TR-1028-5

IMPACT OF LOW GRAVITY ON WATER ELECTROLYSIS OPERATION

FINAL REPORT

by

F. T. Powell, F. H. Schubert and M. G. Lee

March, 1989

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the authors or organization that prepared it.

Prepared Under Contract NAS9-17966

by

Life Systems, Inc.
Cleveland, OH 44122

for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center

FOREWORD

The work described herein was conducted by Life Systems, Inc. at Cleveland, OH under Contract No. NAS9-17966 during the period May 23, 1988 through March 22, 1989. The Program Manager was Ferolyn T. Powell. The principal investigator for the experiment is Franz H. Schubert. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Gene Lee, Ph.D.	Electrochemical Designs and System Analysis
Dennis B. Heppner, Ph.D.	Control/Monitor Instrumentation Design
Arthur B. Nagel	Integrated Current Controller Design
Franz H. Schubert	Electrochemical and Mechanical Designs and System Analysis
David W. Novak	Mechanical Design
Ferolyn T. Powell	Flight Experiment Integration Design, and Program Management

Dr. Simon Ostrach, Case Western Reserve University, was a consultant to the program, providing expertise in the area of Low Gravity phenomena.

The Contract's Technical Monitor was Albert F. Behrend, Jr., Chief, Special Projects Branch, Crew and Thermal Systems Division, National Aeronautics and Space Administration Lyndon B. Johnson Space Center, Houston, TX.

TABLE OF CONTENTS

continued-

Table of Contents - continued

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

CCDS	Command, Control and Display Subsystem
C/M I	Control/Monitor Instrumentation
ECLSS	Environmental Control and Life Support System
EPICS	Electrolysis Performance Improvement Concept Studies
EVA	Extravehicular Activity
FCA	Fluid Control Assembly
IE	Integrated Electrolysis
M/EA	Mechanical/Electrochemical Assembly
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
OAST	Office of Aeronautics and Space Technology
OGA	Oxygen Generation Assembly
ORU	Orbital Replaceable Unit
PCA	Pressure Control Assembly
PCSE	Pressure Control/Safety Enclosure
PDU	Performance Display Unit
SFE	Static Feed Electrolyzer
SFWEM	Static Feed Water Electrolysis Module
TCA	Thermal Control Assembly

SUMMARY

Advanced Space Missions will require oxygen and hydrogen utilities for several important operations including the following: (1) propulsion, (2) electrical power generation and storage, (3) Environmental Control and Life Support, (4) Extravehicular Activity, (5) In-Space Manufacturing activities and (6) In-Space Science activities. A key to providing these utilities for Advanced Space Missions will be to minimize resupply from earth requirements and initial earth to orbit launch mass. Static Feed Water Electrolysis technology, using an alkaline electrolyte, has been recognized as a design capable of efficient, reliable oxygen and hydrogen generation with few subsystem components. The Static Feed concept has evolved over the last 19 years under the National Aeronautics and Space Administration and Life Systems, Inc. sponsorship. The overall objective of the present program was to perform a preliminary conceptual design of a flight experiment which investigates ways a low gravity environment may improve water electrolysis performance.

The program was sponsored by the National Aeronautics and Space Administration's Office of Aeronautics and Space Technology and monitored by the Johnson Space Center. The program was a part of the Office of Aeronautics and Space Technology In-Space Technology Experiment Program. The experiment, entitled Electrolysis Performance Improvement Concept Studies, meets all requirements and constraints of a Space Shuttle standard middeck payload. Projected physical characteristics of the Electrolysis Performance Improvement Concept Studies experiment are weight of 37.6 lb, volume of 1.9 ft^3 and 100 W of power.

The program included consideration of the following: (1) end use design requirements, (2) phenomena to be studied (e.g., gas/liquid interfaces, fluid flows, capillary flows, thermal gradients, etc.,), (3) Space Shuttle Orbiter experiment constraints including flight experiment reliability and quality assurance requirements and flight experiment design constraints, (4) experiment descriptions including procedures, timelines and data requirements, and (5) test hardware requirements to obtain the necessary data. The results were integrated to arrive at a flight experiment conceptual design and a preliminary implementation plan which are described in this Final Report.

Design goals and requirements were considered in three subcategories including (1) scientific, (2) engineering and (3) Space Shuttle Orbiter. The scientific and engineering goals are to obtain scientific and engineering data for future research and development. The Shuttle goals and requirements focus on demonstrating and monitoring for safety and meeting design constraints of a standard middeck payload. The National Space Transportation System safety requirements were an important focus throughout the program. These requirements were evaluated and incorporated into the design. Three levels of containment, including O-rings, a nitrogen blanket and a sealed enclosure were incorporated into the experiment hardware design.

The Electrolysis Performance Improvement Concept Studies experiment integrated within a Space Shuttle Orbiter standard middeck locker is illustrated in Figure 1.

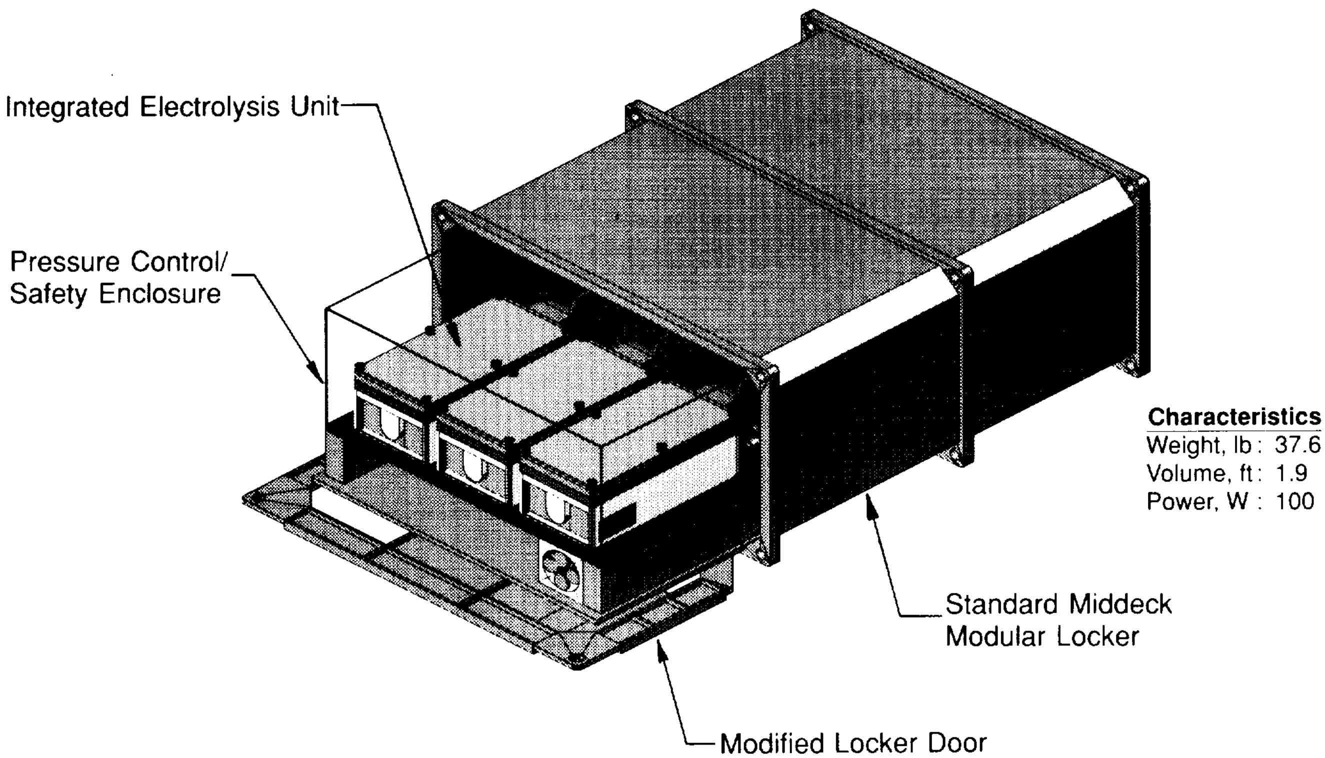


FIGURE 1 EPICS EXPERIMENT PACKAGING CONCEPT (IN LOCKER)

THIS PAGE INTENTIONALLY LEFT BLANK

INTRODUCTION

The National Aeronautics and Space Administration (NASA) Office of Aeronautics and Space Technology (OAST) has developed and initiated a program entitled the In-Space Technology Experiment Program (In-Step). The primary objectives of this program as described by Dr. Leonard Harris at the In-Step Workshop, held December 6 through 9, 1988 in Atlanta, GA, are to obtain data and validate the feasibility of technologies in space. Inherent in these two objectives is the concept of utilizing low gravity as a resource to improve the performance of earth-based technologies. Part of the In-Step Program is to gear up for use of the Space Station Freedom as an engineering research laboratory.

The In-Step Program is divided into two subprograms. These include the Inreach and Outreach Programs. The Inreach Program is aimed at experiments from within the NASA. The Outreach Program includes experiments from industry and universities. The experiment described in this report is one of the 36 initial Outreach experiments. The Outreach Program is subdivided into eight theme topics including:

1. Space Structures
2. Space Environmental Effects
3. Fluid Management and Propulsion
4. Power Systems and Thermal Management
5. Automation and Robotics
6. Sensors and Information Systems
7. Humans In Space
8. In-Space Systems

The Electrolysis Performance Improvement Concept Studies (EPICS) flight experiment described herein has officially been placed in the Humans In Space theme. As described throughout this report, it will become apparent that the EPICS experiment will also provide valuable information to the Fluid Management and Propulsion Theme area as well as the Power Systems and Thermal Management theme area.

Background

Advanced space missions will require oxygen (O_2) and hydrogen (H_2) utilities for several important operations including: (1) propulsion, (2) electrical power generation and storage, (3) Environmental Control and Life Support System (ECLSS), (4) Extravehicular Activity (EVA), (5) in-space manufacturing activities and (6) in-space science activities. A key to providing these utilities for advanced space missions will be to minimize resupply from Earth requirements and initial Earth-to-Orbit launch mass.

This report presents the details of a flight experiment which will investigate the use of low gravity to improve the performance of an electrochemically-based subsystem which provides these utilities. The experiment focuses on the Static Feed Electrolysis (SFE) concept of generating O_2 and H_2. It is important to note that this focus on a specific electrochemical process will not only provide performance design data for that specific process; it will also provide methodologies, flight experiment hardware and performance information applicable to a diverse range of electrochemical processes (e.g., electrolysis of carbon dioxide from the Martian atmosphere.

The SFE technology, using an alkaline electrolyte, has been recognized as a design capable of efficient, reliable O_2 and H_2 generation with few subsystem components. Figure 2 illustrates the use of the SFE technology as a space exploration utility. The static feed concept has evolved over the last 19 years under the NASA and Life Systems, Inc. (Life Systems) sponsorship. During this time, the concept progressed from single-cell operation through the fabrication and testing of multiperson subsystems (for life support) culminating in its selection for the Oxygen Generation Assembly (OGA) of the Air Revitalization System aboard the Space Station Freedom.

Recent developments at Life Systems have demonstrated substantial reduction in the operating voltage of the electrolysis cells and have allowed for the consolidation of ancillary components resulting in the reduction of power, weight, volume and complexity. The overall impact of these state-of-the-art advancements is significant since the OGA is the largest power consuming subsystem of a regenerative life support system and even more significant when considering advanced mission scenarios which require tons of O_2 production per year for propellant.

The technical concepts and prior performance 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, 4] The following subsections briefly summarize the subsystem and cell level concepts and the electrochemical reactions involved.

Basic Process

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

At the cathode:

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

At the anode:

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

These result in the overall reaction of:

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

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

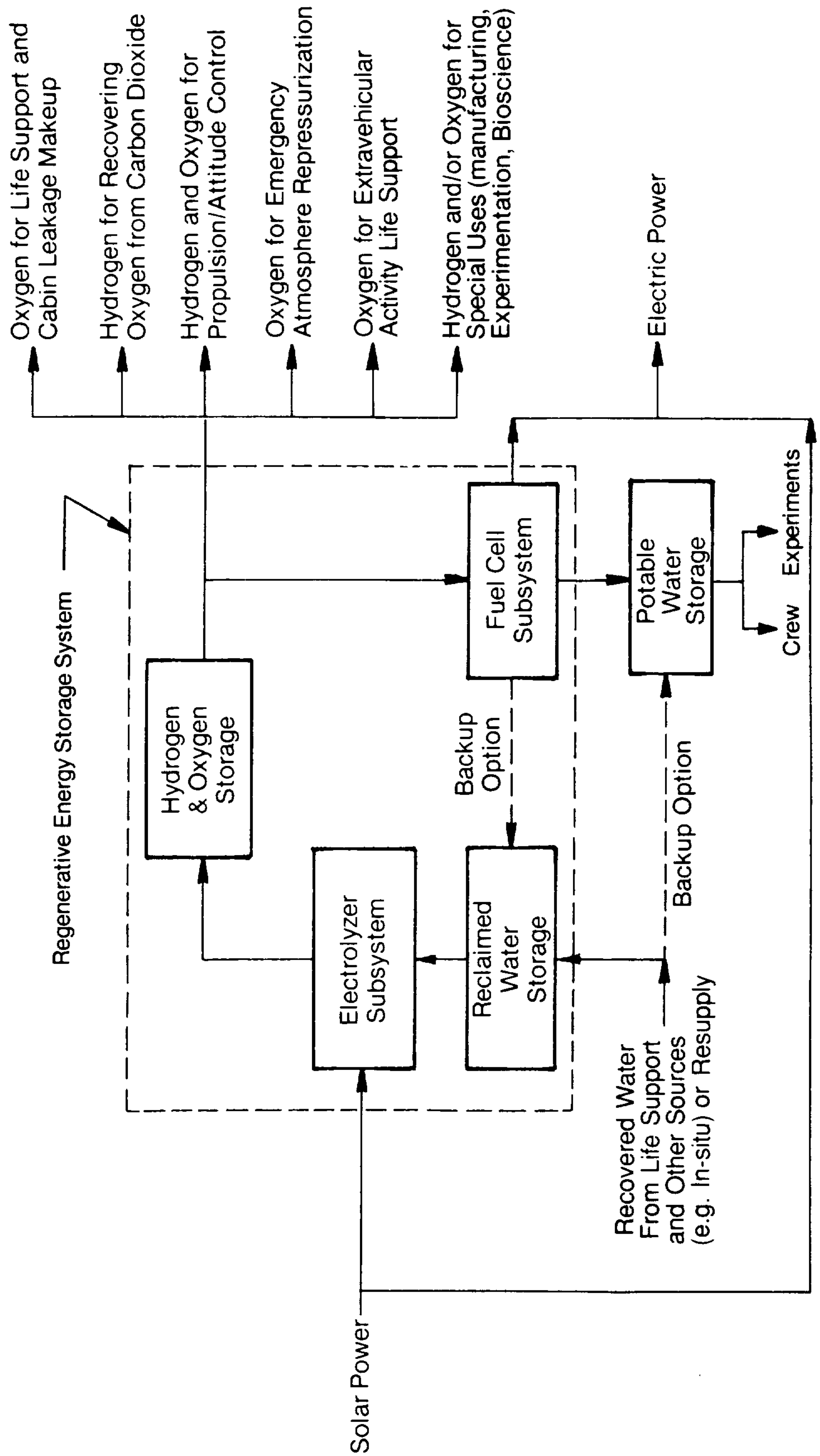


FIGURE 2 STATIC FEED WATER ELECTROLYSIS - A MANNED SPACE EXPLORATION UTILITY

The Static Feed Electrolysis Cell

The efficiency with which these reactions can be used for practical O_2/H_2 generation is, however, highly dependent on cell technology, especially on electrode components. Figure 3 is a functional schematic of a SFE cell. As electrical power is supplied to the electrodes, water in the electrode core is electrolyzed creating a concentration gradient between the water feed cavity and the electrolyte in the electrode core. Water vapor diffuses from the water feed matrix cavity through the water feed membrane to the cathode due to this gradient.

