TR-1415-57

ELECTROLYSIS PERFORMANCE IMPROVEMENT CONCEPT STUDY (EPICS) FLIGHT EXPERIMENT - REFLIGHT

FINAL REPORT

by

056878

F. H. Schubert

September 30, 1997

Prepared Under Contract NAS9-18568
DRL No. T-2244 (Line Item No. 22)
DRD No. SE-1299T

by

Life Systems, Inc.
Cleveland, OH 44122

for the

Lyndon B. Johnson Space Center, National Aeronautics and Space Administration

FOREWORD

This is the Final Report covering the reflight activities for the Electrolysis Performance Improvement Concept Study flight experiment program implemented under Contract NAS9-18568.

Franz H. Schubert was Program Manager and Co-Principal Investigator. Technical support has been provided by the following individuals:

D. N. Case	Electrical and Electronic Assembly
B. J. Chang, Ph.D.	System Mechanical Design and Analysis
M. G. Lee, Ph.D.	Electrochemical and System Engineering and Testing
D. W. Johnson	Control/Monitor Instrumentation and Data Storage and Pre- and Post-Flight Support
F. H. Schubert	System Design and Program Management

The program's Technical Monitor and Co-Principal Investigator was Ms. Sandra L. Brasseaux, 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

continued-

List of Figures - continued

LIST OF TABLES

LIST OF ACRONYMS

ASF	Amperes Per Square Foot
C/M I	Control/Monitor Instrumentation
CMC	Computer Monitor Circuit
ECLSS	Environmental Control and Life Support System
EPICS	Electrolysis Performance Improvement Concept Study
EPROM	Erasable Programmable Read Only Memory
EVA	Extravehicular Activity
GSE	Ground Support Equipment
IEU	Integrated Electrolysis Unit
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LED	Light Emitting Diode
M/EA	Mechanical/Electrochemical Assembly
NASA	National Aeronautics and Space Administration
OGA	Oxygen Generation Assembly
PWM	Pulse Width Modulation
RTD	Resistance Temperature Device
SDSU	Sensor Dedicated Shutdown Unit
SFE	Static Feed Electrolyzer
TCP	Thermal Control Plate
TSA	Test Support Accessories

SUMMARY

The overall purpose of the Electrolysis Performance Improvement Concept Study flight experiment is to demonstrate and validate in a microgravity environment the Static Feed Electrolyzer concept as well as investigate the effect of microgravity on water electrolysis performance. The scope of the experiment includes variations in microstructural characteristics of electrodes and current densities in a static feed electrolysis cell configuration. The results of the flight experiment will be used to aid in the design and to improve efficiency of the static feed electrolysis process and other electrochemical regenerative life support processes by reducing power and expanding the operational range. Specific technologies that will benefit include water electrolysis for propulsion, energy storage, life support, extravehicular activity, in-space manufacturing and in-space science in addition to other electrochemical regenerative life support technologies such as electrochemical carbon dioxide and oxygen separation, electrochemical oxygen compression and water vapor electrolysis.

The Electrolysis Performance Improvement Concept Study flight experiment design incorporates two primary hardware assemblies: the Mechanical/Electrochemical Assembly and the Control/Monitor Instrumentation. The Mechanical/Electrochemical Assembly contains three separate integrated electrolysis cells along with supporting pressure and temperature control components. The Control/Monitor Instrumentation controls the operation of the experiment via the Mechanical/Electrochemical Assembly components and provides for monitoring and control of critical parameters and storage of experimental data. The Electrolysis Performance Improvement Concept Study flight experiment hardware is designed to be a totally self-contained system and mounted into an envelope equivalent to two standard middeck lockers on a Shuttle Orbiter. The Electrolysis Performance Improvement Concept Study hardware mounts directly to payload mounting panels in place of middeck lockers.

The mission for the actual flight experiment is extendable to three consecutive cycles of two days each of approximately eight hours of testing under load each 24-hour day. The test plan consists of two current variations, 2 and 7 A (equivalent to 37 and 129 A/ft^2), over up to a six-day period. The Control/Monitor Instrumentation is designed to handle the complete sequencing of the experiment and storage of data. No special data links or audio visual equipment or special actions by the crew are needed.

The initial experiment was conducted on STS-69 Endeavor in early September 1995.

