non-flowing product gases. The term "non-flowing" refers to the fact that the system pressure regulator (PR1) was initially moved to a fully closed position as module generated gas pressurized the subsystem. PR1 was only opened when the subsystem reached the system pressure control band. All H_2 generated was used to increase system pressure (P1) with very little gas vented through the H_2 vent until the system pressure control band was reached. On the O_2-side a minimal amount of gas was vented through the O_2 vent during the pressurization as the differential pressure regulator (PR2) opened to maintain the O_2-to-H_2 differential pressure.

For completion of this test, modifications were made to the SFE-2 to increase the H_2-side volume and decrease the O_2-side volume. Ideally, an H_2-side volume to O_2-side volume ratio of 2:1 is desired. The O_2 gas side of the water tank remained the largest contributor to total O_2-side volume so a low O_2 volume water tank was added to the SFE-2 to decrease the O_2-side volume. Several gas cylinders were added to the H_2-side to increase the H_2-side volume. Because it has always been a goal of SFE subsystem design to minimize the amount of H_2-side volume, a final H_2-side to O_2-side volume ratio of 1.65:1 was achieved. With the SFE-2 subsystem utilizing an O_2-referenced water tank, the addition of any more H_2-side volume was impractical. In systems that do not reference the water tank to O_2 gas it is achievable to design a H_2-side to O_2-side volume ratio of 2:1.

Twenty-five minutes into the Startup transition, the SFE-2 was shutdown due to an O_2-to-H_2 differential pressure of -17.9 kPa (-2.6 psid). The test proved that in order for a nonflowing O_2 and H_2 startup pressurization to be feasible it is critical to have a H_2-side volume to O_2-side volume ratio in the subsystem of 2:1. No other attempts were made to use this algorithm on the existing SFE-2 hardware.

Optimized Self-Pressurization With Product Gases. A fourth pressurization control algorithm based on the flowing H_2 and O_2 method, developed previously, was also tested. Optimization included incorporating a more rapid system pressure regulator (PR1) turn rate and a "slave" differential pressure regulator. The pressurization and depressurization sequence is depicted graphically in Figure 31.

Figure 31 depicted the rate of pressurization as the H_2 system pressure (P1) increases linearly from ambient pressure to 1,034 kPa (150 psig) in approximately 39 minutes. The nine-minute increase in pressurization time (from 30 minutes) in the baseline startup is due to a feature of the optimized pressurization control algorithm which "freezes" PR1 for 30 seconds in the event of the O_2-to-H_2 differential pressure falling below 0.0 kPa (0.0 psid). The algorithm then slowly raises the pressure from 1,034 to 1,138 kPa (150 to 165 psig) over the next 15 minutes. During this time module generated O_2 and H_2 was used for pressurization.

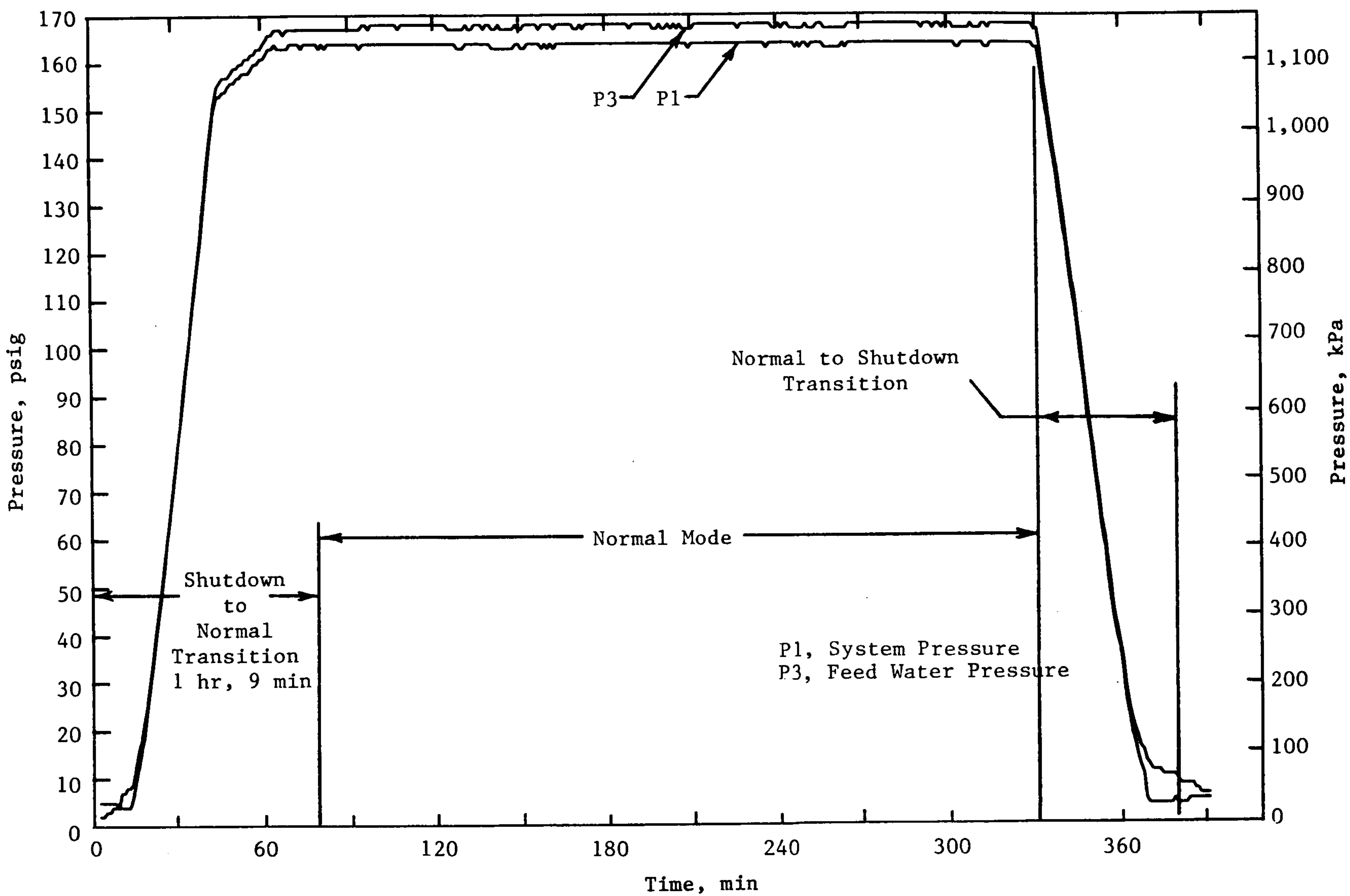

FIGURE 31 SFE FEED WATER PRESSURE AND SYSTEM PRESSURE VERSUS TIME OPTIMIZED FLOWING O_2 AND H_2 PRESSURIZATION ALGORITHM

During this cycle, the O_2-to-H_2 differential pressure was adequately controlled within a -2.1 to 21.4 kPa (-0.3 to 3.1 psid) band. This control proves that there is adequate gas production by the module to pressurize the H_2 and O_2 sides of the module without adverse differential pressures, and without modifying the O_2 and H_2 module volumes, provided excess gas is vented during pressurization.