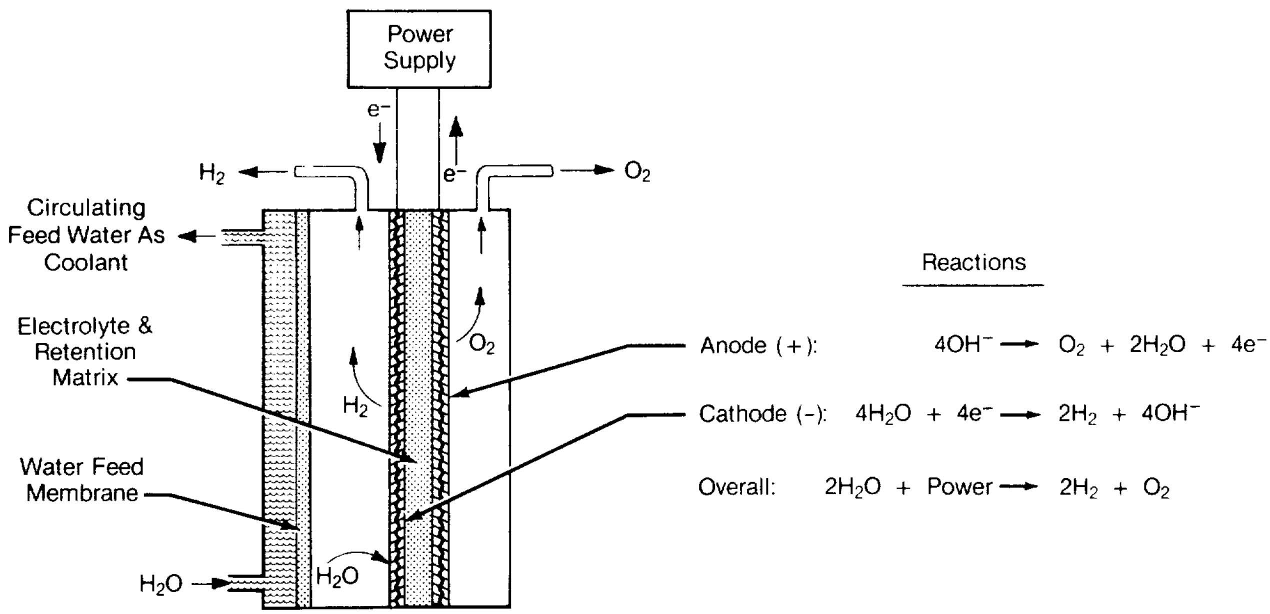


FIGURE 3 ELECTROLYZER CELL SCHEMATIC AND REACTIONS

Subsystem Concept

The basic cells are combined with supporting components to form the subsystem. A simplified process schematic of a static feed electrolysis subsystem is shown in Figure 4. The mechanical/electrochemical portion of the subsystem consists principally of four components: an electrochemical module, a Pressure Control Assembly (PCA), a Thermal Control Assembly (TCA) and a Fluid Control Assembly (FCA). The module consists of a series of individual electrochemical cells stacked fluidically in parallel and connected electrically in series to form the Static Feed Water Electrolysis Module (SFWEM). Oxygen and H_2 are generated in the SFWEM from water supplied by the water supply tank.

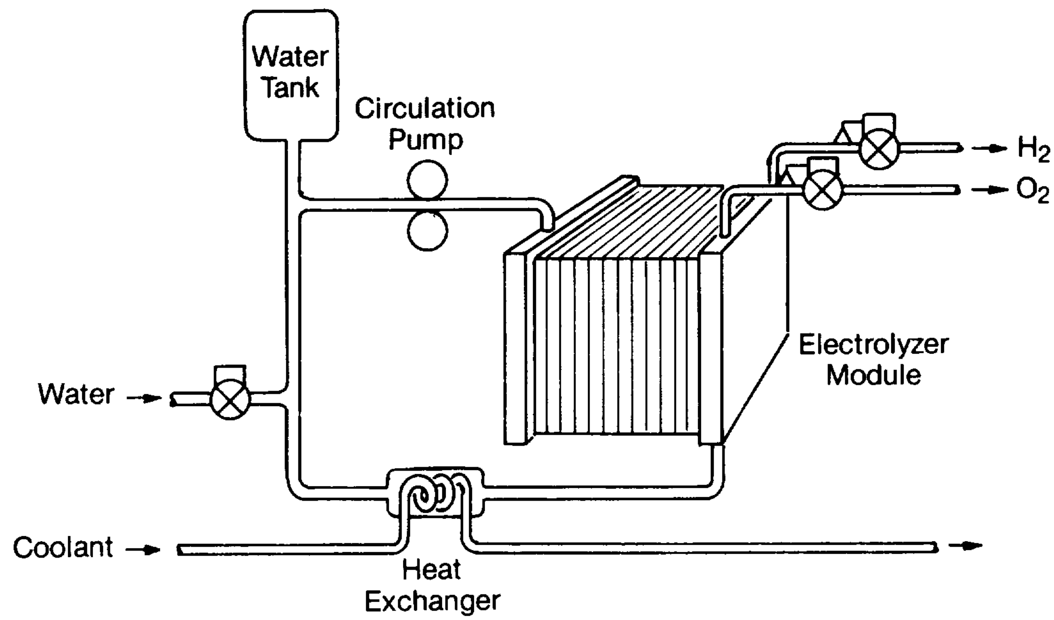


FIGURE 4 SIMPLIFIED SFE PROCESS SCHEMATIC

From the module the product gases pass through the PCA which monitors and adjusts subsystem pressures and maintains proper overall and differential pressures between the O_2, H_2 and water feed cavities of the module. The PCA is an integrated mechanical component which integrates several components into one Orbital Replaceable Unit (ORU), increasing reliability and maintainability. The TCA supplies liquid coolant to the module for thermal control. Again, the TCA integrates several components into one ORU. The heat is transferred from the subsystem by way of a liquid/liquid heat exchanger. Water is supplied to the module by a pressurized, cyclically filled water supply tank. During the fill cycle, the water tank is isolated from the module and depressurized. The subsystem has the capability for separate Nitrogen (N_2) purging of O_2-and-H_2 containing cavities of the SFWEM and for repressurizing of the water feed tank after the water tank fill cycle. The fill cycle of the water tank and the capability for N_2 purging of both the O_2 and H_2 cavities of the SFWEM are controlled by the FCA. The PCA, TCA and FCA are mounted on an interface plate in which a major portion of the plumbing is embedded.

An automatic control/monitor instrumentation (C/M I) provides the following functions: (1) automatic mode and mode transition control, (2) automatic shutdown provisions for self-protection, (3) provisions for monitoring subsystem parameters, (4) automatic fault isolation diagnostics and (5) provisions for interfacing with the operator through a performance display unit (PDU) and/or NASA-provided command, control and display subsystem (CCDS).

Previous Work Accomplished

Major breakthroughs/improvements have been made on electrode performance, cell design, module construction, integrated ancillary mechanical components, packaging, maintainability and C/M I. These breakthroughs/improvements are well documented in final reports, design handbooks, papers and Life Systems' engineering reports and notes. Figure 5 illustrates the overall advancement of the SFE technology.

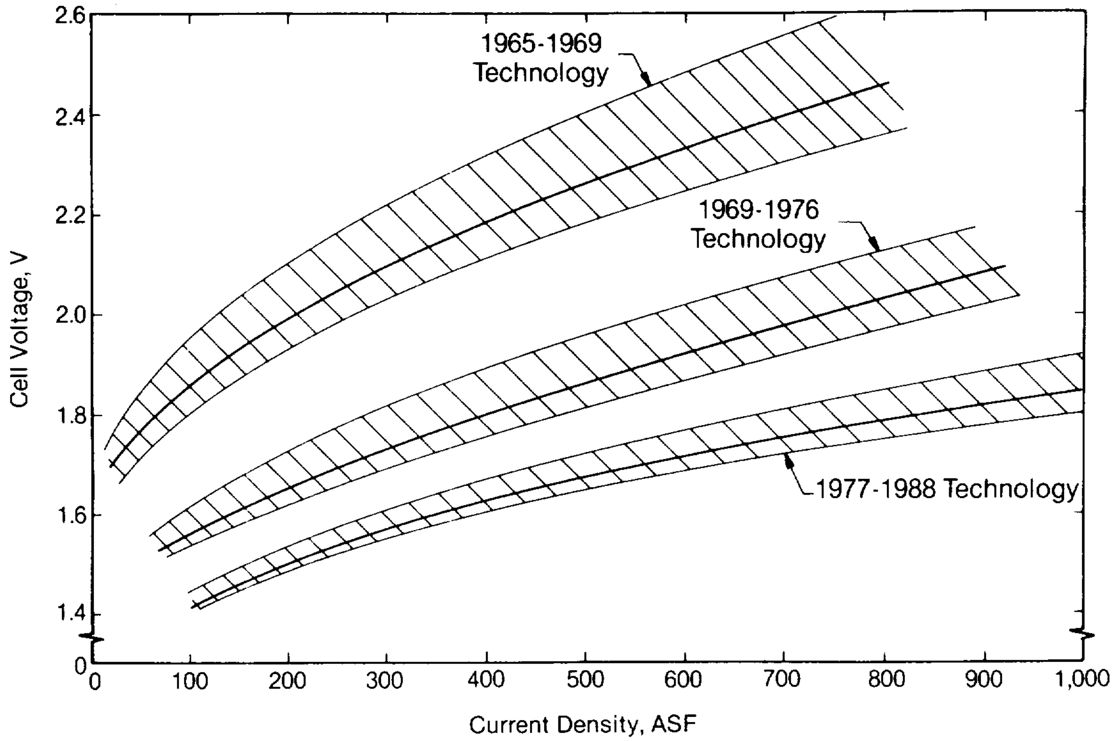
Extensive endurance testing has shown that the operation of the electrolysis module gives long life with little cell degradation. Module endurance test hours that have been achieved within Life Systems' endurance testing program include one cell operating continuously (noncyclically) for over 45,000 hours (five years) and two single cell modules operating cyclically, simulating low earth orbit conditions for over 45,000 hours each. Converting the cumulative 45,000 and 44,000 hours of operation to cyclic time results in over 74,000 and 71,000 hours (over eight years each) of Space Station equivalent life each. Figure 6 summarizes the SFE test program.

The inherent simplicity of the electrolysis module design is directly responsible for these results. The static water addition concept of the SFE, for example, separates the feed water from the cell electrolyte eliminating electrode catalyst contamination. The amount of electrolyte present in the module is very small, resulting in negligible corrosion potential. The extensive endurance testing has shown that the operation of the SFE will meet long-life requirements without cell degradation. There are no moving parts within the module stacks.

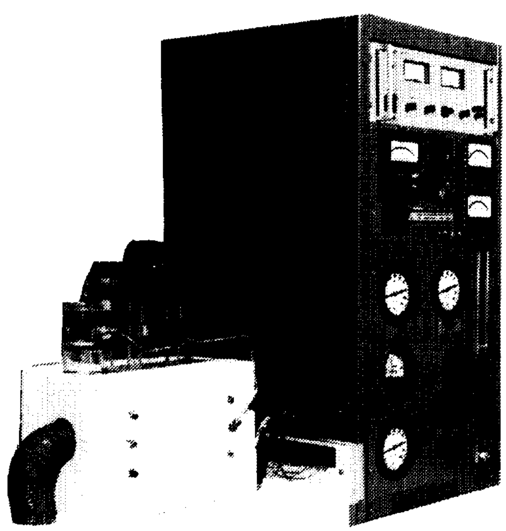
Multicell modules have been built and tested with 0.1 ft^2, 0.25 ft^2 and 1.0 ft^2 active individual cell areas.

Several subsystems have been built and tested for application to the ECLSS and the regenerative fuel cell. Figure 7 pictorially illustrates how the SFE has matured, reducing size and complexity, while improving performance and reliability. Current efforts include a 4-person ECLSS OGA for the NASA Space Station Freedom technology demonstrator program and high pressure gas generation applicable to EVA O_2 bottle recharge and propellant production. Development of the SFE has been sponsored by many organizations for several applications, as shown in Figure 8.

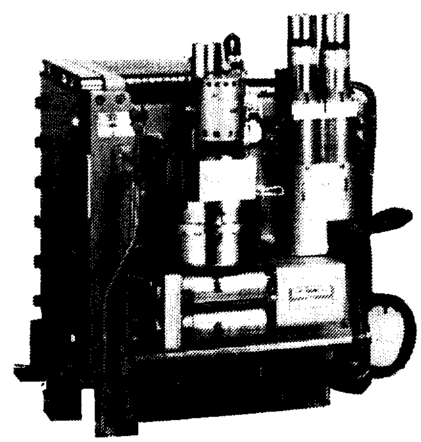
The NASA has and is continuing to conduct an extensive endurance testing program for the ancillary mechanical assemblies of the SFE. The objective of this testing program is not to generate Mean Time Between Failure data in the conventional way, but to highlight the types of mechanical improvements and problems which should be addressed to ensure long life and reliable operation, yet stay within typical research and development funding. The basic functions of the mechanical assemblies under test will remain the same for the SFE propulsion application on the Space Station Freedom. However, the configuration may be changed to feature redundancy, as required, and to incorporate those design changes based upon what was learned during the endurance testing program. Additionally, cycling of the assembly hardware is



Technology Development has Reduced the Voltage and Power Requirement by ⅓.



Electrolysis Module Parametric Test System, 1965



Static Feed Electrolyzer 1988

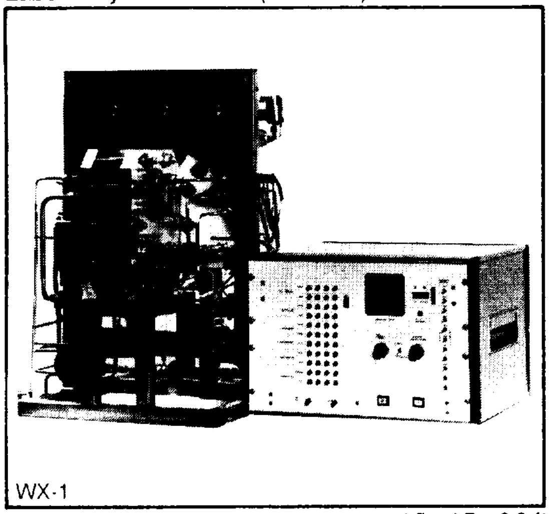
FIGURE 5 ADVANCEMENT IN WATER ELECTROLYSIS TECHNOLOGY

Test Item	Cell Size, ft²	No. Cells	Total Hrs
SINGLE CELLS			
Test Stand 122	0.1	1	45,197
Test Stand 123	0.1	1	45,450
Test Stand 124	0.1	1	44,061
Test Stand 131	0.25	1	1,292
MECHANICAL COMPONENTS			
PCA	—	—	28,360
FCA	—	—	25,560
CCA	—	—	36,145
MODULES			
Test Stand 84	0.1	10	7,525
Test Stand 126	0.1	12	6,219
Test Stand 127	0.1	6	10,660
Test Stand 143	0.25	12	1,057
SUBSYSTEMS			
WS-1	0.1	6	4,027
WS-3	0.1	30	1,200
WS-6	1.0	6	2,105
RFCSB	1.0	6	1,036
WS-1A	0.25	5	3,316
SFE-1	0.25	12	900
SFE-2	0.25	12	1,035
SFE-2	0.25	24	2,200
SFE-3	0.25	12	1,335

As of 03/03/89 at 8:00 a.m.