The initial EPICS flight experiment aboard STS-69, although shortened by unforeseen shutdowns, achieved the following:

1. Successful demonstration of the Static Feed Electrolyzer concept for on-orbit oxygen generation at 37 A/ft^2.

2. Successful demonstration of a unitized regenerative fuel cell concept for energy storage application.

3. Slight performance improvement in electrolysis operation.

4. Soundness of the water electrolysis concept itself and the mechanical design of the flight experiment.

A review of the STS-69 results, conducted by a National Aeronautics and Space Administration Johnson Space Center review team, resulted in the recommendation and subsequent implementation of certain hardware and software modifications and eventual reflight of the experiment. The results of these activities are discussed and presented in this final report and summarized below.

The flight hardware and software were upgraded by replacing a failed temperature sensor and adding a line of software code. Also, an electrical connector was added to the instrumentation for ease of ground testing and potential on-orbit troubleshooting.

The test program completed as part of the reflight effort consisted of functional verification tests, pre-acceptance and acceptance tests, flight testing aboard the Shuttle Orbiter Atlantis (STS-84) and post-flight testing.

One unit of the Electrolysis Performance Improvement Concert Study Flight Experiment successfully demonstrated on-orbit electrolysis operation for the planned three 48-hour cycles. The remaining two units completed only a portion of the initial cycle due to an undersized fuse and a low oxygen accumulator position indication. While the fuse was readily replaceable for post flight verification, the low oxygen accumulation indication is not yet fully understood and further evaluations are recommended.

The reflight of the Electrolysis Performance Improvement Concept Study Flight experiment achieved the following:

1. The successful demonstration of the Static Feed Electrolyzer concept for on-orbit oxygen generation at 37 A/ft^2 and 129 A/ft^2.

2. Discovery of no adverse or "surprise" side effects of operation in a micro-gravity environment.

3. Identification of thermal behavior and characteristics for future electrolyzer design inputs.

Based on the results obtained from the reflight activities it is recommended that an activity be initiated to define and investigate in detail the oxygen accumulator behavior observed with one unit, followed by a reflight at the earliest opportunity.

INTRODUCTION

The Electrolysis Performance Improvement Concept Study (EPICS) is a flight experiment to demonstrate and validate in a microgravity environment the Static Feed Electrolyzer (SFE) concept which was selected for the use aboard the International Space Station (ISS) for oxygen (O_2) generation. It also is to investigate the impact of microgravity on electrochemical cell performance. Electrochemical cells are important to the space program because they provide an efficient means of generating O_2 and hydrogen (H_2) in space. Oxygen and H_2 are essential not only for the survival of humans in space but also for the efficient and economical operation of various space systems. Electrochemical cells can reduce the mass, volume and logistical penalties associated with resupply and storage by generating and/or consuming these gases in space.

An initial flight of the EPICS was conducted aboard STS-69 from September 7 to 8, 1995. A temperature sensor characteristics shift and a missing line of software code resulted in only partial success of this initial flight. Based on the review and recommendations of a National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) review team a reflight activity was initiated to obtain the remaining desired results, not achieved during the initial flight.

Background

Advanced space missions will require O_2 and H_2 utilities for several important operations including: (1) propulsion, (2) electrical power generation and storage, (3) Environmental Control and Life Support Systems (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.

Detailed descriptions of the static feed process, its theory of operation and its performance have been discussed previously.[1,2,3,4] Figure 1 shows the electrolyzer cell schematic and reactions for the alkaline electrolyte process, while Figure 2 presents the simplified process schematic for the SFE concept. More detailed descriptions are presented in reference[5], the Final Report for the initial EPICS flight aboard STS-69.

Objectives

The objectives of the overall EPICS flight experiment activities are demonstration and validation of the SFE concept in microgravity and also to investigate how a microgravity environment may improve water electrolysis performance by experimenting with various cell components of different microstructural characteristics and different current densities.