Following the pressurization cycle described above, the SFE-2 was run for several hours. Performance of the cells was within normal operating ranges thereby indicating that the flowing product gas pressurization sequence had no effect on cell performance. The optimized version reduced the overall time for the Shutdown-to-Normal mode transition by approximately ten minutes but more importantly verified that this could be accomplished with a slave regulator.

During the Normal-to-Shutdown transition, the module current was immediately turned off and the system began to depressurize without N_2 introduced into the system. This was significant in proving that the system is capable of a safe and orderly depressurization without N_2. When system pressure reached ambient pressure a ten-minute N_2 purge was introduced to remove the remaining O_2 and H_2 from the system. The rate of system depressurization is faster using this algorithm (46 minutes) compared to the baseline algorithm (129 minutes) which incorporates three 30-minute waits to reduce the residual pressure in the feed water cavity. However, a very small residual pressure did remain in the feed water cavity during this optimized algorithm. It was recommended that the depressurization algorithm should be slowed down slightly to remove the residual pressure.

Comparison of Results and Recommendations. The results for the various techniques tested under the alternative pressurization evaluation are summarized in Table 14. Based on these results, the optimized technique with flowing H_2 and O_2 is recommended for future systems.

Pressure Control Assembly Design Modifications

Based upon the multi-cell test results and analyses, a new PCA design which incorporates the slave regulator concept was developed. The schematic of the PCA is shown in Figure 32 (Table 15 represents the accompanying schematic legend). Dual metal bellows with an inert liquid in between was used to separate O_2 from H_2 in the slave regulator. Metal bellows were also used in the H_2 regulator to provide isolation of H_2 from ambient. These features are illustrated in Figure 33. Individual pressure relief valves in each of the SFE product gas streams are included to provide overpressure protection. Separate filters are employed to prevent the regulator seats from being contaminated. A list of the design features for the SFE PCA are given in Table 16.

Fluids Control Assembly Design Modifications

In order to enhance the reliability and maintainability of the SFE, an FCA was developed to replace the WSA. The new FCA design incorporates a water tank, valves, filters, restrictors and a pressure sensor into one component. The

TABLE 14 SUMMARY OF SFE ALTERNATIVE PRESSURIZATION TESTING RESULTS

Pressurization Technique	Shutdown-to-Normal Transition Time, min	Nitrogen Consumption During Startup, L	Normal-to-Shutdown Transition Time, min	Differential Pressure Regulator Mode
Baseline, Flowing N_2	110	72	129	Operating
Non-flowing N_2	94	17	39	Slave
Flowing $H_2 + O_2$	79	0	38[(a)]	Operating
Optimized Flowing $H_2 + O_2$	69	0	46	Slave

(a) Did not include a ten-minute N_2 purge after the unit returned to ambient pressure.

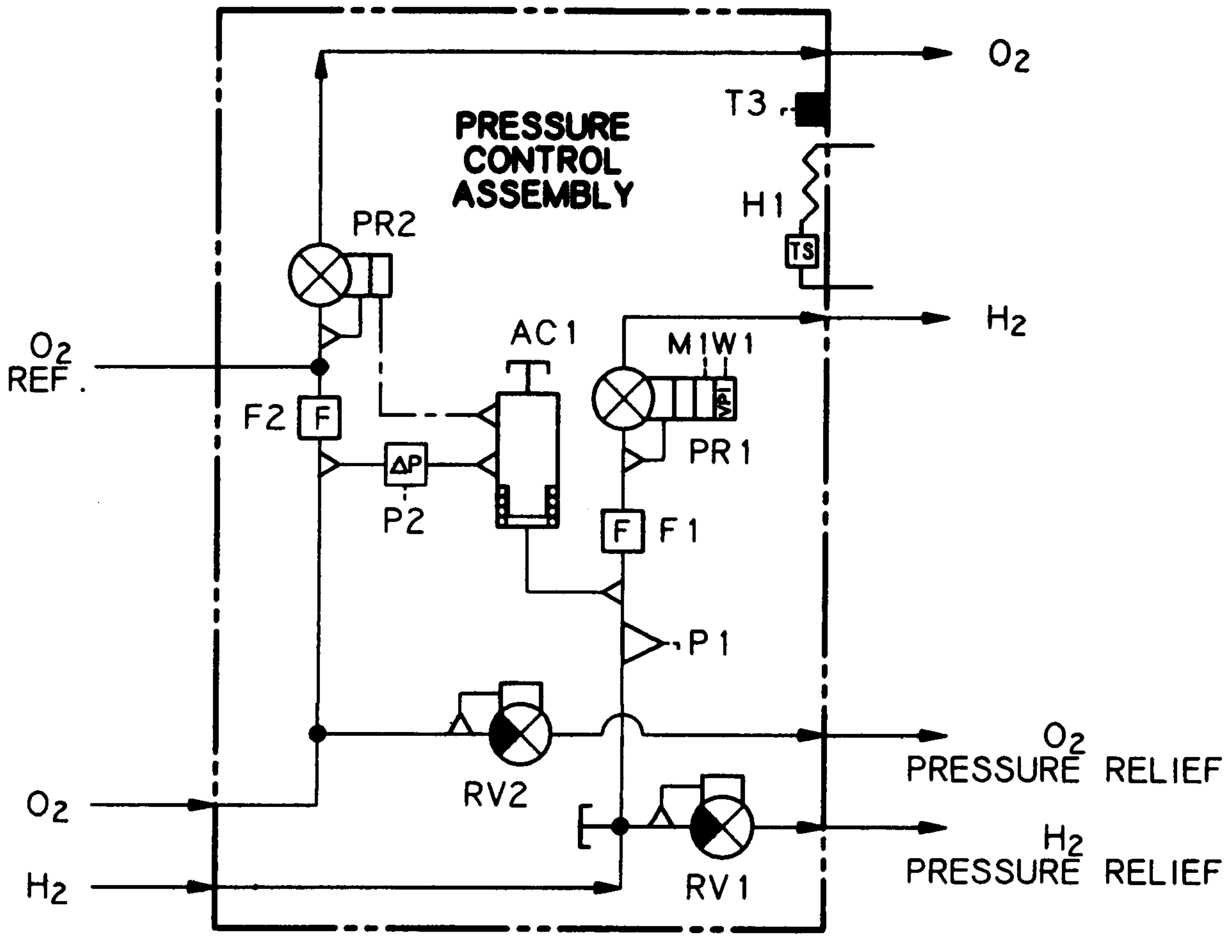

FIGURE 32 SCHEMATIC OF SFE PRESSURE CONTROL ASSEMBLY

TABLE 15 PCA MECHANICAL SCHEMATIC LEGEND

Schematic Symbol	Component
AC1	Accumulator
F1	Filter (Gas)
F2	Filter (Gas)
H1	Heater
M1	Motor
P1	Pressure Transducer
P2	Pressure Transducer
PR1	Pressure Regulator (Motor-driven)
PR2	Pressure Regulator
RV1	Relief Valve
RV2	Relief Valve
T3	Thermocouple
W1	Valve Position Indicator