FIGURE 6 SFE CELL, MODULE AND COMPONENT TEST PROGRAM

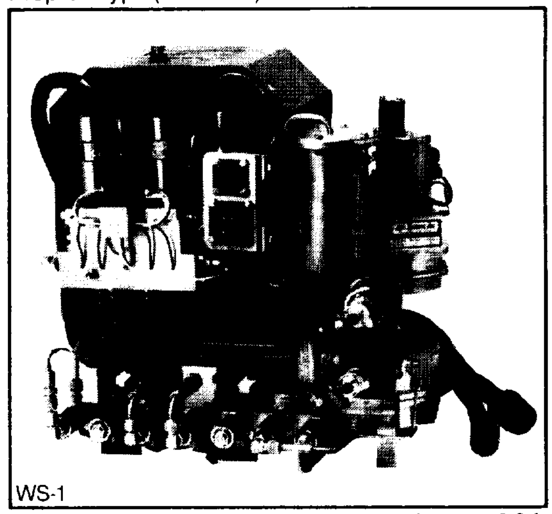
Laboratory Breadboard (1 Person)



WX-1

1.5 x 1.7 x 2.3 ft

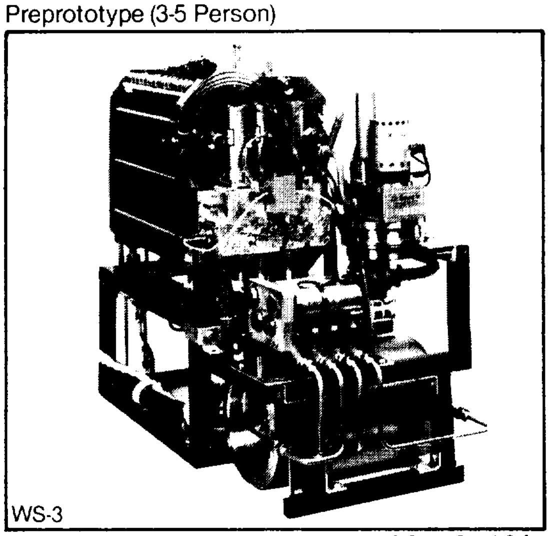
Preprototype (1 Person)



WS-1

1.2 x 1.4 x 0.9 ft

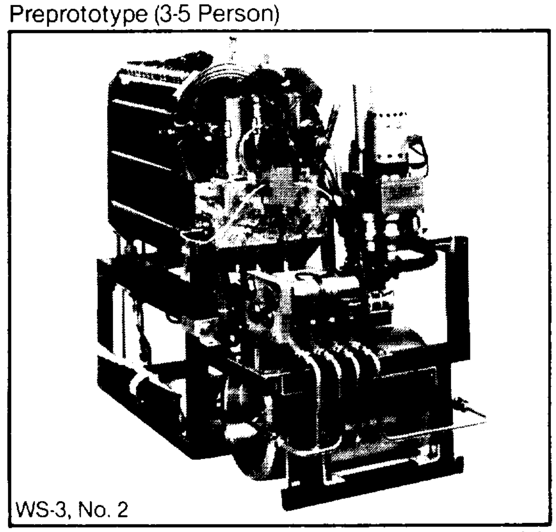
Preprototype (3-5 Person)



WS-3

0.9 x 1.8 x 1.9 ft

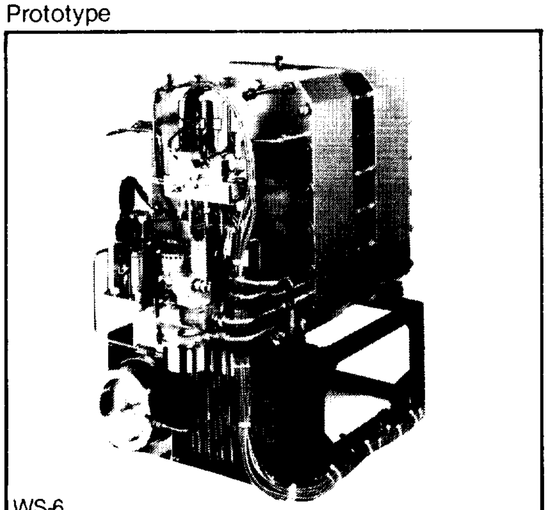
Preprototype (3-5 Person)



WS-3, No. 2

0.9 x 1.8 x 1.9 ft

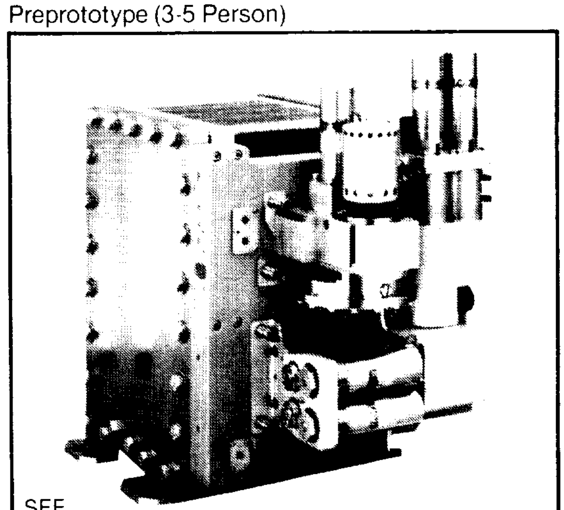
Prototype



WS-6

1.3 x 1.9 x 1.7 ft

Preprototype (3-5 Person)

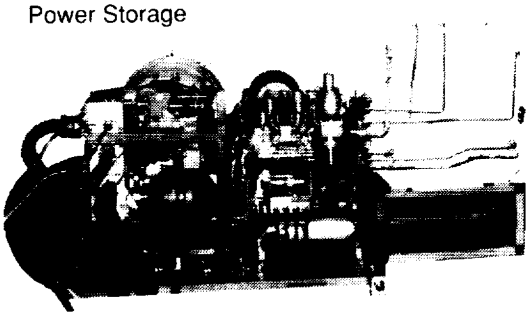


SFE

1.3 x 1.3 x 1.0 ft

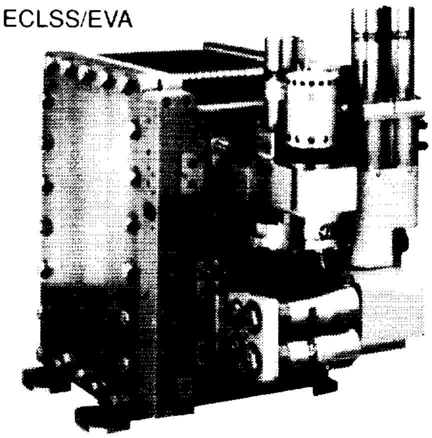
FIGURE 7 STATIC FEED WATER ELECTROLYSIS TECHNOLOGY IS MATURE

Power Storage



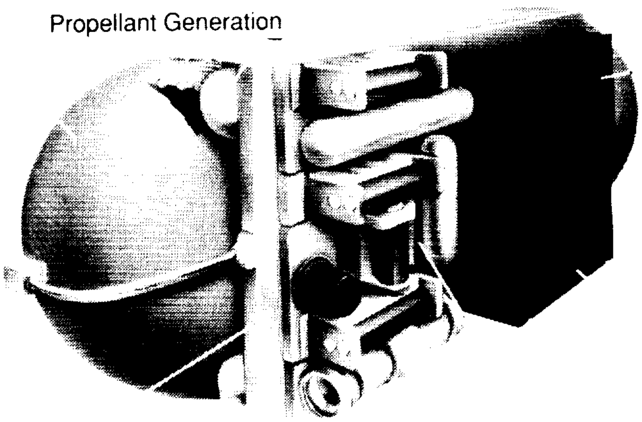
Regenerative Fuel Cell

ECLSS/EVA



O_2 Generation

Propellant Generation



High Pressure Oxygen/Hydrogen

NASA Center	Application
Johnson Space Center	Propulsion and Power Life Support EVA
Marshall Space Flight Center	Propulsion Life Support
Lewis Research Center	Power
Ames Research Center	Life Support

FIGURE 8 NASA CONSIDERING SEVERAL APPLICATIONS OF SFE

being accelerated much beyond what would be required onboard the Space Station Freedom. This, in effect, leads to increased endurance testing of these components above the actual hours over which they have operated.

The mechanical assemblies do contain moving and rotating components where reliability and operating constraints must be considered. These assemblies should be and are being examined as units rather than a series of individual components. Simplicity of design, installed redundancy, low speed motors, integrated gear shaft and aerospace-quality hardware are incorporated into each assembly design to ensure reliable operation and greater than 100,000 hours of operation.

FLIGHT EXPERIMENT OBJECTIVE/SCOPE

The overall objective of the EPICS flight experiment is to investigate how a low-G environment may improve water electrolysis performance by experimenting with various cell components of different microstructural characteristics, fluid flows, current densities and thermal conditions within the cell. The results will be used to improve static feed electrolysis process efficiency for propulsion, energy storage, life support, EVA, in-space manufacturing activities and in-space science activities.

Specific objectives of the experiment include:

1. Investigate the impact on cell performance of varying electrode characteristics, porosity and thickness, in low-G.

2. Evaluate performance improvement in low-G over a range of current densities.

4. Develop flight experiment hardware which is easily adaptable to other electrochemical research activities.

5. Develop flight experiment hardware which is safe and reliable.

6. Develop flight experiment hardware which requires minimal interaction by the crew, yet provides for means of positive intervention to enhance experiment success if necessary.

7. Develop flight experiment hardware which requires minimal National Space Transportation System (NSTS) integration efforts.

8. Bring attention to the concept of using low-G as a local resource.

JUSTIFICATION FOR CONDUCTING EPICS EXPERIMENT

The SFE technology is very important to meeting NASA mission needs/goals as illustrated in Figure 9. Hydrogen and Oxygen are key to the survival of humans in deep space and the technology is key to a Hydrogen/Oxygen based economy.

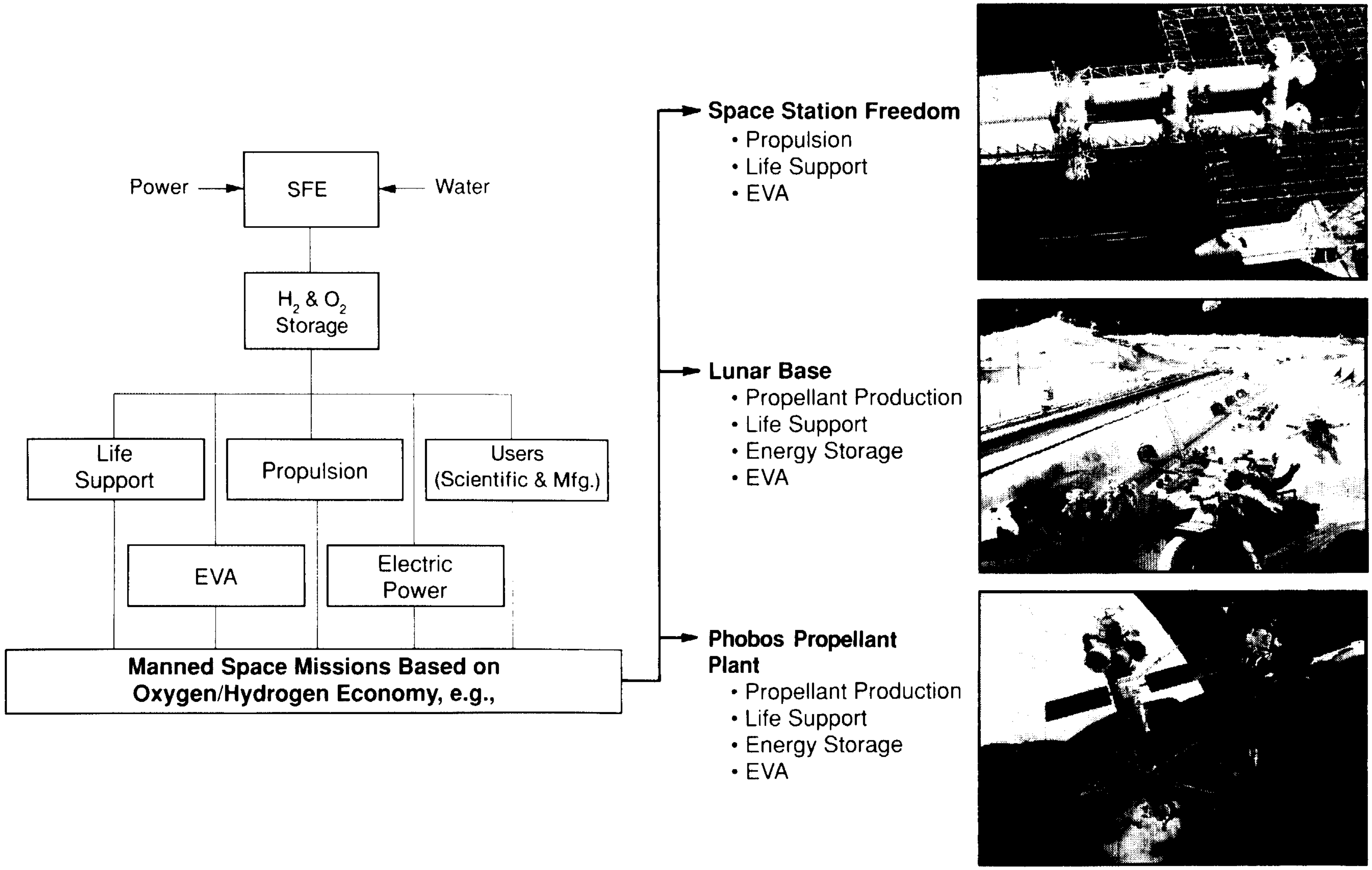


FIGURE 9 SFE APPLICATIONS MEET NASA MISSION NEEDS/GOALS

It is hypothesized that the low gravity environment will improve the performance of the SFE. This improvement would be a result of eliminating the effects of gravity on the electrolyte fluid distribution and electrolyte density distribution. (Further analysis of this is described in this report in the section entitled Analytical and Experiment Results.) Also, it should be noted, that demonstration of an improvement in performance of this electrochemical process would indicate, by correlation, definite improvement possibilities in the performance of other electrochemical processes. This impact will be very significant in view of the fact that electrochemical process technology will be a key to the industrialization of space.

The use of parabolic aircraft flights would not provide sufficient periods of low gravity environment for this investigation (25 to 30 seconds). As described previously, years of design effort and thousands of hours of testing in a one-G environment have been performed on the SFE technology to arrive at an efficient and reliable design applicable to manned space missions. The effects of low gravity on fluid flows and two phase systems have been analyzed and conservatively accounted for within the design of the SFE. Tests have also been performed on the hardware in several orientations to ensure that orientation has no noticeable effect on the operation. The result is a design which will perform reliably and efficiently, but does not incorporate the performance improvement factor of operating in low-G. The use of low gravity to enhance performance of the SFE must be demonstrated and investigated in a low gravity environment before mission planners will incorporate the benefits.

An example of the potential benefits/payoffs of SFE technology performance improvement is given by considering a lunar base advanced mission scenario, where O_2 is to be produced to meet the propellant requirements of advanced space exploration missions. The O_2 propellant production requirement is 1,000 tons per year for this scenario. An electrolysis performance improvement of only 0.01 V per cell would result in a savings in power generation capacity of approximately 4 kW for this scenario's O_2 production requirement. A voltage improvement of 0.02 V per cell would result in a savings of almost 8 kW. The improvement in performance can be realized as a savings in power generation capacity as described or as a savings in launch mass and volume, depending on the more critical design driver, i.e., if a nuclear power source is available, then launch mass and volume would be more important than power.

Interrelationship to Other Organizations

Development of the SFE technology has been a multi-agency effort. Figure 10 outlines the relationship of the technology development to the NASA organizations as well as other organizations involved. Also provided in Figure 10 is a listing of organizations which have supported the development of the static feed water electrolysis technology.

TECHNICAL DESCRIPTION OF EPICS FLIGHT EXPERIMENT

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

SFE Technology

National Research Council of Canada
- Power

National Aeronautics and Space Administration
- Power
- Propulsion
- Life Support
- EVA
- In-Space Manufacturing
- In-Space Science

Department of Energy
- Power

Department of Defense
- Power
- Propulsion
- Life Support
- EVA

ORGANIZATIONS SUPPORTING AND/OR HAVE SUPPORTED OUR WATER ELECTROLYSIS TECHNOLOGY DEVELOPMENT

- NASA Johnson Space Center, Propulsion and Power Division
- NASA Johnson Space Center, Crew and Thermal Systems Division
- NASA Lewis Research Center
- NASA Ames Research Center
- Boeing Aerospace Company
- TRW, Inc.
- Rocketdyne Division of Rockwell International
- Department of Energy (Via Brookhaven National Lab.)
- Defense Advanced Research Projects Agency (Via U.S. Navy)
- National Research Council (NRC) of Canada
- Life Systems, Inc.