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

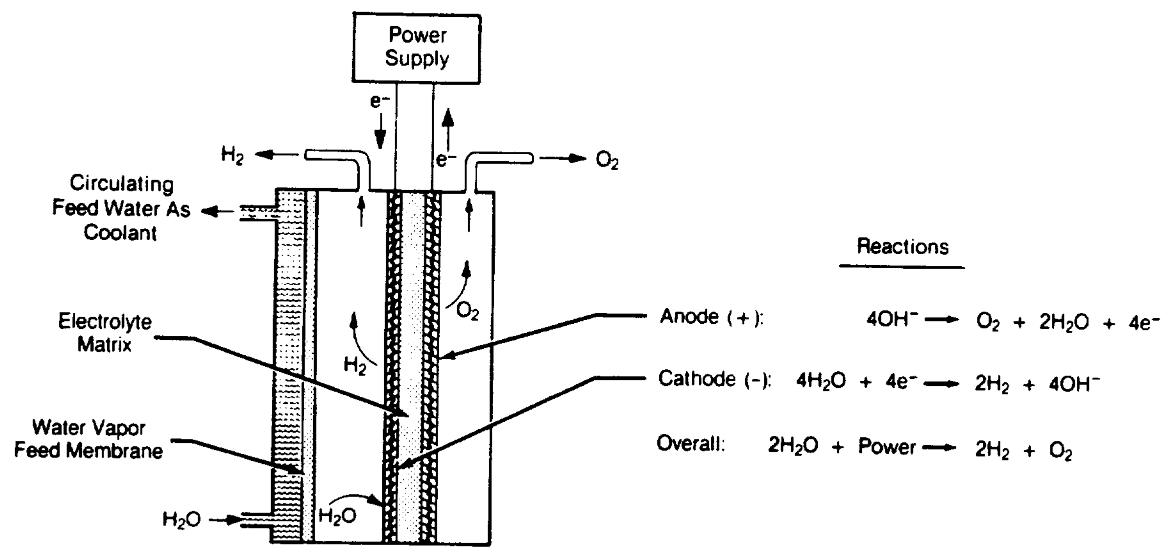


FIGURE 1 ELECTROLYZER CELL SCHEMATIC AND REACTIONS

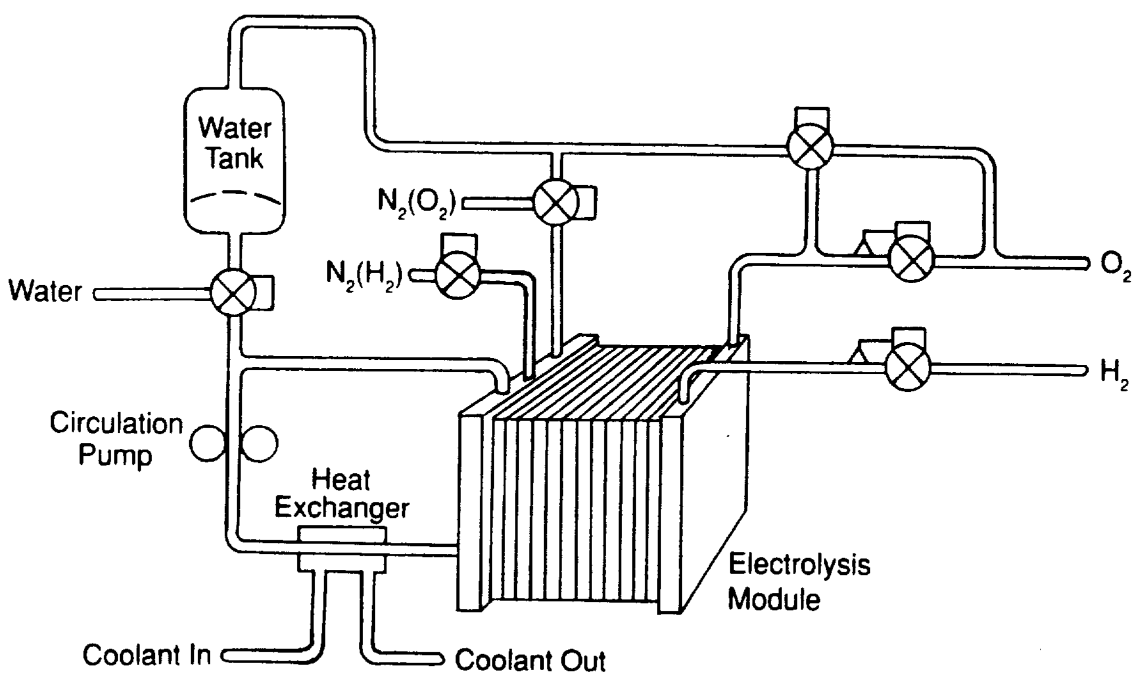


FIGURE 2 SIMPLIFIED SFE PROCESS SCHEMATIC

The experiment results will be useful in improving and understanding of factors influencing static feed electrolysis process efficiency for propulsion, energy storage, life support, EVA, in-space manufacturing activities and in-space science activities.