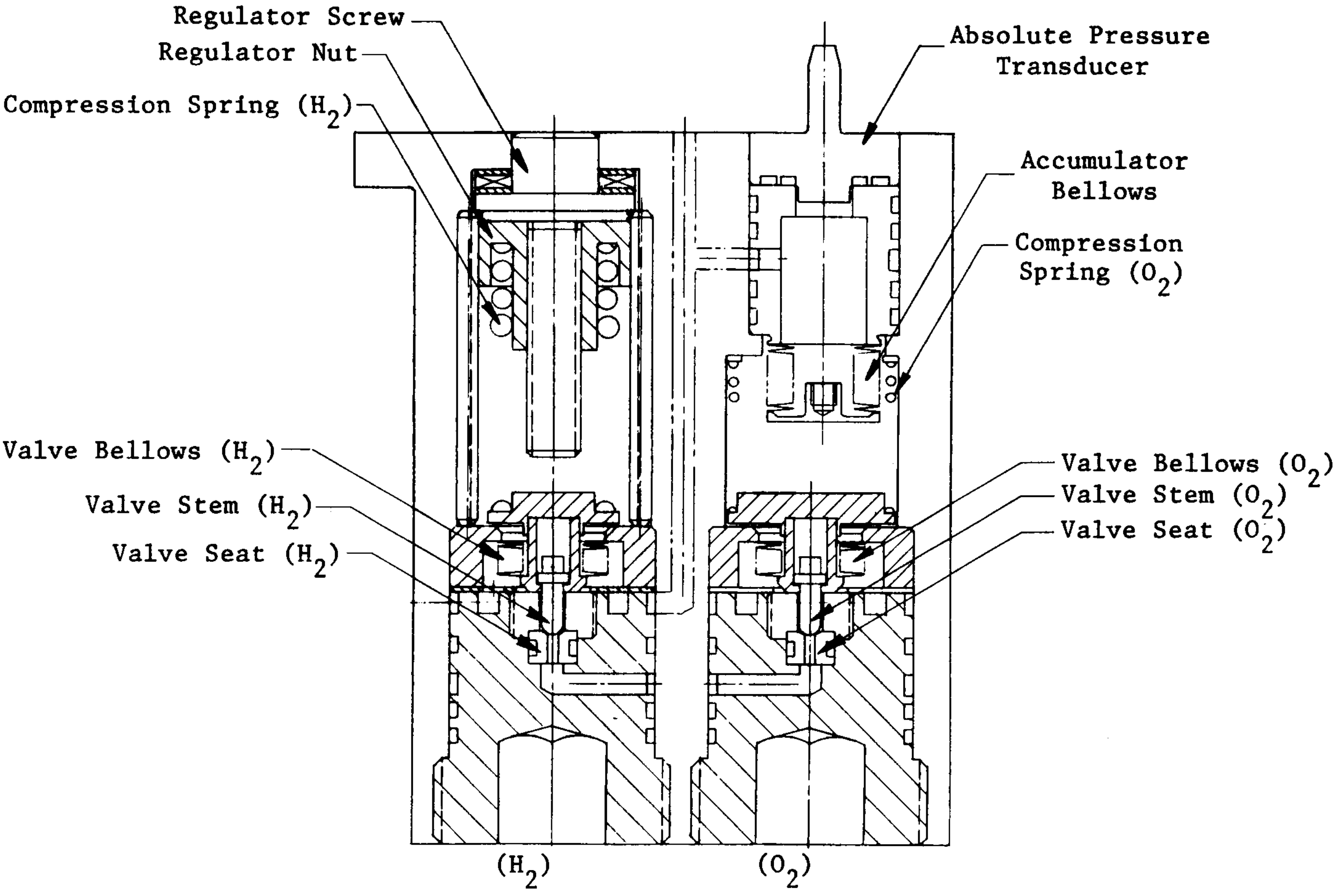

FIGURE 33 SCHEMATIC OF SYSTEM AND SLAVE REGULATORS OF PCA

TABLE 16 SFE PRESSURE CONTROL ASSEMBLY DESIGN FEATURES

- Dual Redundant Metal Bellows to Isolate O_2 from H_2 In Slave Regulator
- Haynes Valve Poppet
- Double O-Ring Gas Interface Seals
- Captive Fasteners
- Explosion Proof 28 VCD Actuator
- Thermal Switch for Over Temperature Protection
- Non-Welded Unibody Assembly (Simplified Fabrication Process)
- Locking Devices for all Threaded Members
- Relief Valves for Overpressure Protection
- Fine-Mesh Inlet Gas Filters to Prevent Contamination of Valve Seats

FCA provides for control of fluids (gas and liquid) into and out of the SFE subsystem. Figure 34 shows a schematic of the FCA designed for use with electrolyte circulation. Symbol labels on the schematic are identified in Table 17. Figure 35 shows the FCA design for pure water circulation. This schematic differs from the electrolyte circulation case by removing check valve CV5 from the FCA and locating it, reversed in direction, downstream of the TCA connection near the inlet of the SFE module. This prevents water from entering the module after the subsystem is shutdown.

The FCA design combines a water tank, nine valves, four filters, three restrictors, two pressure sensors and six check valves into one component and is to be packaged as shown in Figure 36. This design facilitates replacement, if needed, of a key component of the SFE.

There are four basic functions of the FCA. These are:

1. Supply water to the electrolysis module to replenish the water that is electrolyzed.

2. Refill the water tank (WT1).

3. Provide reference pressure to the water tank.

4. Provide N_2 purge for the system.

Selection of the appropriate FCA operating mode permits the above functions to be carried out.

Thermal Control Assembly Design Modifications

Based upon the multi-cell test results, the preliminary layout of the TCA was modified to include a solenoid valve (V9). The addition of this valve did not change the original packaging envelope of the TCA as can be seen from the TCA front and back views, Figures 37 and 38, respectively. The dimensions of the TCA layout are currently estimated to be 25.7 cm x 17.8 cm x 11.0 cm (10.12 in x 7.00 in x 4.35 in) (HxWxD). The modification of the TCA for pure water circulation is shown in Figure 39. The TCA mechanical schematic legend is shown in Table 18.

The current TCA design features a positive displacement gear pump with a hermetically-sealed magnetic drive and self-aligning flowing drive coupling. Cross-sectional schematics of the magnetically-driven gear pump and the sliding diverter valve concept are shown in Figures 40 and 41, respectively. In addition, the design has provided for self-venting and self-cooling of the bearings and magnetic drive and incorporates a tapered motor shaft to avoid oscillation or fretting. The diverter valve concept utilizes a threaded spool to drive a diverter spool which can be positioned to divert liquid flow to either of two paths, and has been sized to also permit partial flow to both paths.