19 Years of Development, 40 Contracts

FIGURE 10 INTERRELATIONSHIP OF EPICS EXPERIMENT TO NASA AND OTHER AGENCIES

Overall Experiment Design

The overall experiment design is shown pictorially in Figure 11 and schematically in Figure 12. The M/EA contains the integrated electrolysis units and all supporting pressure and temperature control components. The C/M I controls all operations of the M/EA and provides for monitoring and control of critical parameters and storage of data. Therefore, as shown in Figure 12, these two assemblies are interactive.

Table 1 lists general objectives for the design of the EPICS. The design specifications for the EPICS is given in Table 2. Fluid interfaces/resources of the EPICS hardware are defined in Table 3. Interface accommodations and safety requirements were defined in NSTS documentation.[5, 6, 7]

The EPICS has three different operating modes, as illustrated in Figure 13 and defined in Table 4. Three different transitions between the operational modes are permissible and are programmed into the C/M I.

Mechanical/Electrochemical Assembly

The M/EA of an EPICS experiment is illustrated in Figure 14 and schematically shown in Figure 15. The weight, power and volume characteristics are listed in Table 5. The functions of the various components are illustrated in Figure 15 and described here. Three Integrated Electrolysis (IE) units are enclosed in a Pressure Control/Safety Enclosure (PCSE). The IE units are thermally controlled using a heat pipe and heater configuration. Waste heat from the IE units is rejected to the heat pipe, which then rejects it to the circulating N_2 atmosphere within the PCSE. The heater transfers heat via the heat pipe to the electrolysis cell prior to start-up. Product gas pressures are controlled by direct interface between the PCSE and the product gas accumulators. The feed water is continuously replenished through automatic recombining of the product gases. No additional feed water, other than that contained in the original electrolyte, is needed. The manual valves are used during preparation of the IE units and are closed and capped off prior to flight.

The subsystem components are described in greater detail below.

Integrated Electrolysis Unit

A single IE unit is shown in Figure 16 with an exploded view of an IE unit shown in Figure 17. The major components of the IE unit include the following:

1. The electrolysis cell integrated with the oxygen/hydrogen recombiner.

2. The thermal control plate.

3. The oxygen and hydrogen accumulators.

THIS PAGE INTENTIONALLY LEFT BLANK

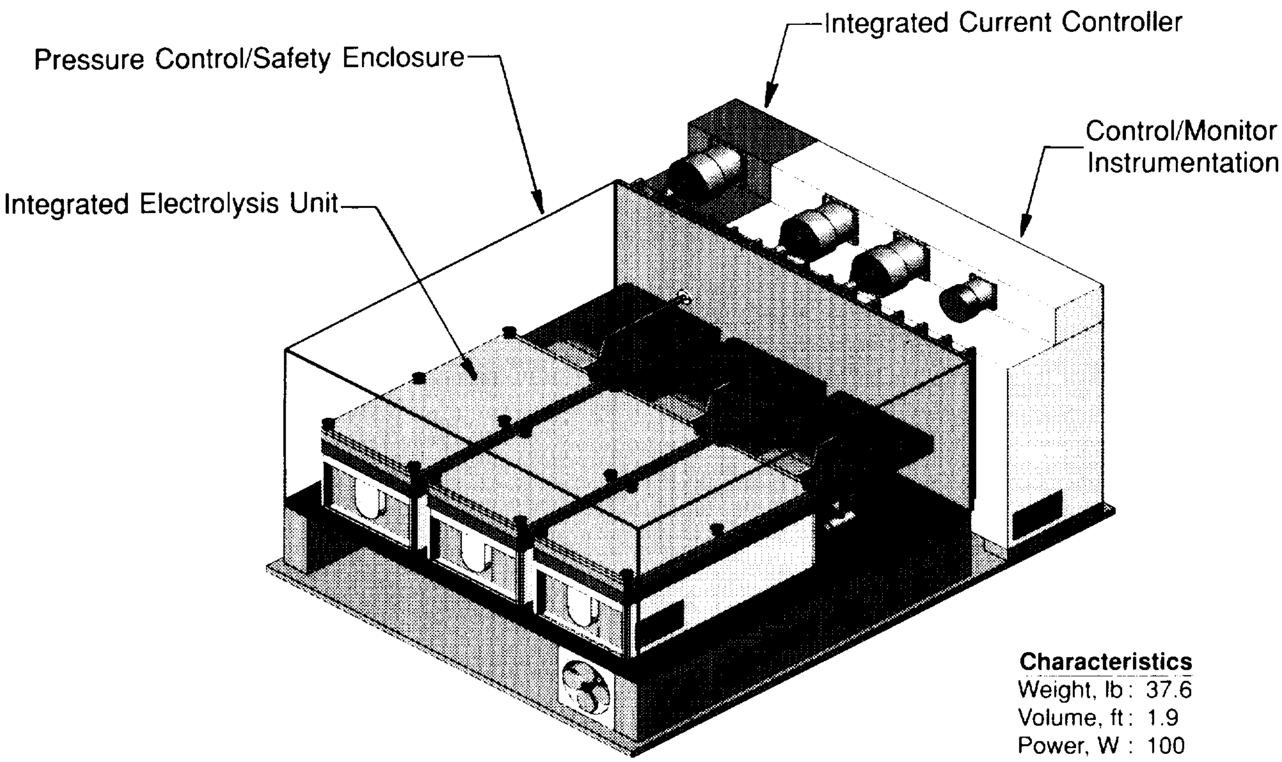


FIGURE 11 EPICS EXPERIMENT PACKAGING CONCEPT

THIS PAGE INTENTIONALLY LEFT BLANK

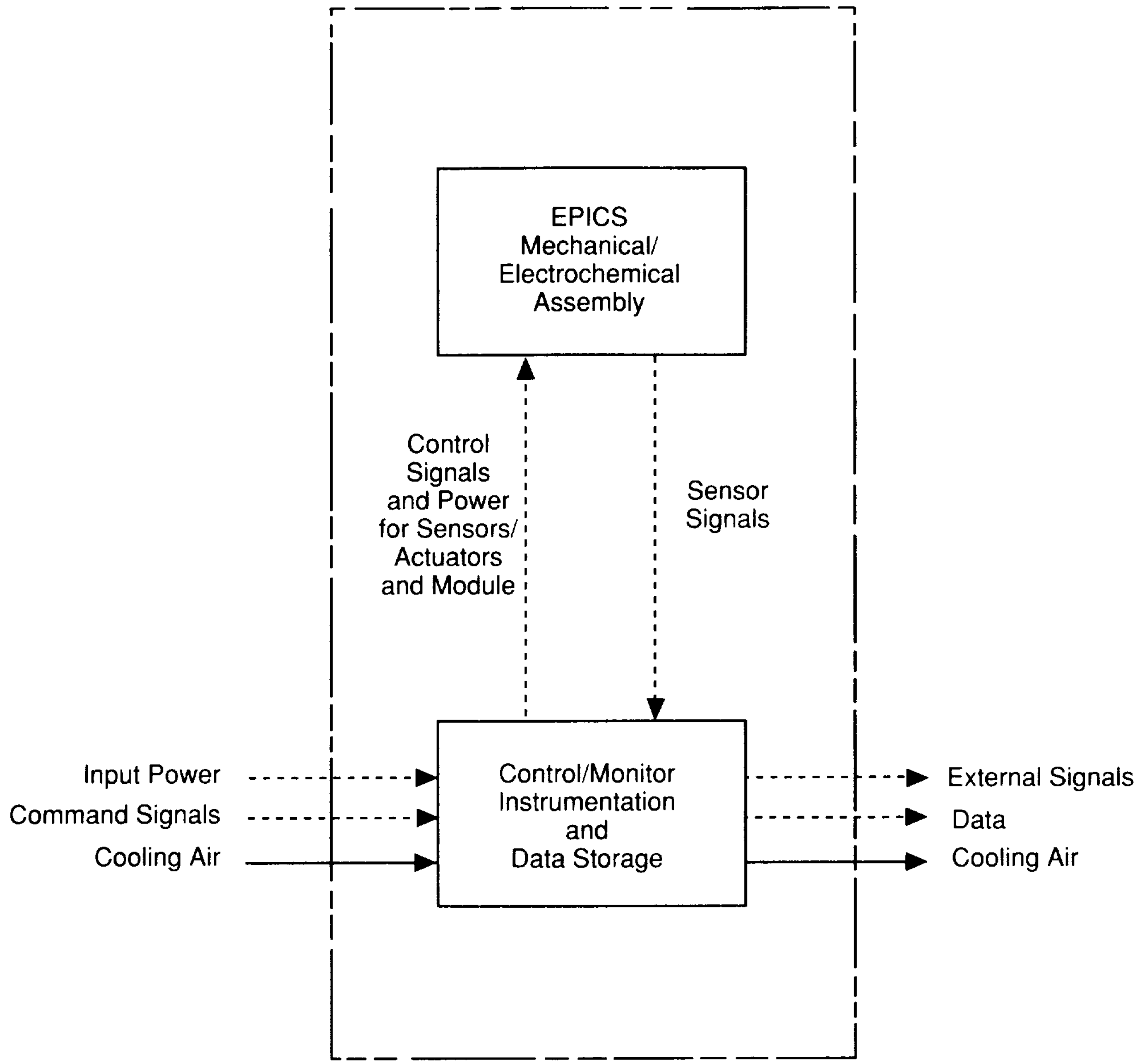


FIGURE 12 EPICS INTERFACE BLOCK DIAGRAM

TABLE 1 EPICS GENERAL DESIGN OBJECTIVES

Independent operation, requiring only electrical energy, and cooling air
Eliminate all variables except those being investigated
Fail-Safe Operation
Three Levels of Containment
Automatic Operation
C/M I Package Separately within Locker
Computer Based Instrumentation with Data Storage Capability
Shelf Life of up to 6 months
Compatible with Low, Partial and 1-G testing
Compatible with Standard Middeck Payload Requirements
- Weight – less than 54 lb
- Power – less than 115 W (maximum continuous DC)
- Power – none during ascent/descent
- Heat Rejection – Heat Pipe/Air cooling
- Does not require late installation
- Does not require early removal

All materials Flight Qualifiable

TABLE 2 EPICS DESIGN SPECIFICATION

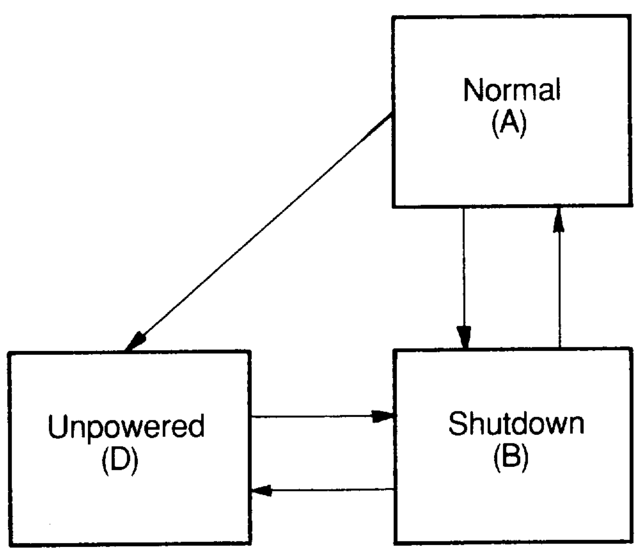
Vehicle Data	
Middeck Total Pressure, psia	14.7 ± 0.2
Middeck Temperature, F	65 to 80
Nominal Operating Conditions	
Number of Units	3
Number of Cells/Unit	1
Current Density, ASF	24-144
Operating Pressure, psia	13.7 ± 0.2
Operating Temperature, F	150 ± 2
Touch Temperature, F	≤113
Coolant Source	
Type	Heat Pipe to Air
Pressure, psia	14.7 ± 0.2
Temperature, F	65 to 80

TABLE 3 EPICS INTERFACES

Interface/Resource	Source
Water Supply	Self-contained in experiment
N_2 Supply	Self-contained in experiment
Coolant (air cooled)	Space Shuttle
Electrical Power	Space Shuttle
Data Acquisition/Storage	Self-contained in experiment
Crew Intervention/Operation	Single on actuator of experiment by operator. Crew intervention required only to enhance experiment success if an anomaly occurs.
Tools	No tools required

TABLE 4 EPICS OPERATING MODES AND UNPOWERED MODE DEFINITIONS

Mode (Code)	Definition
Shutdown (B)	IE Units are at ambient temperature. Current is at zero. The PCSE is at 14.7 psia. The experiment is powered and all sensors are working. The Shutdown mode is called for by: • Manual actuation • Low IE Unit Cell Voltage • High IE Unit Cell Voltage • High IE Unit Temperature • High PCSE Pressure • High PCSE Temperature • Power on reset from Unpowered Mode (D) • Mode transition from Shutdown Mode (B) to Normal (A) was not successful
Normal (A)	The IE Unit(s) are performing their function, as specified by the test sequence. The unit(s) are at normal operating temperature. The Normal Mode is called for by: • Automatic actuation
Unpowered (D)	No electrical power is supplied to the EPICS. The Unpowered Mode is called for by: • Manual actuation • Electrical power failure



• 3 Modes
• 2 Operating Modes
• 5 Mode Transitions
• 3 Programmable, Allowable Mode Transitions