Relationship to NASA Goals

The EPICS flight experiment has a direct relationship with future National Aeronautics and Space Administration (NASA) mission needs/goals. The primary reason for this is that the experiment focuses on the SFE process for generating O_2 and H_2. Hydrogen and O_2 are key to the survival of humans in deep space and for the efficient and economical operation of numerous space systems. These space systems typically include: (1) ECLSS, (2) energy storage, (3) propulsion, (4) EVA and (5) special applications. The ECLSS application utilizes O_2 for the crew, the air lock repressurization and to replenish other external leakage. The ECLSS application also utilizes H_2 for the reduction of Carbon Dioxide (CO_2). The energy storage application utilizes O_2 and H_2 as reactants for a fuel cell. The propulsion application utilizes high pressure O_2 and H_2 as propellants. The EVA application utilizes ultra-high pressure O_2 to recharge the O_2 bottle in the extravehicular mobility unit. The special applications have unique O_2 and H_2 requirements to support in-space science and/or manufacturing activities.

The utilization of SFE technology as a space exploration utility is illustrated in Figure 3. It should be noted that although the primary focus of the flight experiment is the SFE electrochemical process, the information obtained from the flight experiment is applicable to a diverse range of electrochemical processes (i.e., recovery of O_2 from CO_2 in the Martian atmosphere, electrochemical CO_2 and O_2 separation, etc.).

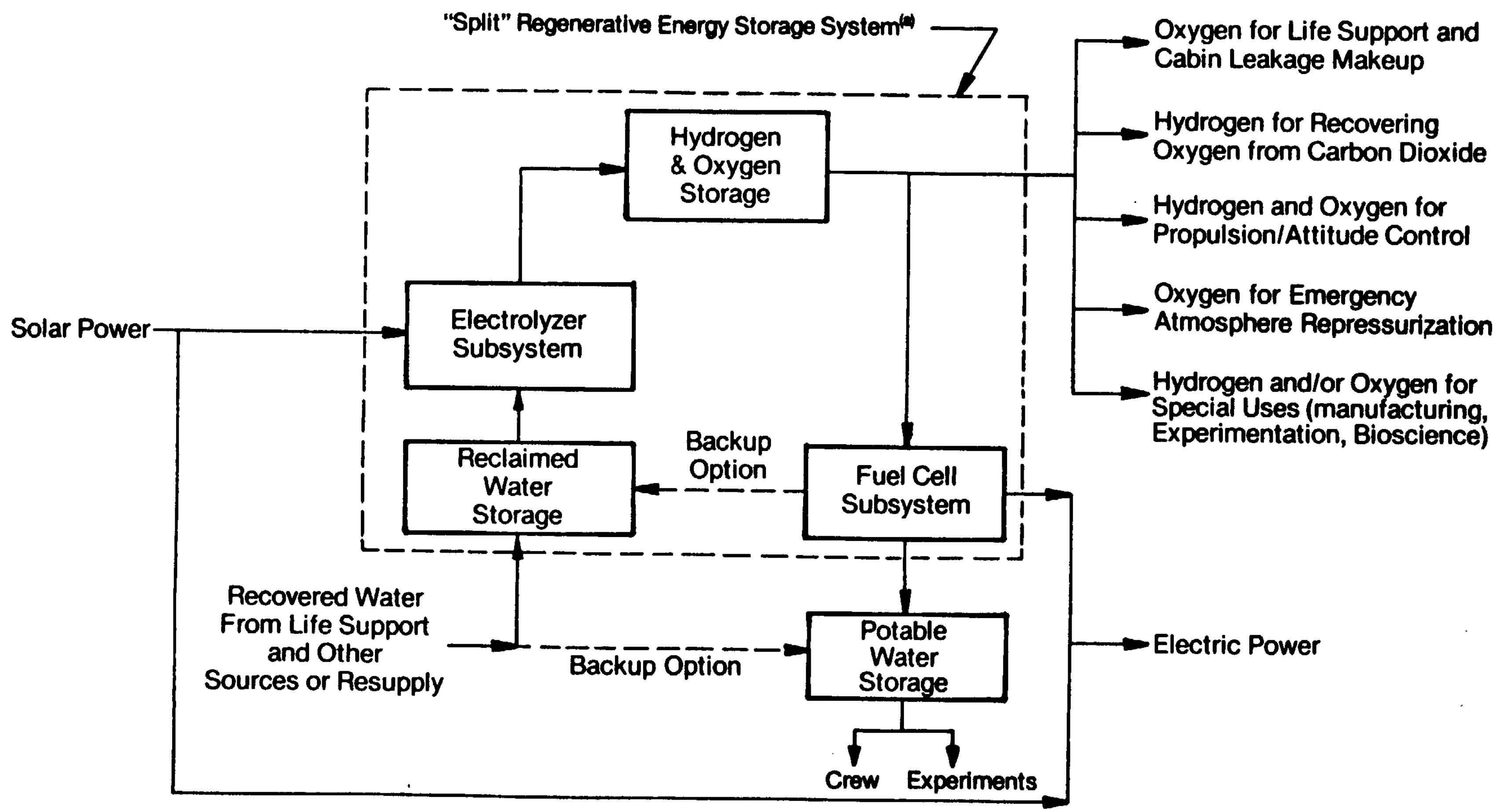
Timeliness of the Flight Results in Relation to Goals