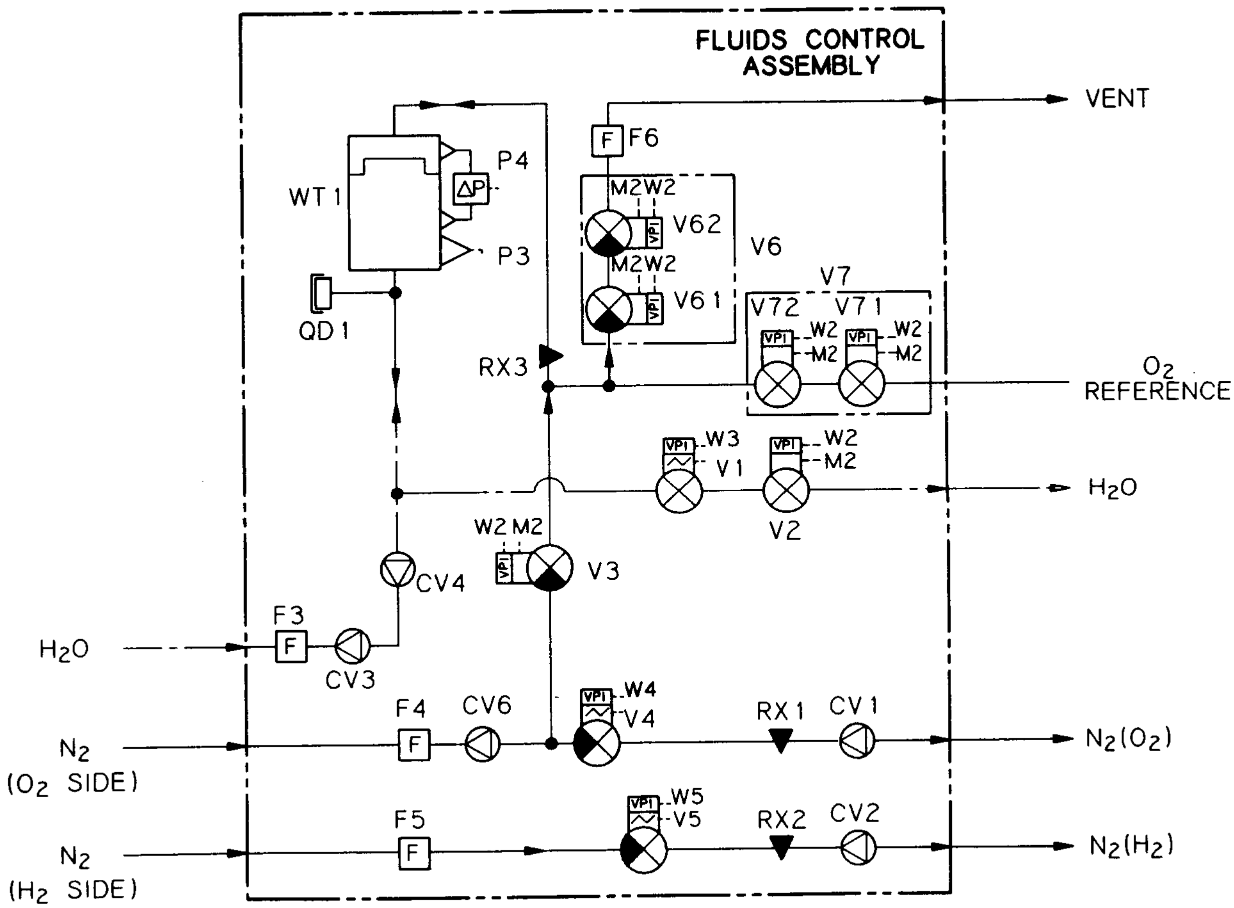

FIGURE 34 SCHEMATIC OF FLUIDS CONTROL ASSEMBLY WITH CIRCULATING ELECTROLYTE IN FEED COMPARTMENTS

TABLE 17 FCA MECHANICAL SCHEMATIC LEGEND

Schematic Symbol	Component
CV1	Check Valve
CV2	Check Valve
CV3	Check Valve
CV4	Check Valve
CV5	Check Valve
CV6	Check Valve
F3	Filter (Liquid)
F4	Filter (Gas)
F5	Filter (Gas)
F6	Filter (Muffler)
M2	Motor
P3	Pressure Transducer
P4	Pressure Transducer
QD1	Quick Disconnect
RX1	Restrictor
RX2	Restrictor
RX3	Restrictor
V1	Shutoff Valve (Solenoid)
V2	Shutoff Valve (Motor-driven)
V3	Shutoff Valve (Motor-driven)
V4	Shutoff Valve (Solenoid)
V5	Shutoff Valve (Solenoid)
V61	Shutoff Valve (Motor-driven)
V62	Shutoff Valve (Motor-driven)
V71	Shutoff Valve (Motor-driven)
V72	Shutoff Valve (Motor-driven)
W2	Valve Position Indicator
W3	Valve Position Indicator
W4	Valve Position Indicator
W5	Valve Position Indicator
WT1	Water Tank