FIGURE 13 EPIC'S MODES AND ALLOWABLE MODE TRANSITIONS

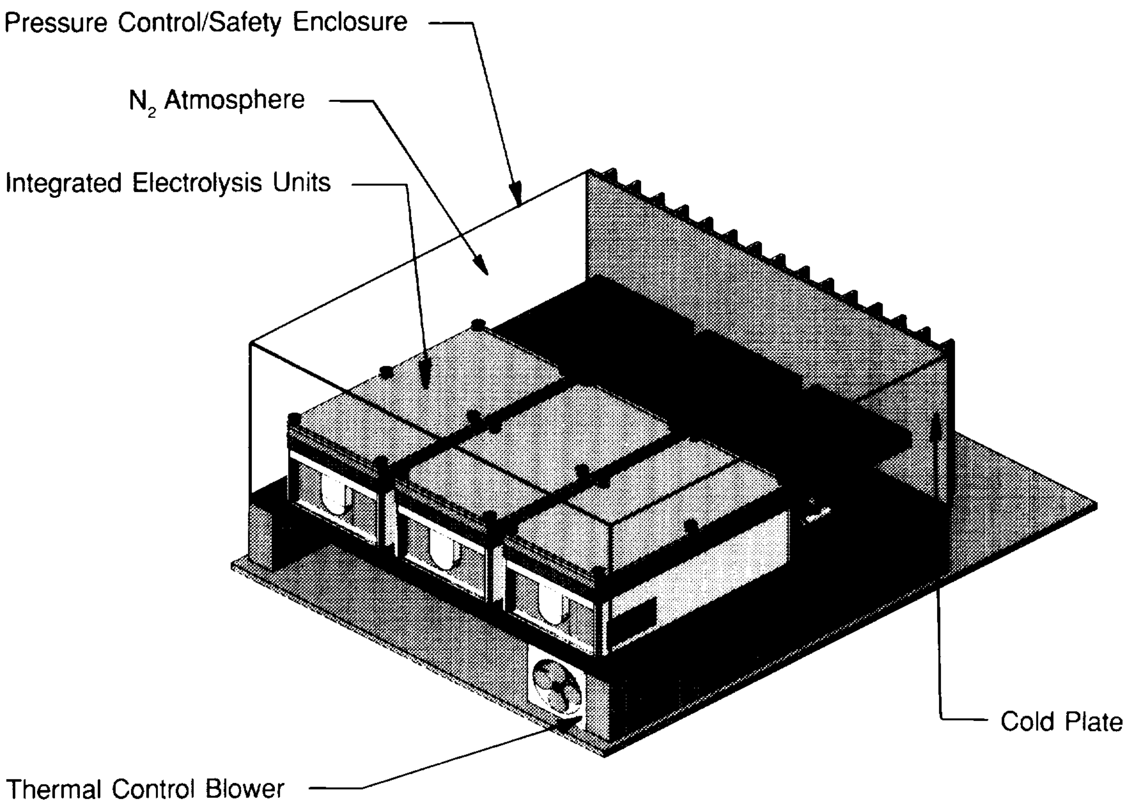


FIGURE 14 EPICS MECHANICAL/ELECTROCHEMICAL ASSEMBLY

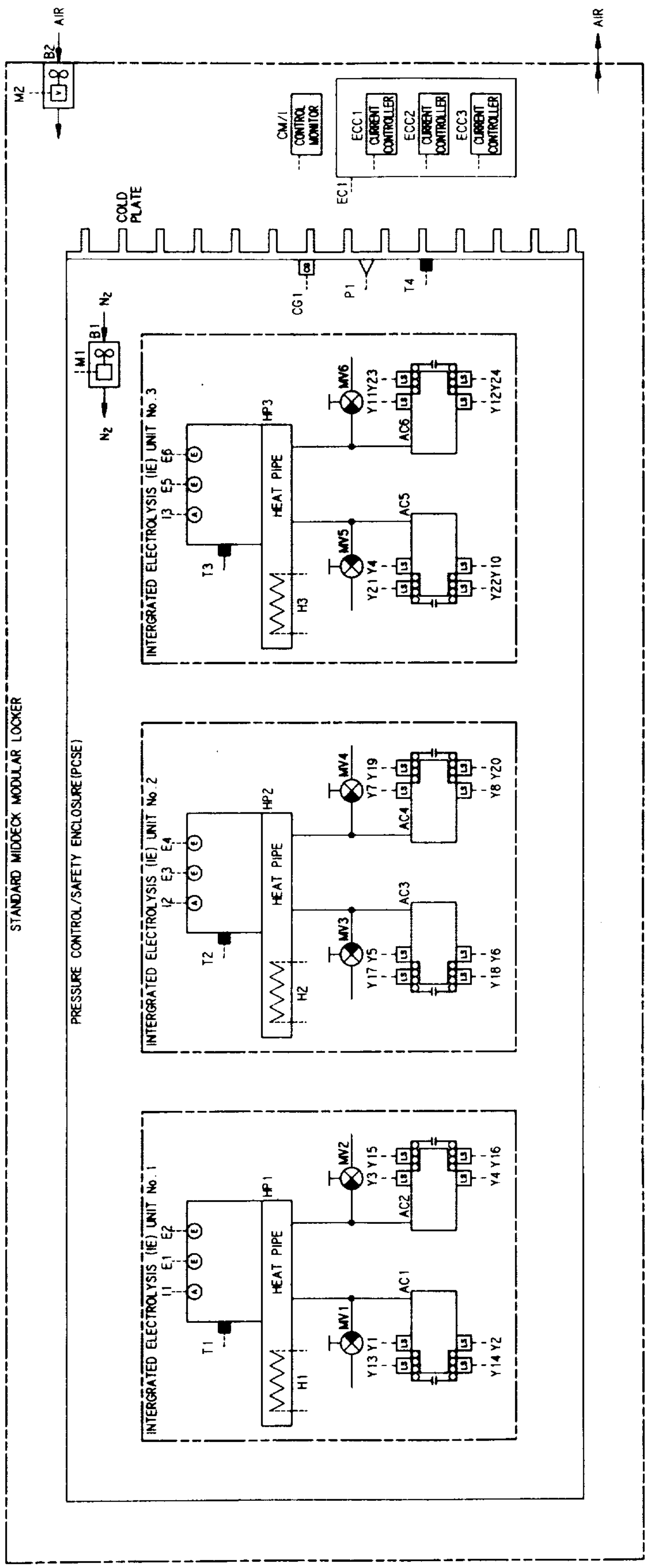


FIGURE 15 EPICS DETAILED MECHANICAL SCHEMATIC WITH SENSORS

TABLE 5 EPICS CHARACTERISTICS

Item No.	Description	Schematic Symbol	Qty.	Weight, lbs	Volume, ft^3	Power,[a] W
1	Integrated Electrolysis Unit	IE1, IE2, IE3	3	15.6	0.6	36
2	Blower	B1, B2	2	0.6	0.0	7
3	Combustible Gas Sensor	CG1	1	1.0	0.0	3
4	Pressure Sensor	P1	1	0.4	0.0	2
5	Temperature Sensor	T4	1	0.2	0.0	1
6	Pressure Control/Safety Enclosure	PCSE	1	5.1	1.0	0
7	Integrated Current Controller	IEC	1	3.0	0.1	33
8	Control Monitor Instrumentation	C/M I	1	7.2	0.2	18
9	Tray	–	1	4.5	0.0	0
10	Wiring	–	–	0.4	0.0	0
	Total			37.6	1.9[b]	100

(a) Operation at peak current of 12 Amps per IE Unit, all three operational.
(b) Not additive.

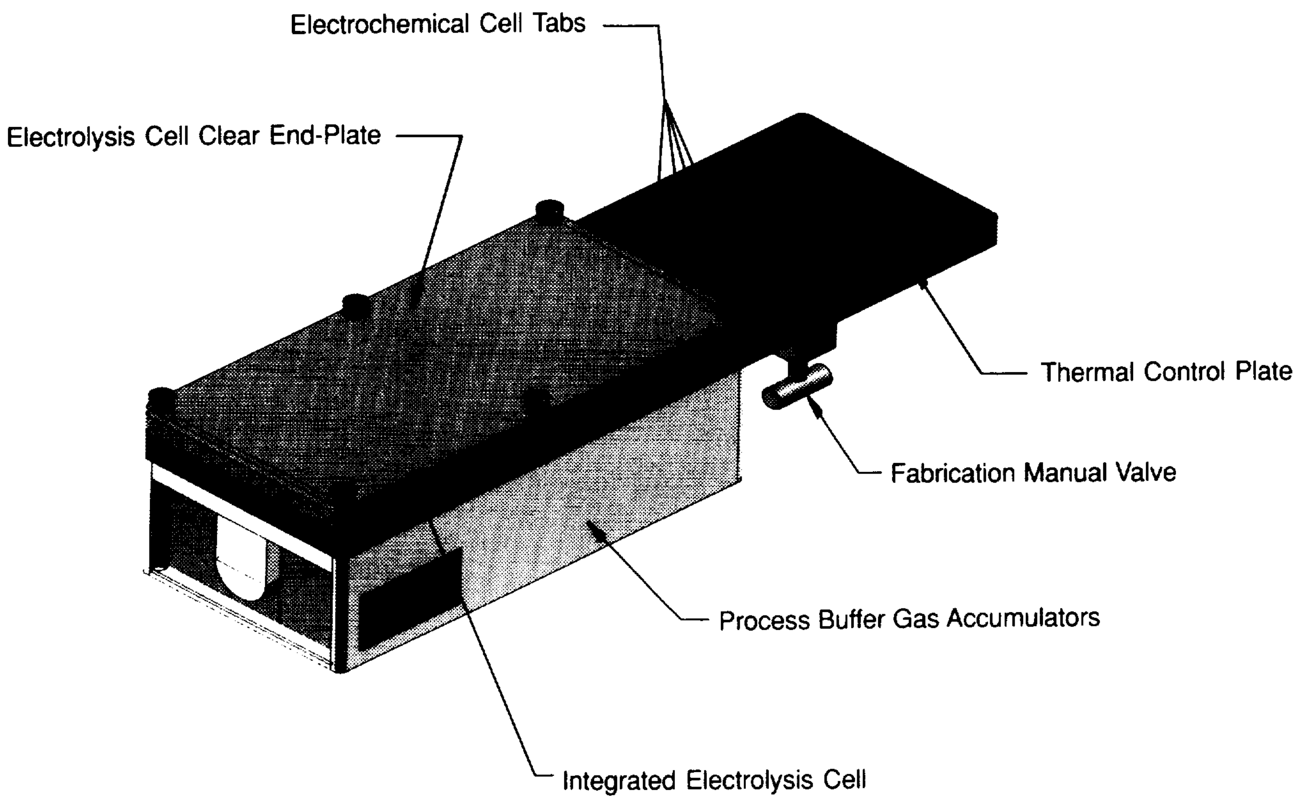


FIGURE 16 INTEGRATED ELECTROLYSIS (IE) UNIT

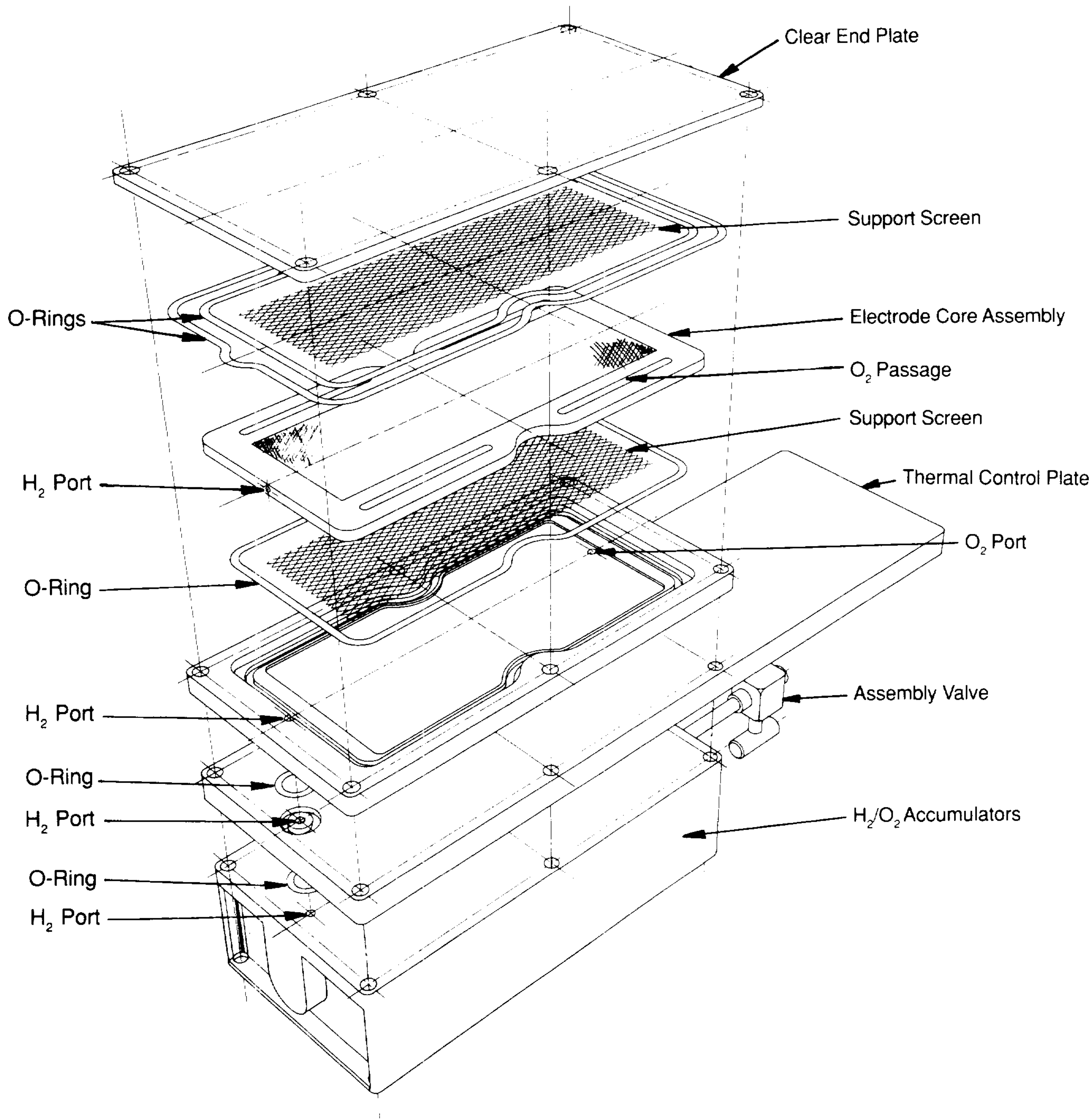


FIGURE 17 EXPLODED VIEW OF IE UNIT

Three IE units, weighing approximately 5.2 lb each, having different electrode configurations are included within the EPICS experiment. These electrode configurations, as well as the other components of the IE unit, are described in further detail below.

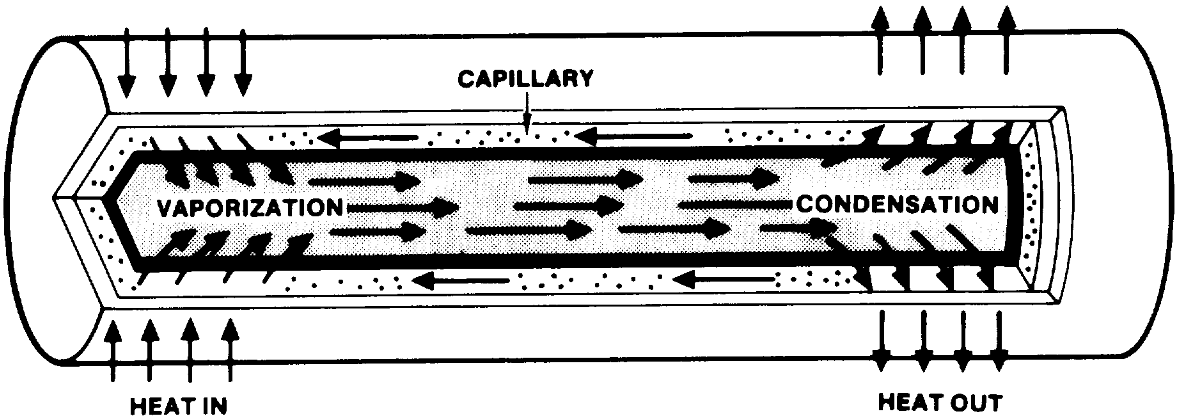
Electrolysis Cell - As described previously, the water electrolysis cells are the heart of the static feed water electrolysis subsystem. Three configurations of the electrolysis cell are included in the design of the EPICS as described in Table 6. The IE Unit No. 1 configuration is that of the baseline state-of-the-art SFE subsystem. The baseline configuration, as described for IE Unit No. 1, is an optimized configuration resulting from one-G testing. The IE Unit Nos. 2 and 3 vary from the baseline configuration to investigate a low-G optimum design.

TABLE 6 INTEGRATED ELECTROLYSIS UNIT CELL CONFIGURATIONS

	IE Unit No.		
Parameter	**1**	**2**	**3**
Matrix Thickness, mil	Baseline	(0.67) Baseline	Baseline
Electrode Thickness, mil	Baseline	Baseline	Baseline
Pore Size, μm	Baseline	Baseline	(0.5) Baseline
Porosity, %	Baseline	Baseline	TBD

Thermal Control Plate - The Thermal Control Plate is used to maintain the operating temperature of the electrolysis cell at 150 F and to provide heat input during the startup of the experiment. Heat pipes are used to maintain thermal control as shown in Figure 18. Variable conductance heat pipes, which maintain isothermal conditions without the use of variable heat sink requirements, i.e., N_2 flow across the condensing portion of the heat pipe, are also being considered. The Hughes Aircraft Company, who currently has a Phase B Outreach Experiment related to heat pipe thermal performance and working fluid behavior, has provided design information and data to the EPICS experiment design program.

Oxygen and Hydrogen Accumulators - The cross-section of the IE Unit given in Figure 19 illustrates the accumulators design. The accumulators are mechanical bellows which interface the higher pressure side of the bellows to the nitrogen atmosphere in the PCSE. This provides a positive pressure gradient from exterior to interior, eliminating the possibility of leakage of O_2 or H_2 from the IE Unit. Prior to startup, the bellows are compressed and the dead volume is minimized by design to minimize the amount of N_2 in the IE



Ref: Basiulis, A., Tanzer, H. and McCabe, S., "Thermal Management of High Power PWBs Through the Use of Heat Pipe Substrates" Sixth Annual International Electronics Packaging Conference, November 17-19, 1986, San Diego, CA.