The results of the EPICS flight experiment are timely for NASA's goals. The EPICS flight experiment results are obtained in sufficient time for Life Systems to incorporate potential design improvements into the ISS Oxygen Generation Assembly (OGA) Program. The OGA will supply the O_2 required for the crew of the ISS. In addition, the EPICS results could be utilized for other future manned missions to the moon or Mars.

Program Organization

To meet the objectives of the reflight activities the following eight tasks were defined and completed:

1. Review Results of First Flight (STS-69) and Define Upgrades and Modifications
2. Upgrade the Mechanical/Electrochemical Assembly
3. Upgrade the Control/Monitor Instrumentation



(a) Split less than a projected modular unit (e.g., <8 kW's worth)

Life Systems
CLEVELAND OHIO

B136

FIGURE 3 STATIC FEED WATER ELECTROLYSIS - A MANNED SPACE EXPLORATION UTILITY

4. Testing, Data Reduction and Analysis

5. Product Assurance

6. Pre- and Post-Flight Support

7. Program Documentation

8. Program Management and Control

End Products

The end products of the Reflight portion of this contractual effort are:

1. Drawings. Modified drawings.

2. Space Shuttle-Related Documentation. New and modified documentation required for Space Shuttle safety and integration activities.

3. Project Documentation. Program required documents, including this Final Report.

4. Flight Hardware. Upgraded and modified flight hardware and software and necessary support equipment delivered to the Kennedy Space Center (KSC) for reflight aboard the Space Shuttle STS-84.

5. Flight Data.

    a. Floppy disks containing the data gathered during the STS-84 flight, reduced to engineering units.

    b. Summary data plots and tables (contained in this report).

Report Organization

The following sections include separate discussions on the EPICS flight experiment hardware and software, Ground Support Equipment (GSE), Post-Flight (STS-69) hardware and software upgrades and modifications for the STS-84 reflight, Pre Flight, Flight (STS-84) and Post-Flight test results, followed by conclusions and recommendations. The discussions of the EPICS Flight Hardware and Software and of the GSE are only summarized herein, with detailed discussions presented in the Program's Initial Final Report(5).

EPICS FLIGHT EXPERIMENT HARDWARE

A block diagram representation of the EPICS flight experiment hardware design is shown in Figure 4. The EPICS design incorporates two primary hardware assemblies: the Mechanical/Electrochemical Assembly (M/EA) and the Control/Monitor Instrumentation (C/M I). The M/EA contains three separate integrated electrolysis cells along with supporting pressure and temperature control components. The C/M I controls the operation of the experiment via the M/EA components and provides for monitoring and control of critical parameters and storage of experimental data.

The EPICS flight experiment hardware is designed to be a totally self-contained system that can be mounted into an envelope equivalent to two standard middeck lockers on the Shuttle Orbiter. The EPICS hardware mounts directly to payload mounting panels in place of middeck lockers. The basic packaging concept is illustrated in Figure 5. Figures 6 and 7 show pictures of the flight hardware.

The EPICS flight hardware is mounted to two separate payload mounting panels. The M/EA and the C/M I have their own enclosures. The enclosures and the internal components, i.e., Integrated Electrolysis Units (IEUs), card cages, etc., are attached to mounting plates. The mounting plates are attached to the payload mounting panels.