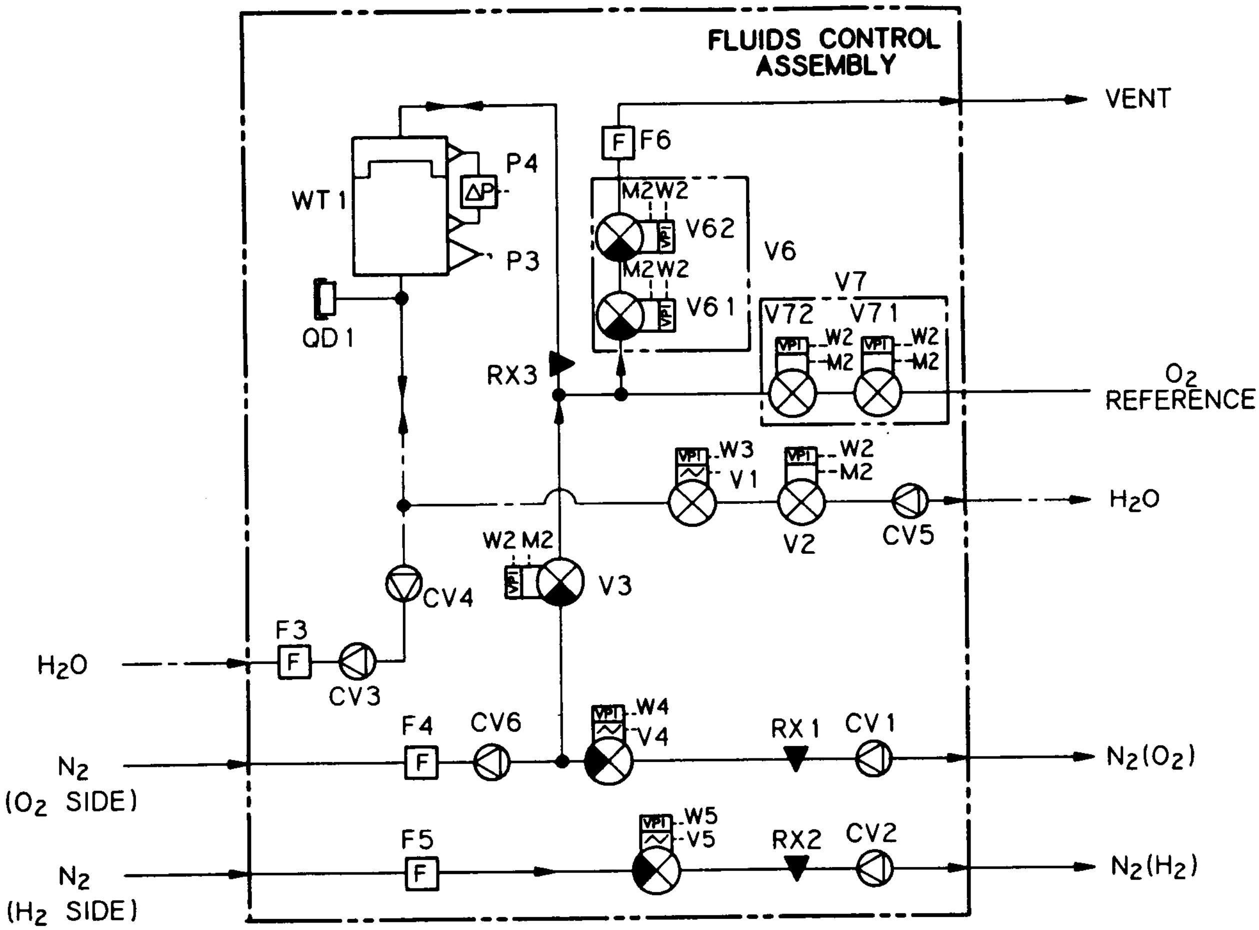

FIGURE 35 SCHEMATIC OF FLUIDS CONTROL ASSEMBLY WITH PURE WATER CIRCULATION IN FEED COMPARTMENTS

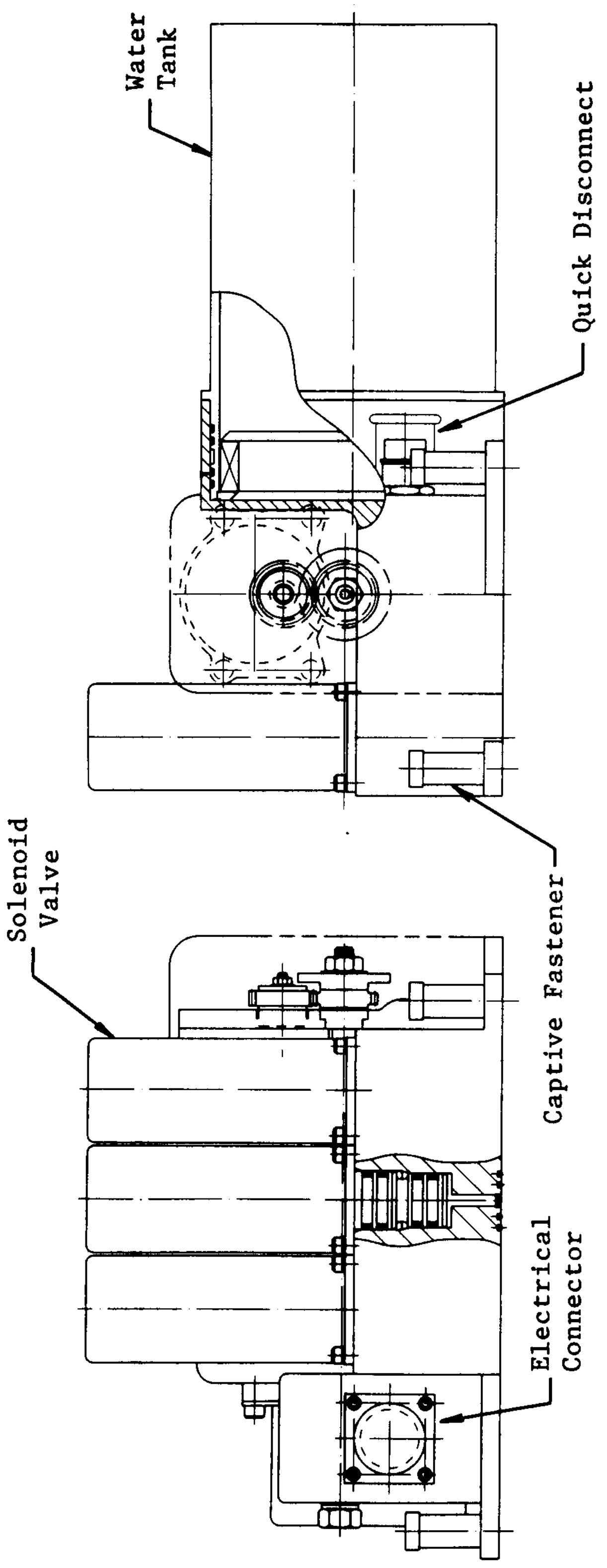

FIGURE 36 FCA ASSEMBLY

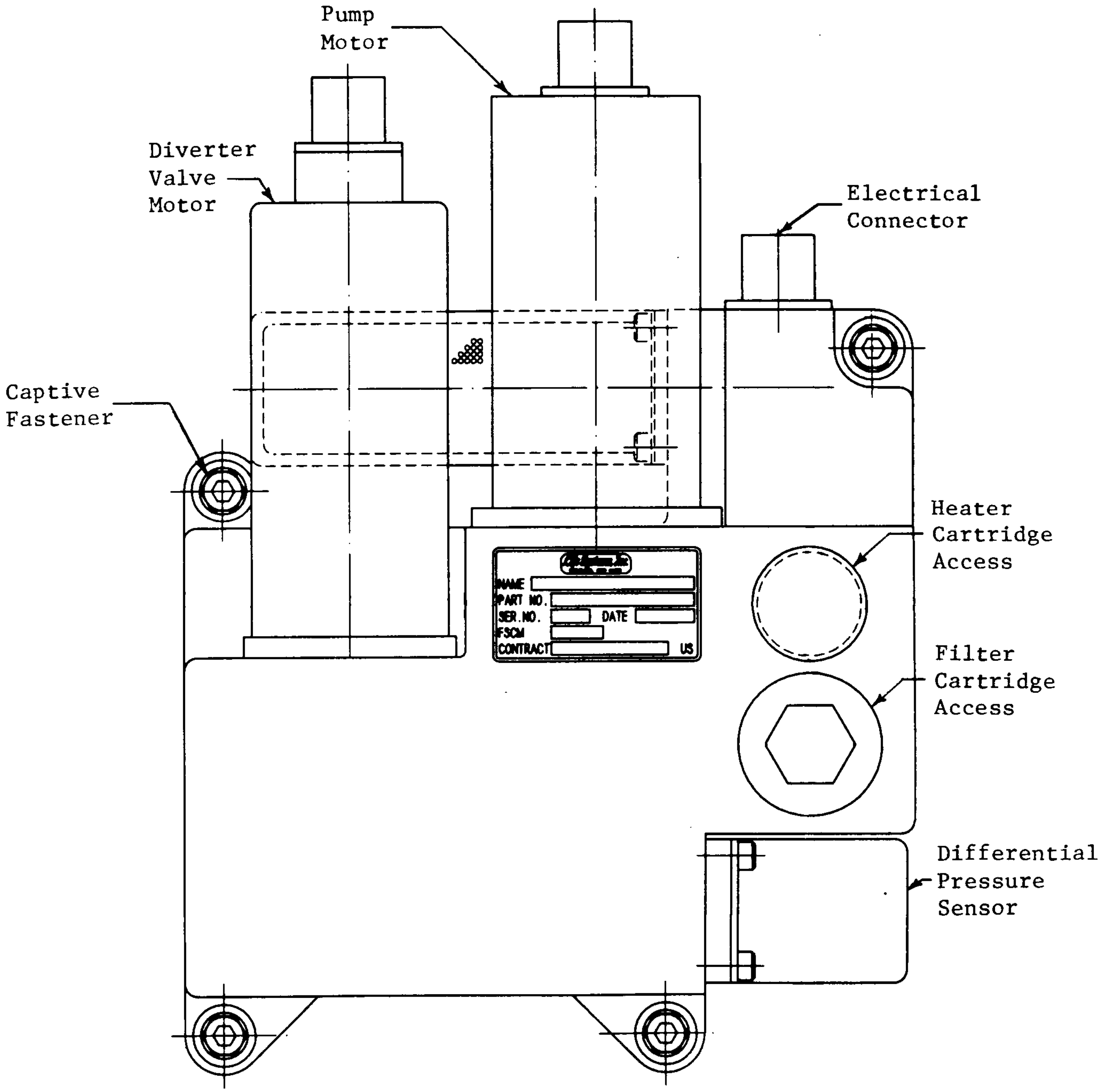

FIGURE 37 SCHEMATIC OF TCA - FRONT VIEW