FIGURE 18 TYPICAL CYLINDRICAL HEAT PIPE

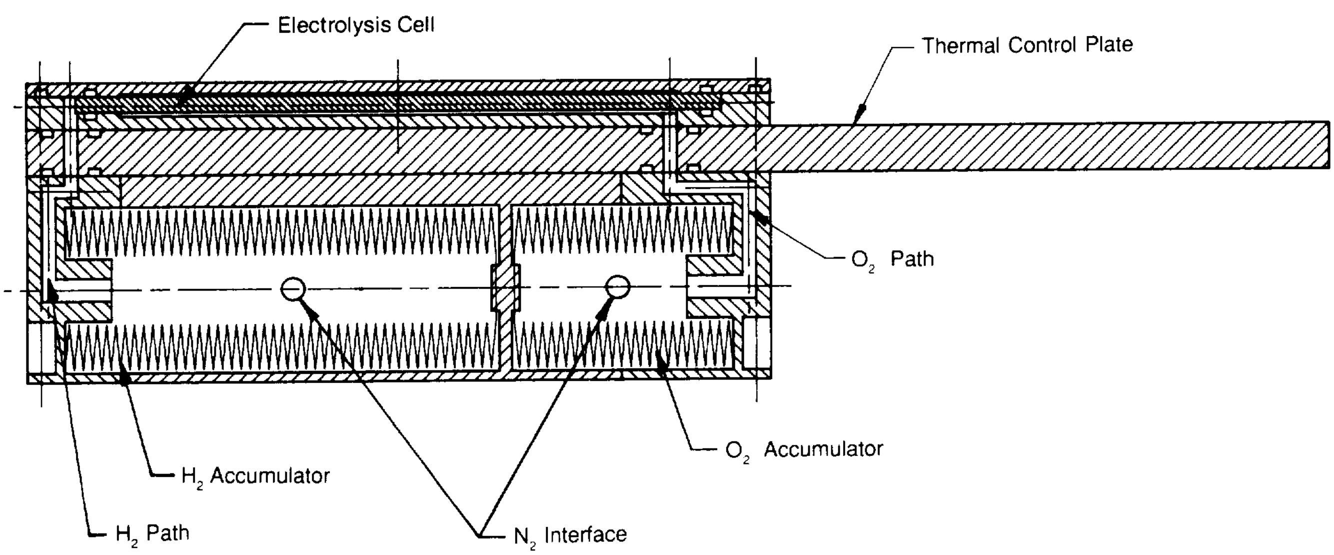


FIGURE 19 CROSS SECTION OF IE UNIT

unit. During startup, O_2 and H_2 generation occurs without O_2/H_2 recombination until the accumulators are at their full setpoint. This dilutes the amount of N_2 within the IE unit to an insignificant level. Bellow position sensors, Y1 through Y12, are used during startup to indicate that a specified amount of O_2 and H_2 generation has been completed. When this setpoint is reached, the O_2/H_2 recombiner is automatically activated. Position sensors Y13 through Y24 are included for safety and indicate a shutdown should be initiated if the amount of O_2 and/or H_2 is greater than the specified setpoint.

Pressure Control and Safety Enclosure

The PCSE is used to provide multiple functions, including: (1) pressure control of the IE Units, (2) safety via a N_2 blanket and (3) a heat sink for thermal control of the IE Units. The structure of the PCSE is made of Lexan or similar, with the back wall being made of aluminum with fins for heat rejection. Sealing of the PCSE joints to ensure that the N_2 atmosphere is maintained was evaluated. Two options for sealing the PCSE are illustrated in Figure 20. The PCSE interior pressure is 14.7 psia and the touch temperature is $\leq$113 F.

Ancillary Components

The ancillary components consist essentially of two blowers and standard temperature and pressure sensors. The first blower circulates the N_2 atmosphere within the PCSE while the second blower circulates middeck atmosphere through the locker, both of which are included for thermal control. There are no solenoid valves, pumps or separators required in the EPICS experiment. Tables 7 and 8 list the experiment actuators and sensors.

Control/Monitor Instrumentation

A microcomputer-based instrumentation hardware concept was selected to provide for parameter control, automatic mode and mode transition control, automatic shutdown for self-protection, monitoring and storage of subsystem parameters and interfacing with data acquisition facilities. Also included in this discussion is a description of the EPICS current controller, which controls the current supplied to each of the IE Units. The C/M I and Current Controller are illustrated in Figure 21. Figure 22 is a block diagram of the interactive sections and interfaces of the C/M I, current controller, M/E A and the middeck locker. A more detailed block diagram of the EPICS current controller is given in Figure 23. Design characteristics for the C/M I and Current Controller are listed in Tables 9 and 10.

C/M I General Description

The C/M I receives or transmits signals from or to the M/EA sensors and actuators and the current controller. Through these signals it controls and monitors flow rates, temperatures, voltages and currents in each operating mode (shown in Figure 13 and described in Table 4). It implements each mode as initiated automatically and provides fail-safe operational changes to protect the mission and experiment if malfunctions occur.

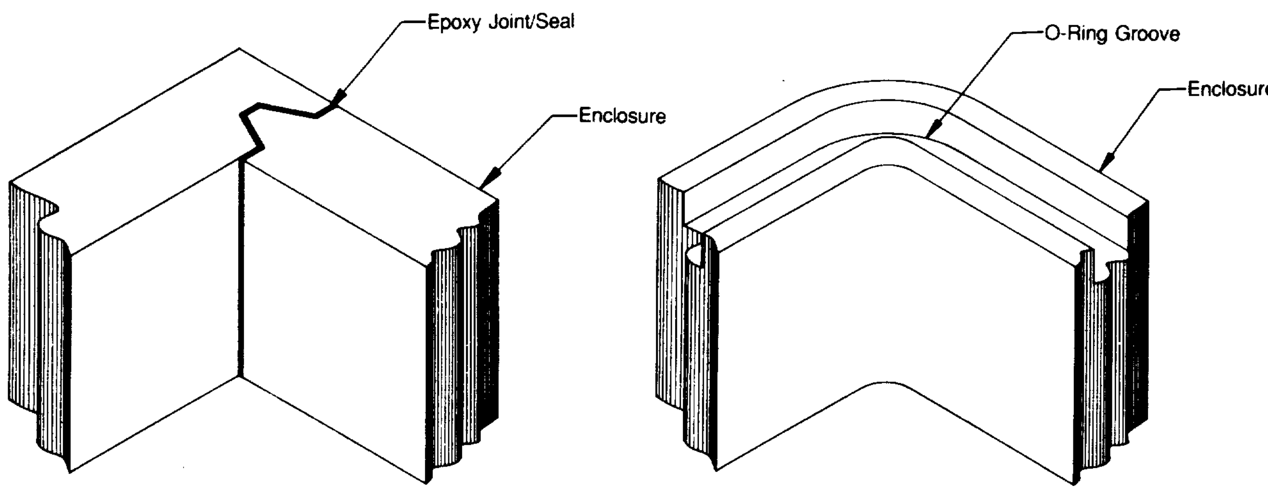


FIGURE 20 PRESSURE CONTROL ENCLOSURE SEAL OPTIONS

TABLE 7 EPICS FLIGHT EXPERIMENT ACTUATOR LIST

No.	Description	Qty.	Symbol	Type
1	PCSE Fan	1	B1	DC Motor
2	Locker Fan	1	B2	DC Motor
3	Thermal Control Plate Heater	3	H1, H2, H3	DC resistance
4	Current On/Off	3	X11, X21, X31	0 to 5 V Digital
5	Current Level	3	X21, X22, X23	0 to 5 V Analog
		11		

TABLE 8 EPICS FLIGHT EXPERIMENT SENSOR LIST

No.	Description	Qty.	Symbol	Type
1	Cell Voltage	6	E1 to E6	Voltage Tabs
2	Cell Current	3	I1, I2, I3	Shunt
3	Cell Temperature	3	T1, T2, T3	RTD
4	Enclosure Temperature	1	T4	RTD
5	Enclosure Pressure	1	P1	Strain Gauge/Bridge
6	Combustible Gas Sensor	1	CG1	Catalyzed Bead
7	Accumulator Level	24	Y1 to Y24	Hall Effect Switch
	Total	39		

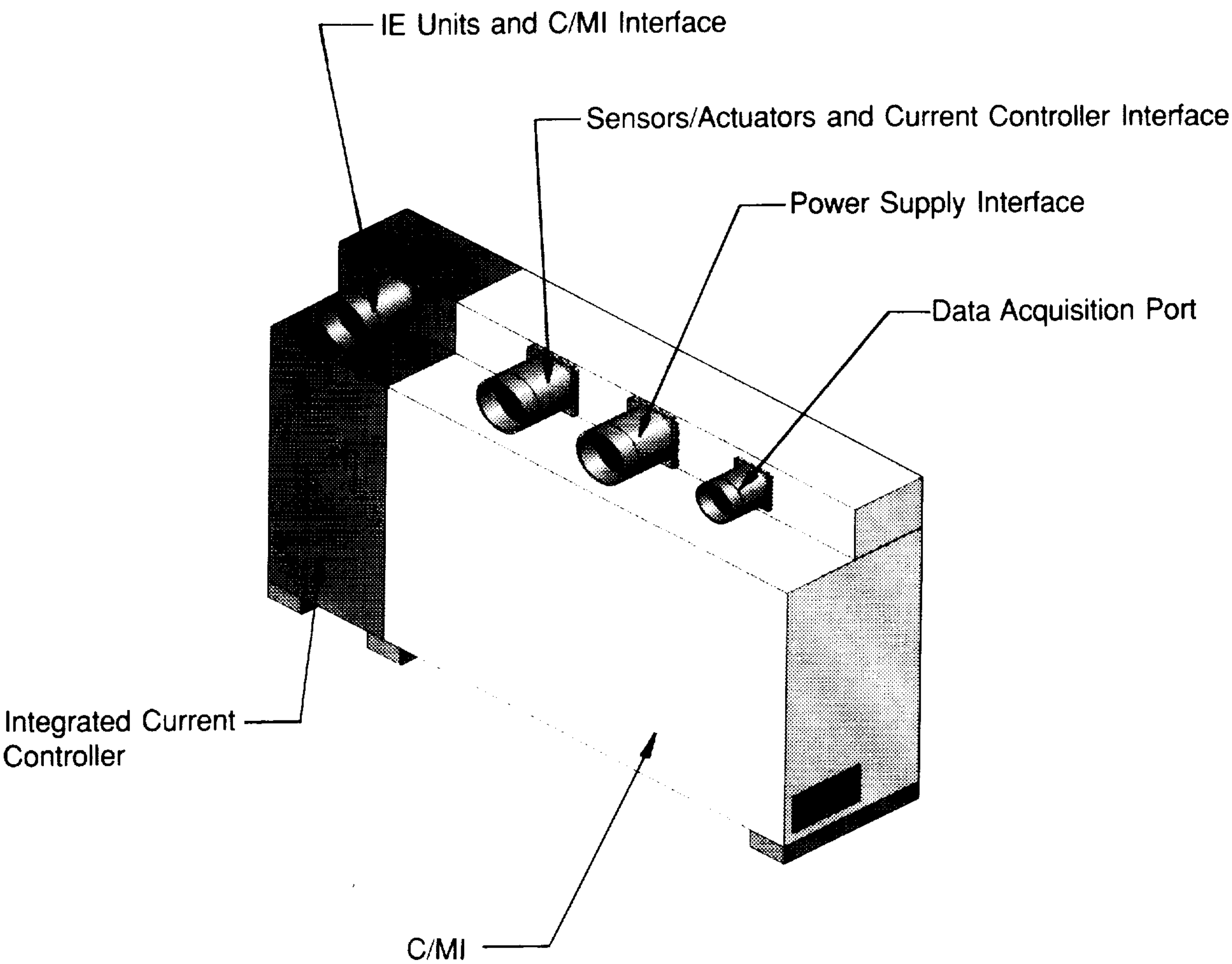


FIGURE 21 EPICS C/M I AND INTEGRATED CURRENT CONTROLLER PACKAGING

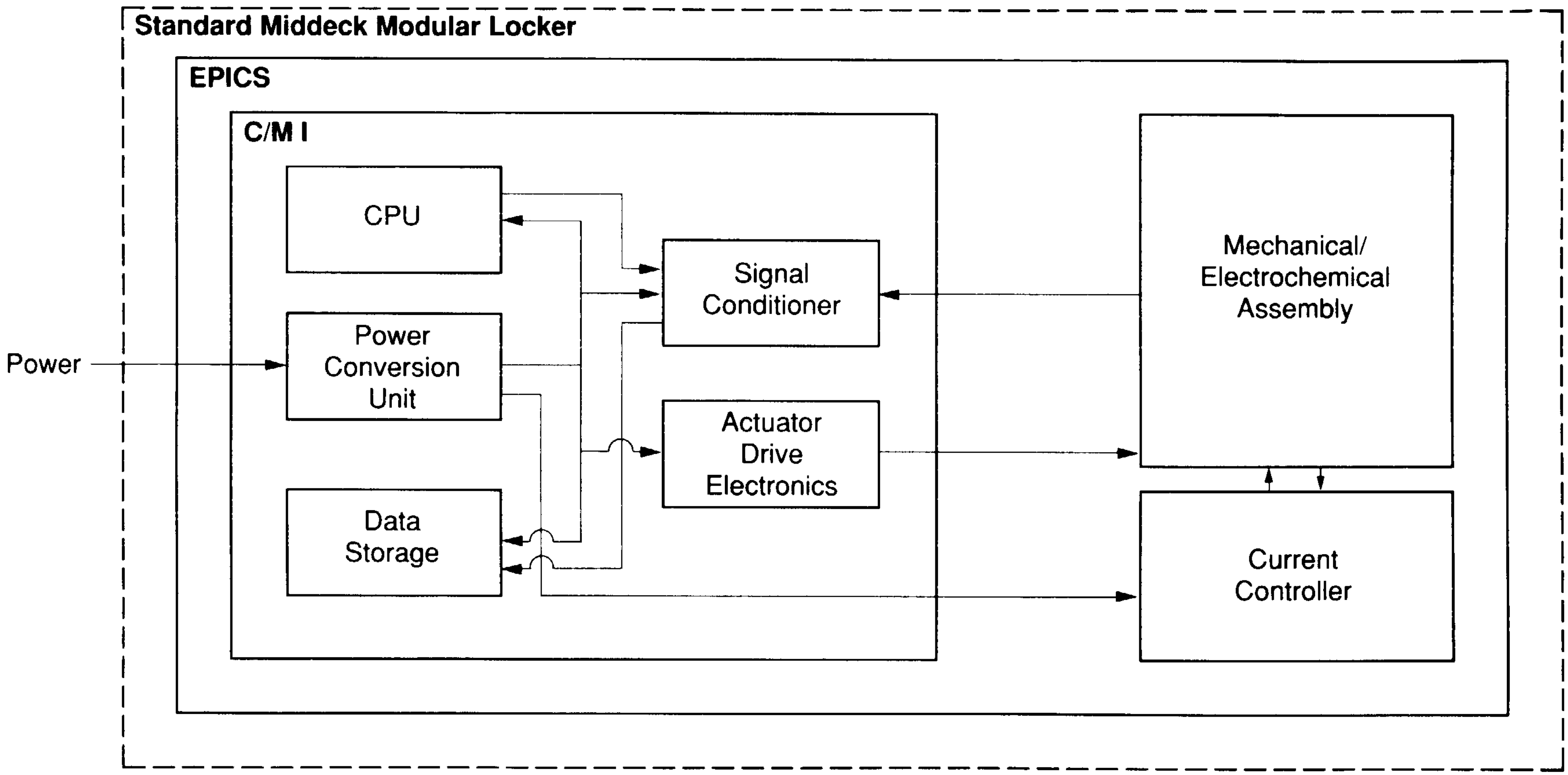


FIGURE 22 EPICS ELECTRICAL BLOCK DIAGRAM

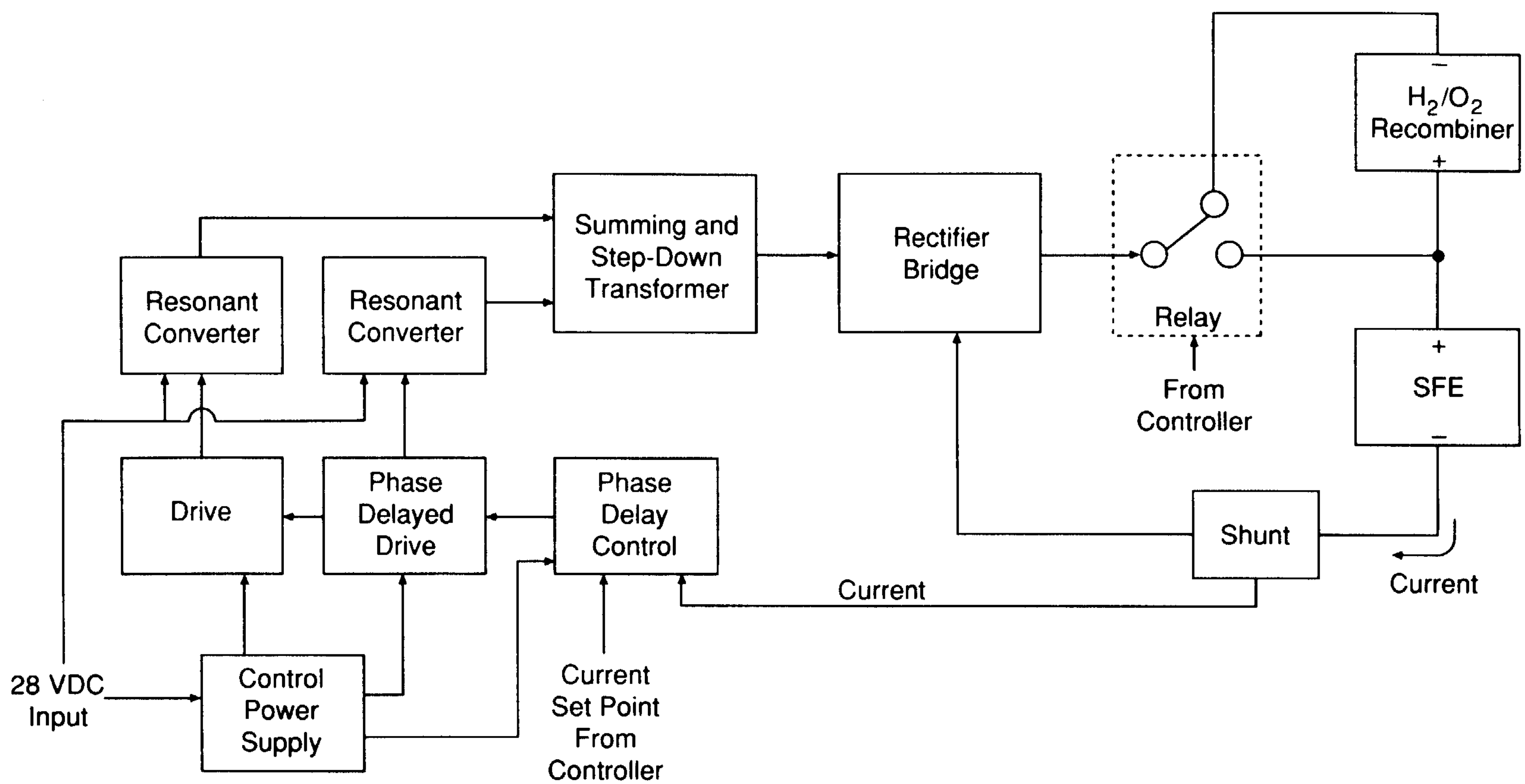


FIGURE 23 DETAILED BLOCK DIAGRAM OF EPICS CURRENT CONTROLLER (1 of 3)

TABLE 9 EPICS C/M I ENCLOSURE CHARACTERISTICS

No.	Description	Weight, lb	Size, in H	W	D	Vol, in³	Power, W
1.	Signal Conditioning						
	Excitation	0.2	0.75	4.75	4.75	16.9	3
	Multiplexer	0.1	0.75	4.75	4.75	16.9	1
	Signal Conditioning	0.1	0.75	4.75	4.75	16.9	1
	A/D & Comp. I/F	0.1	0.75	4.75	4.75	16.9	2
	Card Rack	0.6	3.0	5.0	5.0	75.0	–
2.	Computer card	0.3	0.60	6.75	4.5	18.2	6
3.	Power Supplies	1.3	2.5	3.0	2.2	16.5	2
4.	Connectors/Wiring	0.6	–	–	–	12.0	–
5.	Actuator Drive, Electronics	0.9	3.2	4.0	4.5	57.6	2
6.	Data Storage	0.8	3	8	12	288	1
7.	C/M I Enclosure	2.2	4	8	12	384	–
	Total	7.2	4 x 8 x 12 (Envelope)			384	18

TABLE 10 EPICS INTEGRATED CURRENT CONTROLLER CHARACTERISTICS

No.	Element	Qty.	Weight, lbs	Size, in H	W	D	Volume, in³	Power[a] Loss, W
1	Resonant Converter	6	0.94	3.0	7.5	1.7	38.4	6.0
2	Drive for Res. Conv.	6	0.12	1.2	1.5	1.3	2.4	0.6
3	Transformer	3	0.21	1.5	1.5	0.7	4.8	3.0
4	Rectifier Bridge	3	0.06	1.5	1.0	0.8	1.2	18.0
5	Control Board	1	0.20	3.7	7.7	0.5	14.2	1.0
6	Control Power Supply	1	0.10	1.0	1.0	0.3	0.5	1.0
7	Shunt	3	0.06	1.0	0.2	1.5	0.3	3.0
8	Relay	3	0.30	1.0	1.0	0.5	1.5	0
9	Enclosure	1	1.0	4	8	3	96	0
	Total		3.0	4 x 8 x 3 (Envelope)			96	32.6

(a) Operation at peak current of 12 Amps per IE unit and all three IE Units operational.

Operating Mode Control includes sequencing of actuators and checking parametric conditions as the transitions proceed. This procedure for control is fully automated by the C/M I so that the operator only needs to press the mode transfer request button to initiate startup or shutdown.

Experiment Control - Control algorithms/concepts were defined for specific subsystem parameters and sequences. The IE Unit current and temperature are controlled to preset values using closed loop, feedback controls.

Subsystem Monitoring - Critical EPICS experiment parameters were selected for monitoring and data storage to provide for automatic shutdown and self-protection. These parameters are given in Table 11 for the normal operating mode. Shutdown levels were selected for above and/or below nominal operating values. Parameter values which are stored in the data storage capability of the C/M I are listed in Table 12.

ANALYTICAL AND EXPERIMENTAL RESULTS

The results of prior analytical and experimental efforts have been incorporated into the design of an SFE capable of reliable and efficient O_2 and H_2 generation for space missions. The EPICS experiment is designed to further investigate ways by which a low gravity environment may improve water electrolysis performance by experimenting with various cell components of different microstructural characteristics, fluid flows, current densities and thermal conditions within the cell as the electrode core components are key to the performance of the SFE.

One-G experimental results provided the information required to design an SFE which maintains proper gas/electrolyte interfaces in the cathode and the anode of the electrode core. In this context, properly refers to the one-G design which maintains an electrolyte distribution which balances the resistances for optimum performance. The optimum design is one which has a uniform distribution of electrolyte and electrolyte composition across the entire area of the electrode core. Uniform composition and depth of electrolyte along an entire electrode area would provide even resistance to gas and liquid diffusion, even electrical resistance and consequently result in optimum performance.

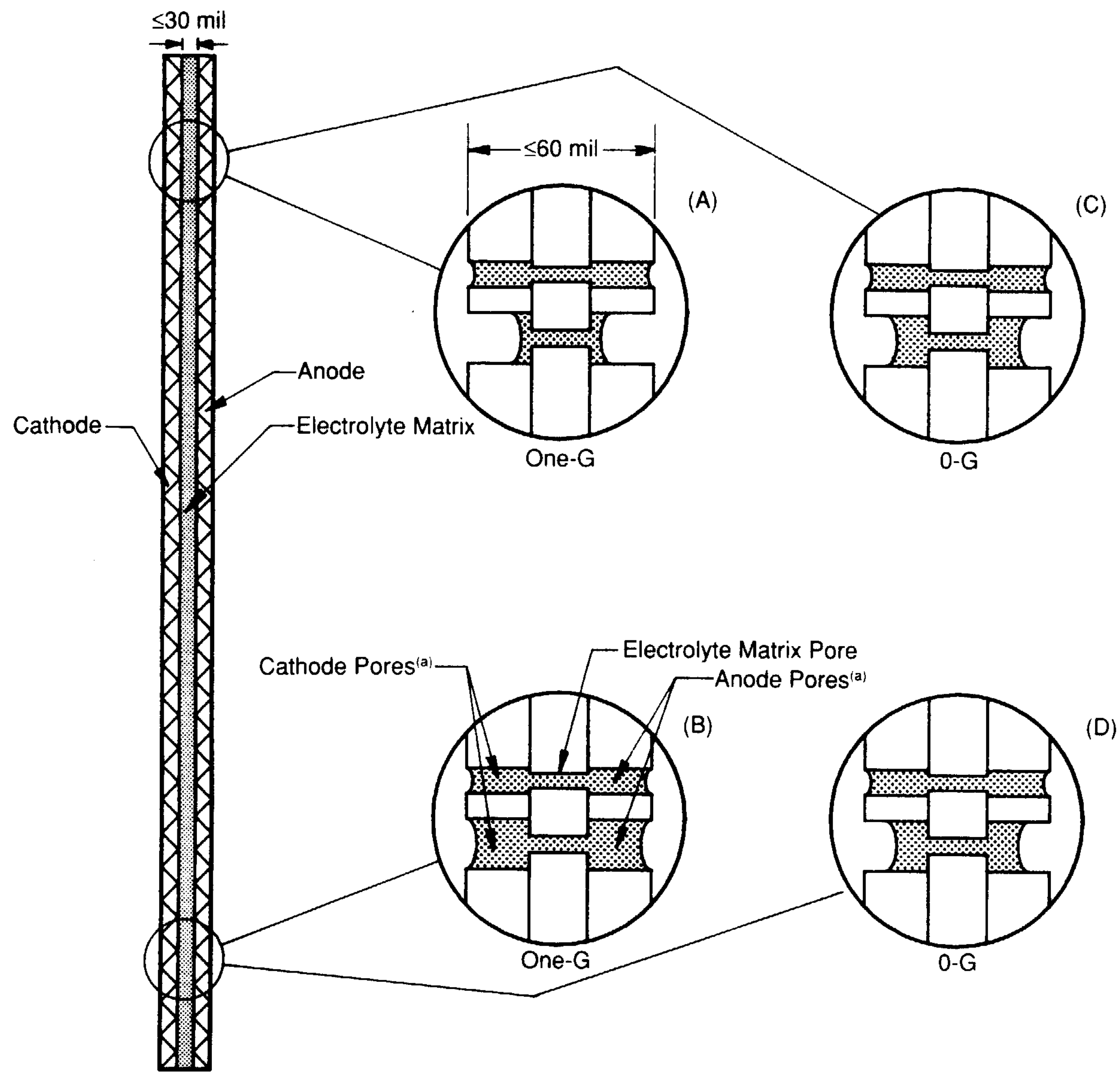
Figure 24 illustrates the gravity effects on the gas/liquid interface/ electrolyte distribution in a cross section of the electrode core. The illustration magnifies the electrode core to make the individual pores of the cathode, matrix and anode visible. As illustrated, there will be a range of pore sizes throughout each section of the core, i.e., cathode, matrix and anode. The matrix will have much smaller pores than either the cathode or anode, whose pores have similar pore size range. The capillary force of the smaller pores will be greater than that of the larger pores. The capillary forces of the larger pores may not be strong enough to completely counteract the force of gravity in one-G. This is seen in the illustration in circle A, where the electrolyte only partially fills the cathode and anode pores, compared to the complete filling of the same size pore in circle B. Circles C and D illustrate the same pores magnified in a 0-G condition. In the latter case, the capillary effects are not resisted by gravity and there is an even

TABLE 11 EPICS SHUTDOWN PARAMETERS

Parameter	Shutdown Level	
	Low	High
Cell Voltage	✔	✔
PCSE Pressure		✔
Accumulator Level		✔
IE Temperatures	✔	✔
PCSE Temperature		✔
Combustible Gas Sensor		✔

TABLE 12 EPIC DATA STORAGE PARAMETERS

Parameter	No. Sensors
IE Cell Voltage	3
IE Cell Current	3
IE Cell Temperature	3
PCSE Temperature	1
PCSE Pressure	1



(a) All pores will not be the same size.

NOTE:

1. Capillary effects in one-G may not be strong enough to completely counteract gravity effects.
2. The smaller pores will have stronger capillary force, which may be able to completely counteract gravity.
3. There is a gravity force gradient, from top to bottom in one-G. Resulting in a liquid distribution gradient.
4. In 0-G the gravity gradient is eliminated and therefore the liquid will be distributed evenly.
5. The gravity force gradient will also result in a density difference.

FIGURE 24 MAGNIFICATION OF GRAVITY EFFECTS ON GAS-LIQUID INTERFACE/ELECTROLYTE DISTRIBUTION electrolyte distribution. A density gradient-caused convection of electrolyte can also exist in a one-G environment, which will not exist in a 0-G environment. Eliminating both of these gravitational effects in 0-G should improve performance as shown in Figure 25.

Performance is projected to be improved in two ways. One will be a decrease in cell voltage, resulting in savings in power. The other will be an increase in the operational range of current density, resulting in improved operation flexibility.

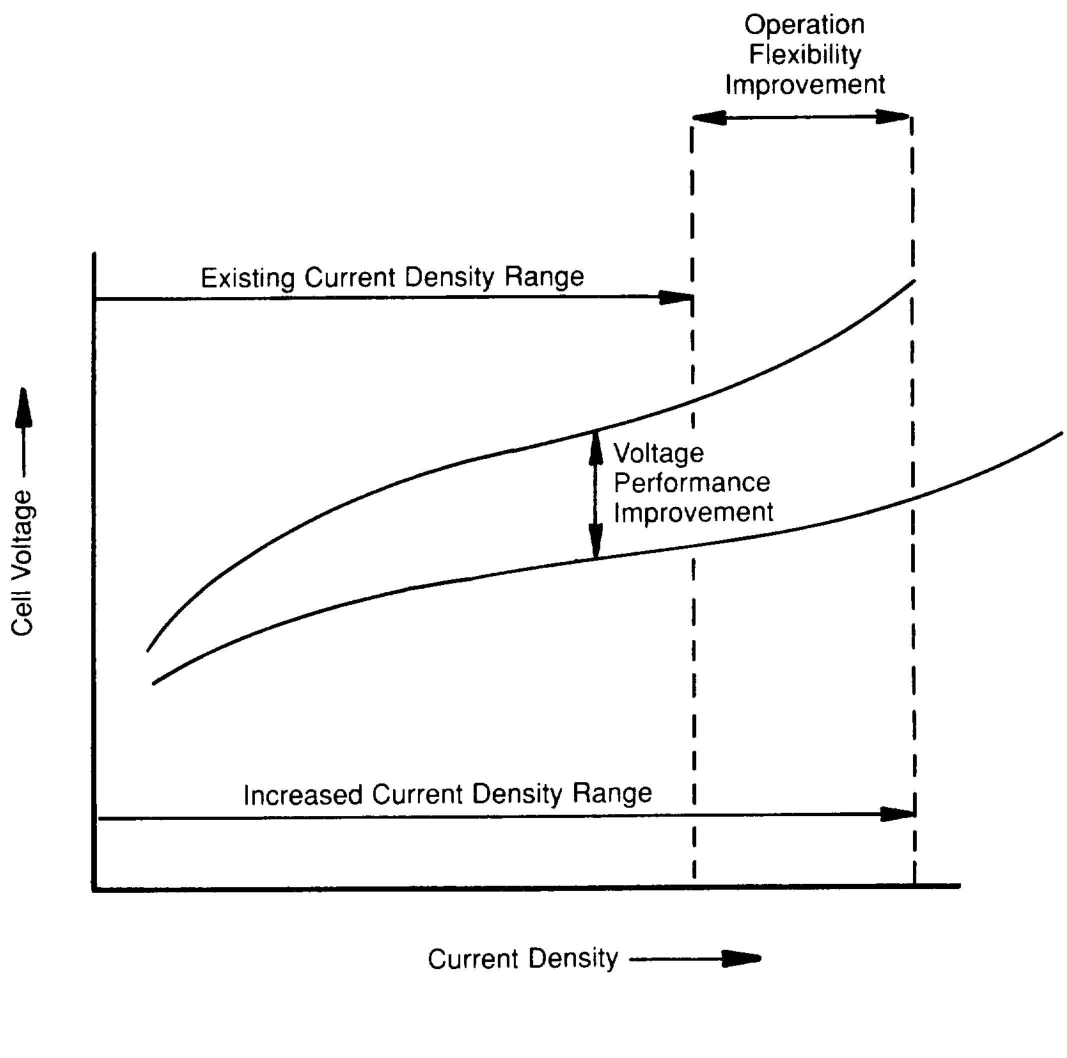


FIGURE 25 PROJECTED SFE PERFORMANCE IMPROVEMENTS OF 0-G ENVIRONMENT

Design Safety Analysis

Following are the results of the design safety analysis performed throughout the preliminary conceptual design program and incorporated into the EPICS design. The NSTS Safety Requirements documentation(7) was referred to throughout the analyses.