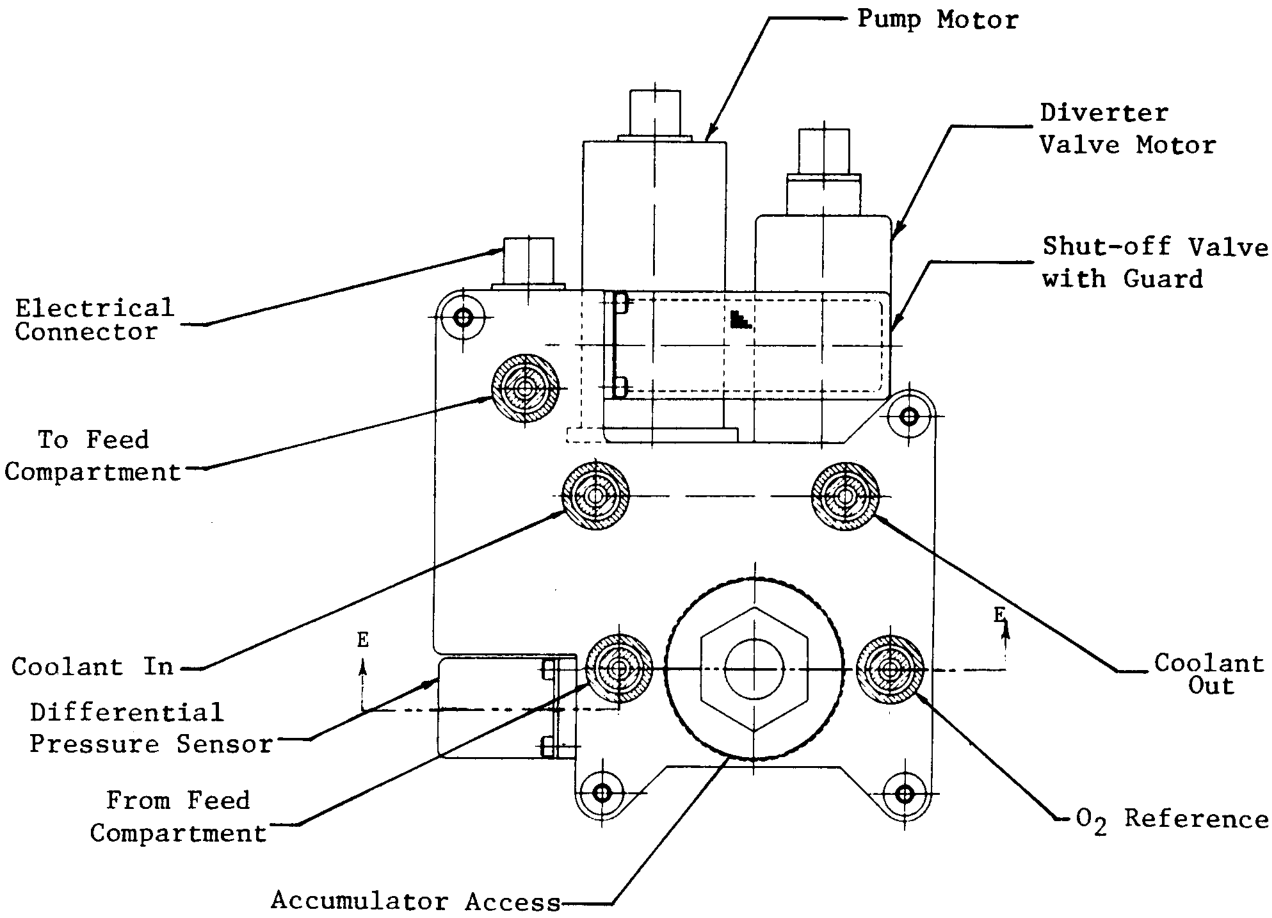

FIGURE 38 SCHEMATIC OF TCA - BACK VIEW

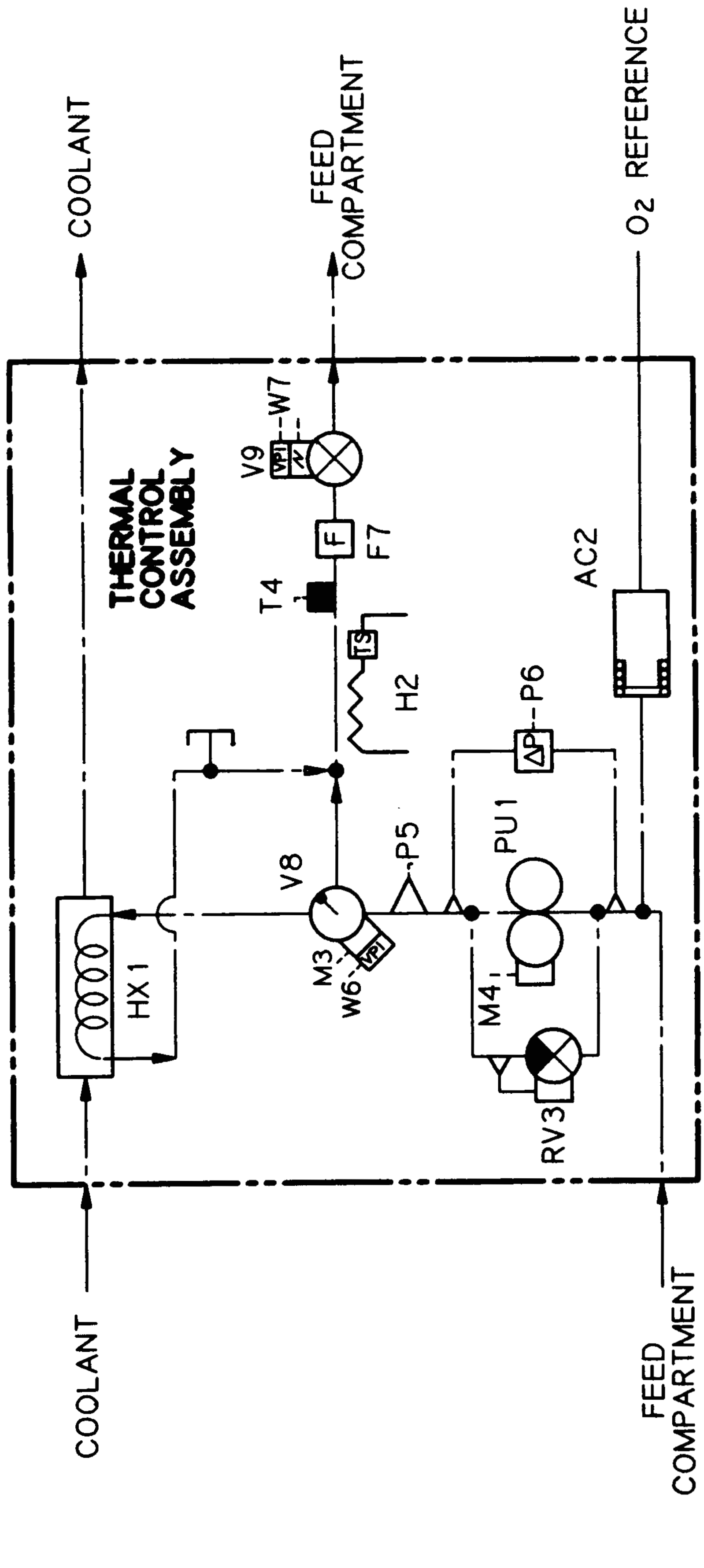

FIGURE 39 SCHEMATIC OF SFE TCA FOR PURE WATER CIRCULATION

TABLE 18 TCA MECHANICAL SCHEMATIC LEGEND

Schematic Symbol	Component
AC2	Accumulator
H2	Heater
HX1	Heat Exchanger
F7	Filter (Liquid)
M3	Motor
M4	Motor
P5	Pressure Transducer
P6	Pressure Transducer
PU1	Pump
QD2	Quick Disconnect
RV3	Relief Valve
T4	Thermocouple
V8	Diverter Valve (Motor-driven)
V9	Shutoff Valve (Solenoid)
W6	Valve Position Indicator
W7	Valve Position Indicator