1. Product gas ports are separated and isolated.
2. Temperature sensing with shutdown protection.
3. Positive differential pressure from exterior to interior of the IE unit by the accumulator bellows.
4. Three levels of containment including O-rings, N_2 blanket and pressure control/safety enclosure.
5. Product gas accumulators are separated by a solid metal and the assembly valve interfaces are on opposite ends of the unit.
6. Pressure fluctuations eliminated by the bellows.
7. Accumulator level sensing with shutdown protection.
8. All product gases are contained within the IE unit.
9. Over-temperature protection is included with the thermal control plate heater.
10. Product gas volumes are minimized.

Design Reliability Analysis

Following are the results of the design reliability analysis performed throughout the preliminary conceptual design effort.

1. Multiple IE units included.
2. Last minute IE unit replacement procedure.
3. Elimination of all solenoid valves, pumps and separators.
4. Long-term database on materials of construction.
5. Low operating pressure (ambient pressure).
6. Accumulator uses metal bellows construction.
7. Few ancillary components to reduce complexity.

INITIAL COST AND SCHEDULE ASSESSMENTS

An initial assessment of the EPICS experiment cost and schedule is given in Table 13. This assessment covers the period beginning from initiation of the final design through the flight readiness review and launch.

Implementation Plan

Figure 26 provides an initial payload development and integration schedule for the EPICS experiment. The schedule contains tasks performed by the Space Transportation System, the payload supplier and joint activities. The overall schedule is 24 months. The NSTS Shuttle/Payload Standard Integration Plan for Middeck-type Payloads(8) and the Implementation Procedure for STS Payloads System Safety Requirements(9) were used as guidelines during the development of this preliminary plan. Figure 27 provides a flow diagram of the payload integration process.

TABLE 13 INITIAL ASSESSMENT OF EPICS COSTS AND SCHEDULE

Task Description	Cost, $ K	Duration, Months
Final Design	200	8
Phase 0 Safety Review		
Preliminary Design Review		
Phase I Safety Review		
Critical Design Review		
Phase II Safety Review		
Fabrication	200	7
Purchase Materials		
Configuration Management		
Quality Assurance		
Assembly		
Engineering Analyses	30	11
Loads Analysis		
Thermal Analysis		
EMI/EMC Analysis		
Testing, Qualification	50	6
Design Verification		
Certification		
Acceptance		
Interface Verification		
Documentation-Interface	25	5
Payload Integration Plan		
Payload/STS ICD		
PIP Annexes-1,2,3,6,7,8,9		
Total	505	24[a]

(a) Not additive since periods overlap.

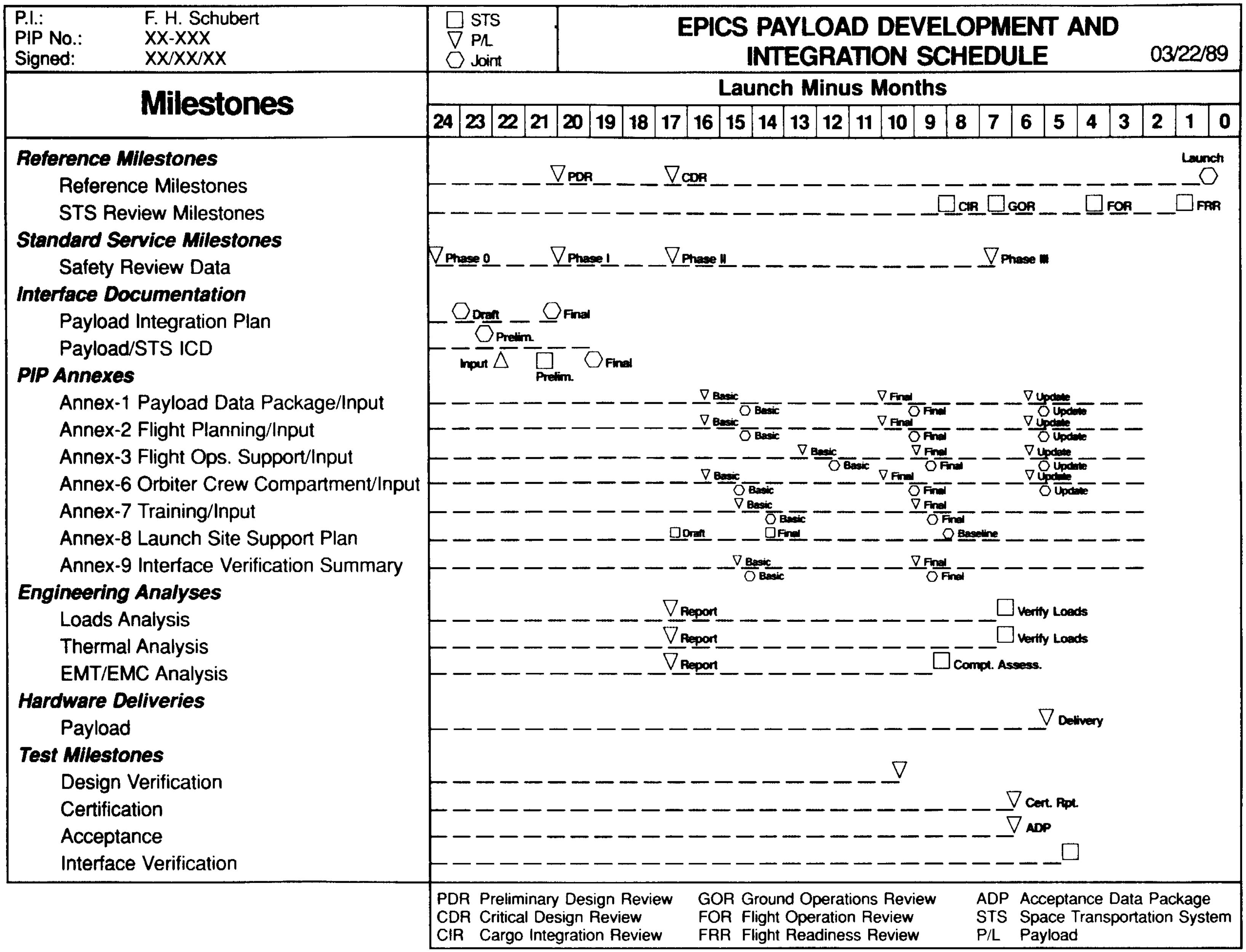
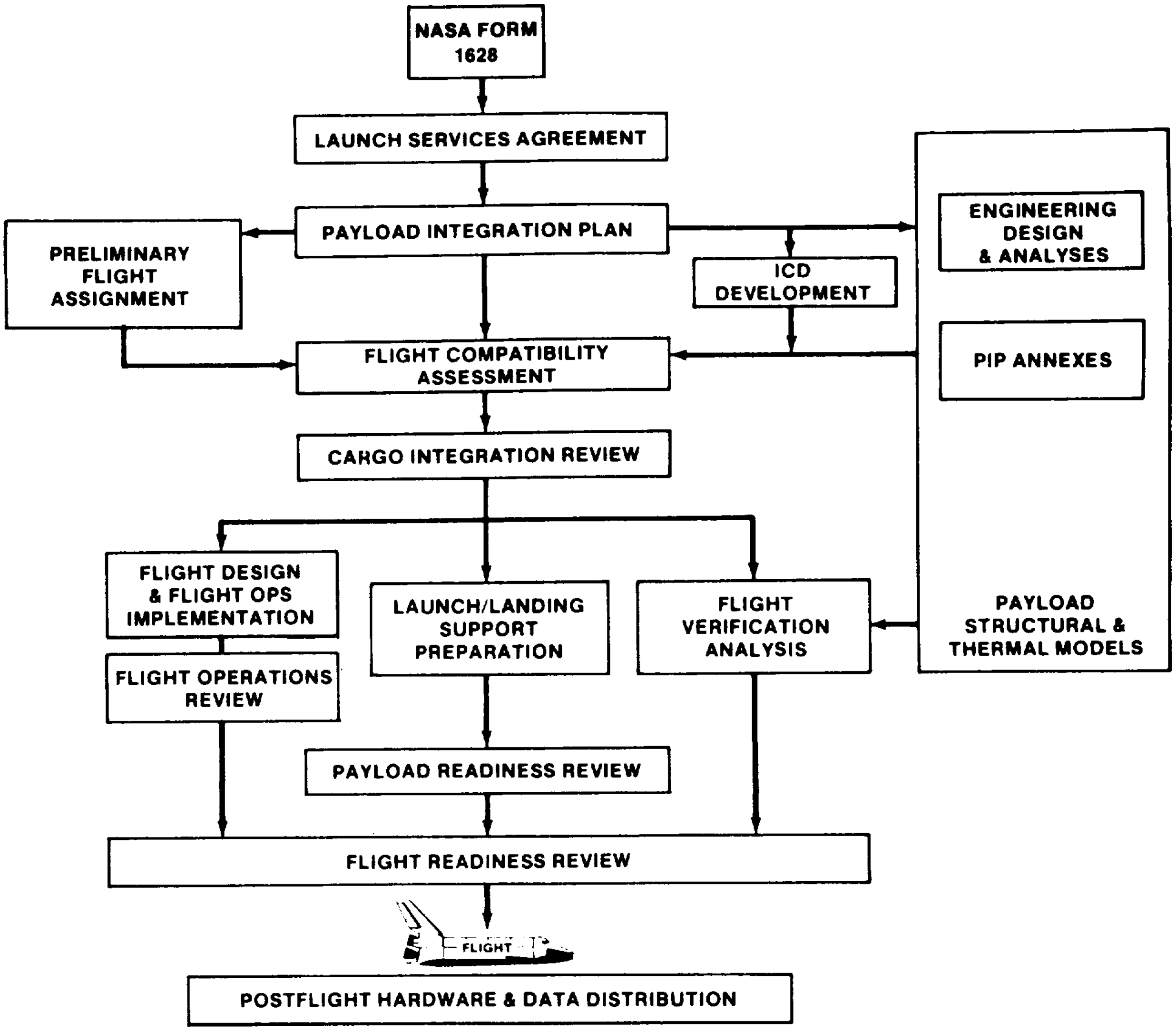


FIGURE 26 PAYLOAD DEVELOPMENT AND INTEGRATION SCHEDULE



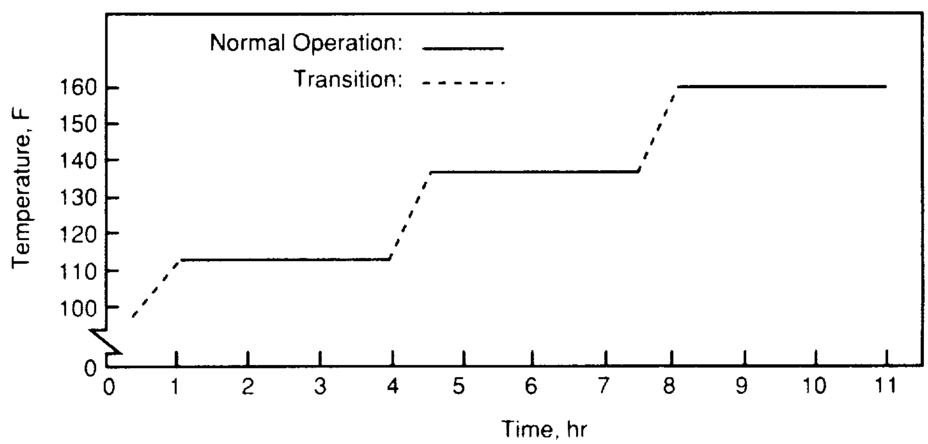
Ref: NSTS 07700, Volume XIV, Space Shuttle System Payload Accommodations, Revision J, 01/27/88

FIGURE 27 PAYLOAD INTEGRATION PROCESS

Preliminary Flight Test Plan Overview

A preliminary top level Test Plan for the EPICS experiment has been developed and summarized in Figure 28. All sequences will be controlled automatically by the C/M I.

Day	**1**	**2**	**3**	**4**	**5**
Current, A	**2**	**3**	**5**	**8**	**12**
Unit No. I, hrs.	10	10	10	10	10
Unit No. II, hrs.	10	10	10	10	10
Unit No. III, hrs.	10	10	10	10	10



Note: Each 10 hr period consists of three 3-hr periods with two one-half-hr periods between them.

FIGURE 28 PRELIMINARY FLIGHT TEST PLAN FOR EPICS EXPERIMENT

CONCLUSIONS

The following conclusions were reached based upon the EPICS experiment conceptual design efforts:

1. An Electrolysis Performance Improvement Case Studies (EPICS) experiment is required to investigate ways a low gravity environment may improve water electrolysis performance.

2. The results of an EPICS experiment will be used to improve static feed electrolysis (SFE) process efficiency for propulsion, energy storage, life support, EVA, in-space manufacturing activities and in-space science activities.

3. The EPICS experiment is capable of meeting all design requirements/ constraints of a standard middeck payload.

4. The EPICS experiment will require minimum crew interface for nominal operation. All modes and mode transitions, parameter monitoring and data storage will be performed automatically by the payload supplied C/M I.

5. The incorporation of certain safety features (O-rings, nitrogen blanket and Pressure Control/Safety Enclosure) meet the NSTS three levels of containment requirement without adding any significant weight, power or volume penalties to the experiment design.

6. The experiment has been defined with a minimum number of moving components to increase reliability.

REFERENCES

1. Schubert, F. H.; Lantz, J. B. and Hallick, T. M., "Development of a Static Feed Water Electrolysis System," Final Report, Contract NAS2-10306, CR-166142, Life Systems, Inc., Cleveland, OH; January 1982.

2. Schubert, F. H.; Lee, M. K.; Davenport, R. J. and Quattrone, P. D., "Water Electrolysis Systems: H_2 and O_2 Generation," Paper No. 78-ENAs-3, Intersociety Conference on Environmental Systems, San Diego, CA; July 10-13, 1978.

3. Schubert, F. H.; Wynveen, R. A. and Jensen, F. C., "Development of an Advanced Static Feed Water Electrolysis Module," Paper No. 75-ENAs-30, Intersociety Conference on Environmental Systems, San Francisco, CA; July 21-24, 1975.

4. Schubert, F. H. and Wynveen, R. A., "Technology Advancement of the Static Feed Water Electrolysis Process," Final Report, Contract NAS2-8682, CR-152073, Life Systems, Inc., Cleveland, OH; November, 1977.

5. Shuttle/Payload Interface Definition Document for Middeck Accommodations, NSTS 21000-IDD-MDK, March, 1988.

6. Space Shuttle System Payload Accommodations, NSTS 07700, Volume XIV, Revision V; January, 1988.

7. Safety Policy Requirements For Payloads Using the Space Transportation System, NHB 1700.7A.

8. Shuttle/Payload Standard Integration Plan for Middeck-Type Payloads, NSTS-2100-SIP-MDK, Revision A; December, 1988.

9. Implementation Procedure for STS Payloads System Safety Requirements, JSC 13830A; May, 1983.