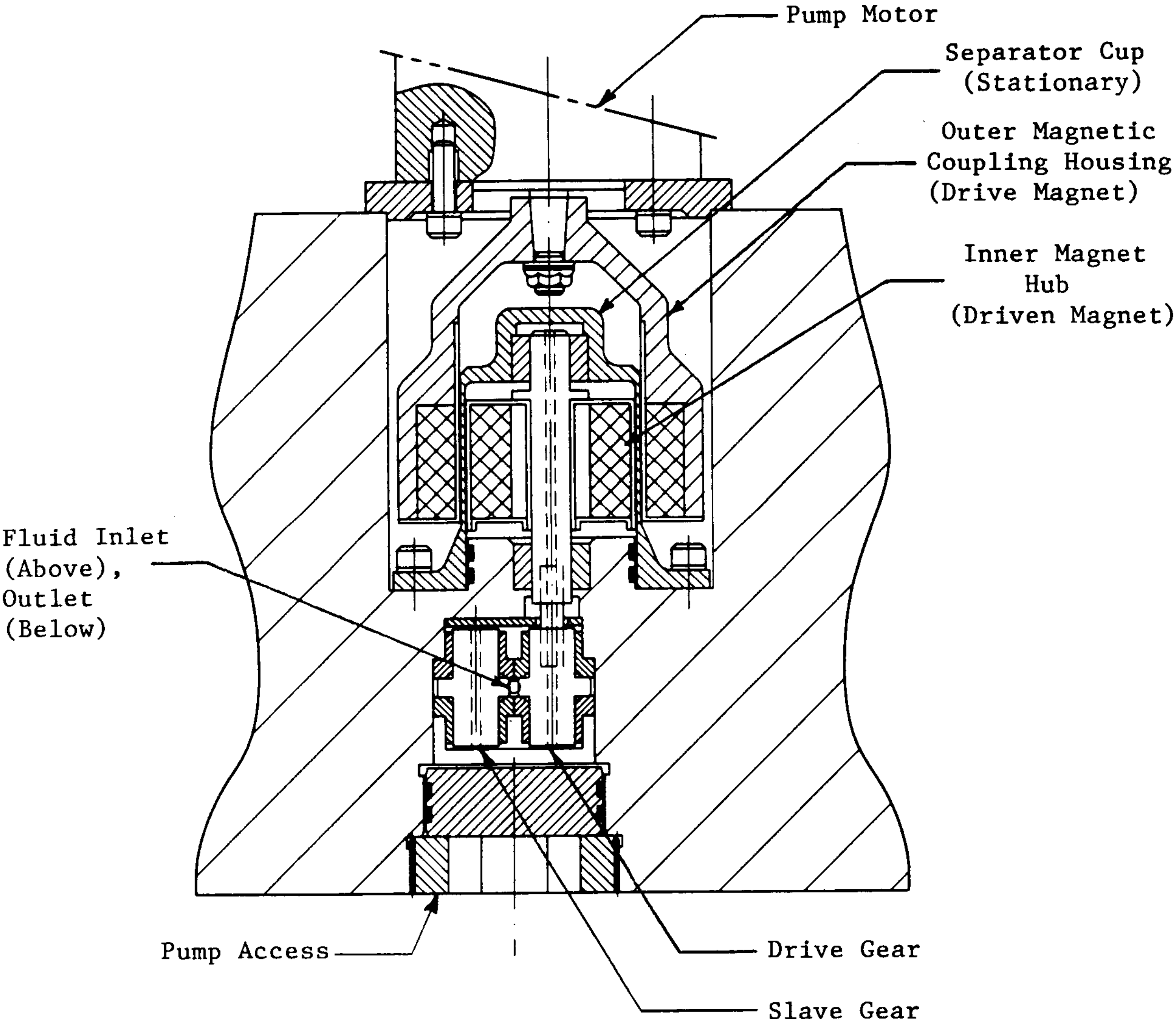

FIGURE 40 TCA CROSS SECTIONAL SCHEMATIC SHOWING MAGNETIC COUPLING AND GEAR PUMP

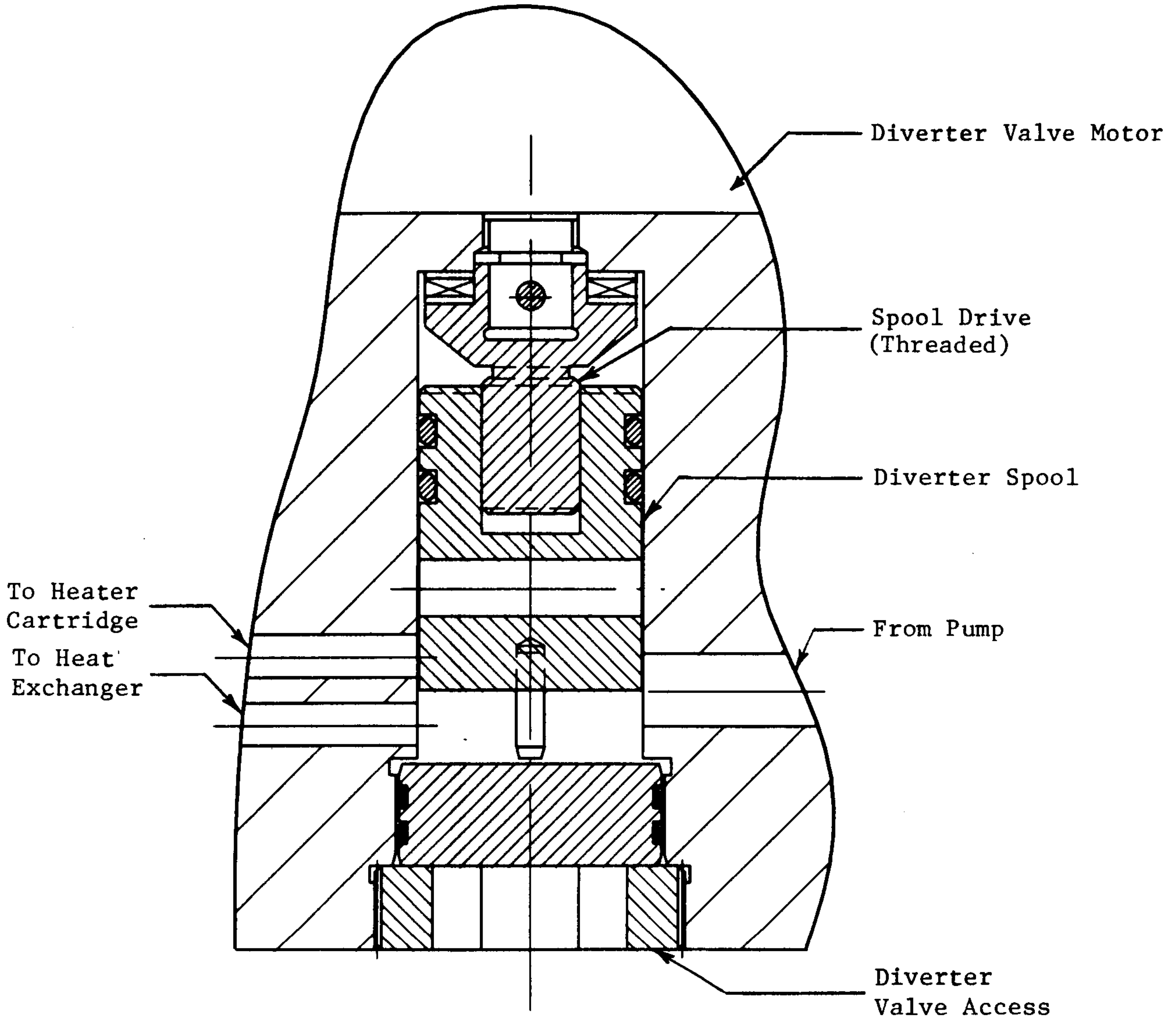

FIGURE 41 TCA CROSS SECTIONAL SCHEMATIC OF DIVERTER VALVE ASSEMBLY

CONCLUSIONS

The following conclusions were drawn as a result of the activities completed.

1. An SFE based Reactant Recharge System (RRS) can be developed based on Life Systems' alkaline SFE and its unique integrated mechanical components. A 10 kW SSP was designed using a 1.0 ft^2 active cell area in a 46 cell module and using integrated mechanical components designed for a 30 kW capacity input power.

2. Metallic and nonmetallic materials of construction are available for Life Systems' alkaline electrolyte based SFE for projected applications as part of an RFCS as well as part of ECLSS aboard NASA's Space Station. In addition, alternative materials were identified that show increased potential for elevated pressures ($\geq$20,684 kPa ($\geq$3,000 psia)).

3. The SFE product gas and purity levels for H_2-in-O_2 and O_2-in-H_2 are primarily caused by permeation through elastomeric compounds (i.e., O-rings, seals, etc.). They are only at a fraction of the LEL and pose no hazard. For current baseline hardware these impurities are nominally equal to 2,000 ppm of H_2-in-O_2 and 20 ppm of O_2-in-H_2. A newly proposed seal design will virtually eliminate all impurities. While recombiners can eliminate such impurities also, they are not recommended since they constitute an ignition source.

4. An electrolyte management practice developed provides for uniform electrolyte charging and module performance repeatability.

5. The design of the mechanical integrated component called the PCA can be simplified by reducing the number of motors from 2 to 1 thus increasing reliability and decreasing power requirements. This slave concept was demonstrated in actual system operations.

6. The need for an external source of N_2 to pressurize and depressurize the SFE can be eliminated by using an optimized, self-pressurization concept using flowing H_2 and O_2 product gases. This simplifies system operation and hardware and reduces expendables.

7. The SFE can be operated in the following configurations: pure water static feed or circulating electrolyte. Of these techniques the most simple and reliable is the noncirculating pure static feed method. This method is recommended for future system designs. In addition, the pure static feed non-circulating technique eliminates one component, the TCA, which contains the only remaining rotating part, a coolant pump. System reliability and life are thus enhanced.

8. Mechanical integrated components can be designed incorporating the simplification and optimization techniques defined under this program. As a result past TCA, PCA and FCA designs were modified and their preliminary design completed.

RECOMMENDATIONS

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

1. Additional endurance testing should be performed to evaluate alternative cell materials identified under the present program. This testing should be performed at end-item operating conditions and end-item configuration. Candidate Materials to be evaluated include new thermoplastics for module insulation plate material, nonreinforced polymeric materials for the unitized cell core frame and alternative module O-ring and matrix materials.

2. Additional testing to evaluate the effects of extreme environmental conditions (From Launch through On-Orbit Operation) on the SFE module should be performed. In these tests, a SFE module should be exposed to conditions of extreme heat and cold with module performance after exposure to both conditions determined.

3. Additional testing to evaluate the effect of long-term storage (i.e., greater than 12 months) on SFE mechanical/electrochemical hardware should be performed. Specific emphasis should be placed on SFE performance repeatability. All sensors and actuators should be analyzed for calibration or functional changes due to the long-term storage.

4. An additional development program should be established to advance water electrolysis technology as a utility for the Space Station and beyond. This program will emphasize improving efficiency, operability and mechanical components. This technology will enhance the existing SFE database and provide a strong foundation for future SFE improvements.

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