Mechanical/Electrochemical Assembly

The EPICS M/E A is represented schematically in Figure 8. The M/E A includes three separate IEUs and ancillary components. These components are described below.

Integrated Electrolysis Unit

The IEU is an assembly of components that provide the physical capability for conducting the EPICS experiment. The functional schematic and the three dimensional view of an IEU are shown in Figures 9 and 10, respectively. The major components of an IEU include the following:

- Integrated electrolysis cell
- Thermal Control Plate (TCP)
- O_2 and H_2 accumulators

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

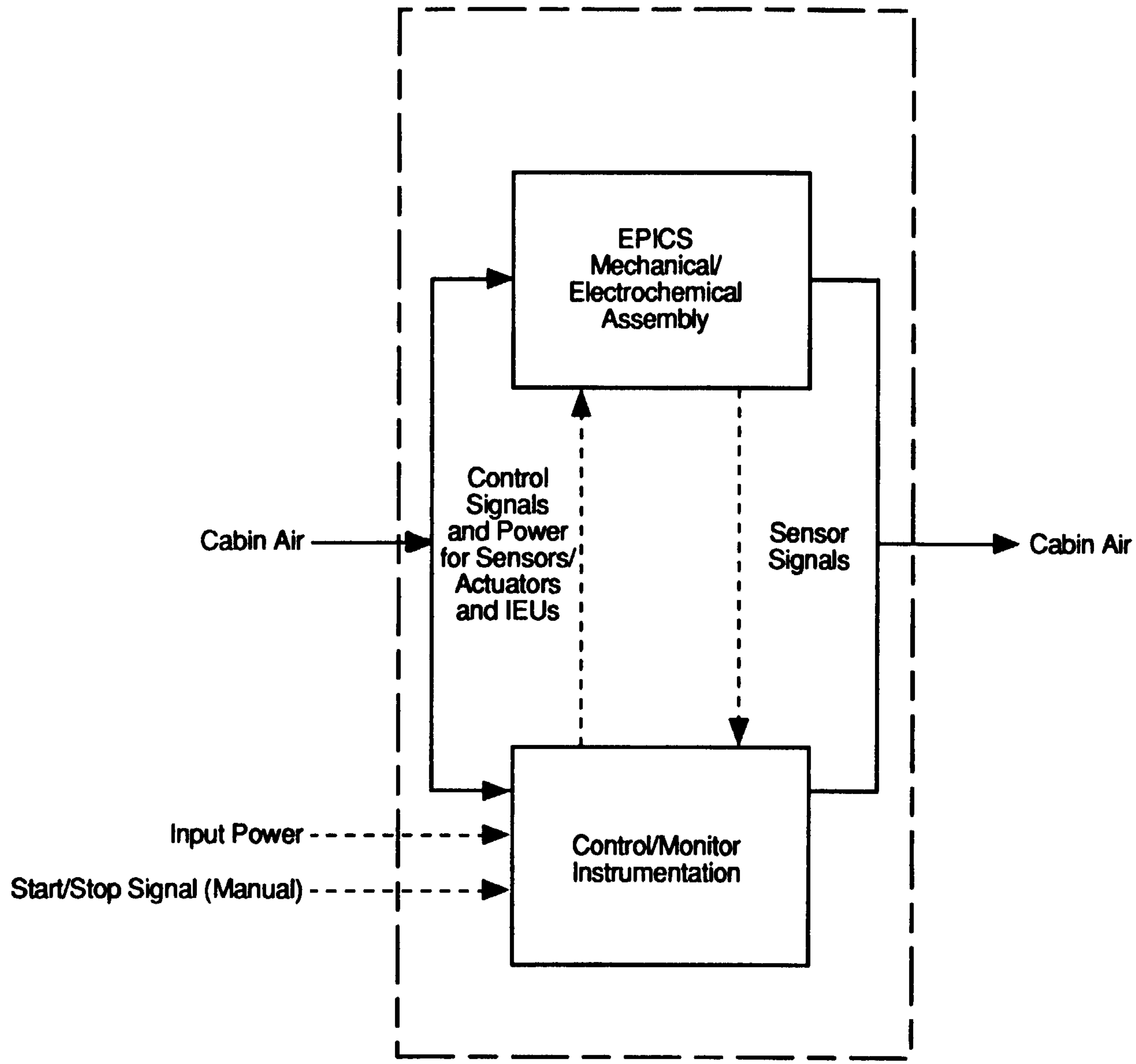


FIGURE 4 EPICS INTERFACE BLOCK DIAGRAM

Life Systems
CLEVELAND, OHIO

5063B

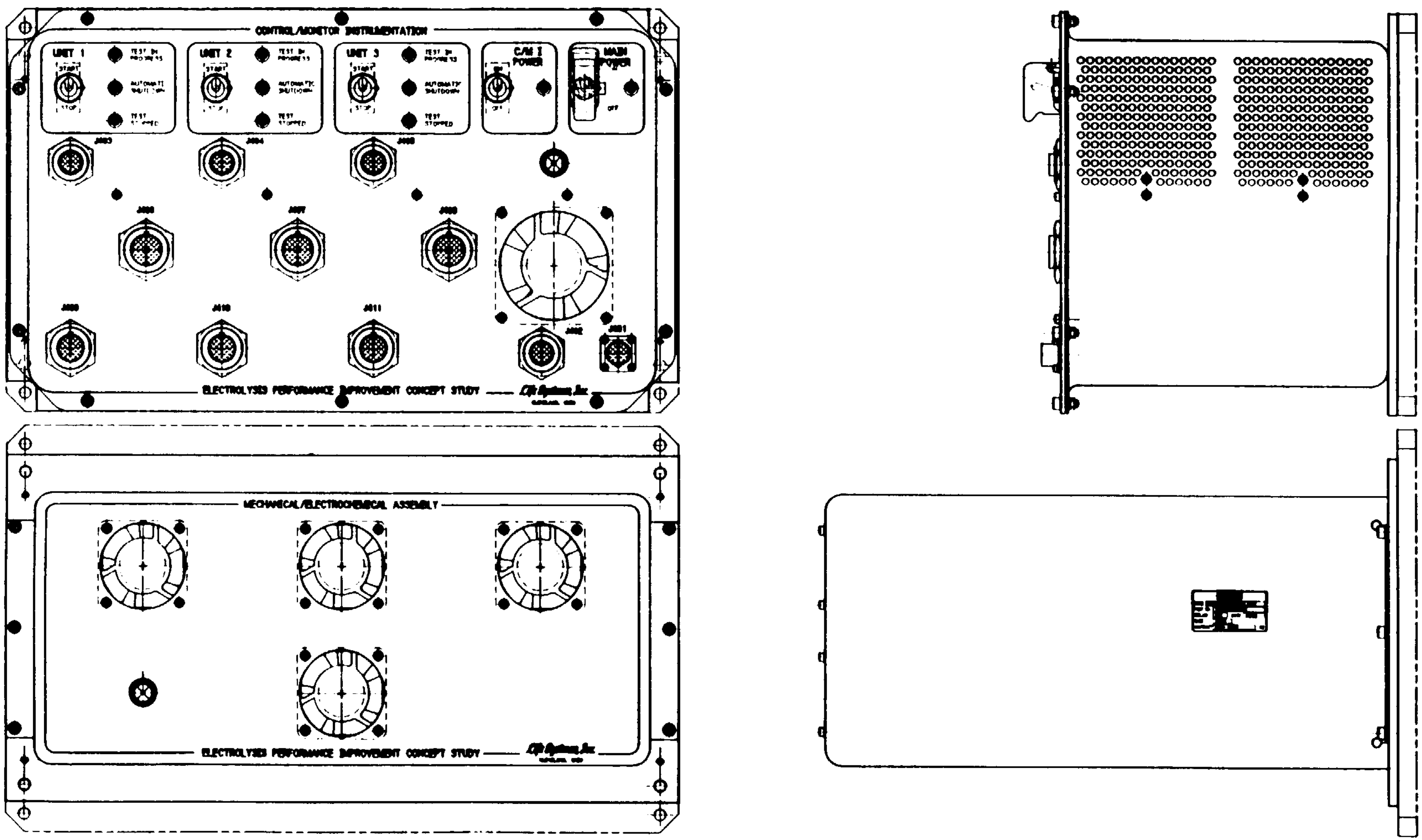


FIGURE 5 EPICS FLIGHT EXPERIMENT HARDWARE PACKAGING

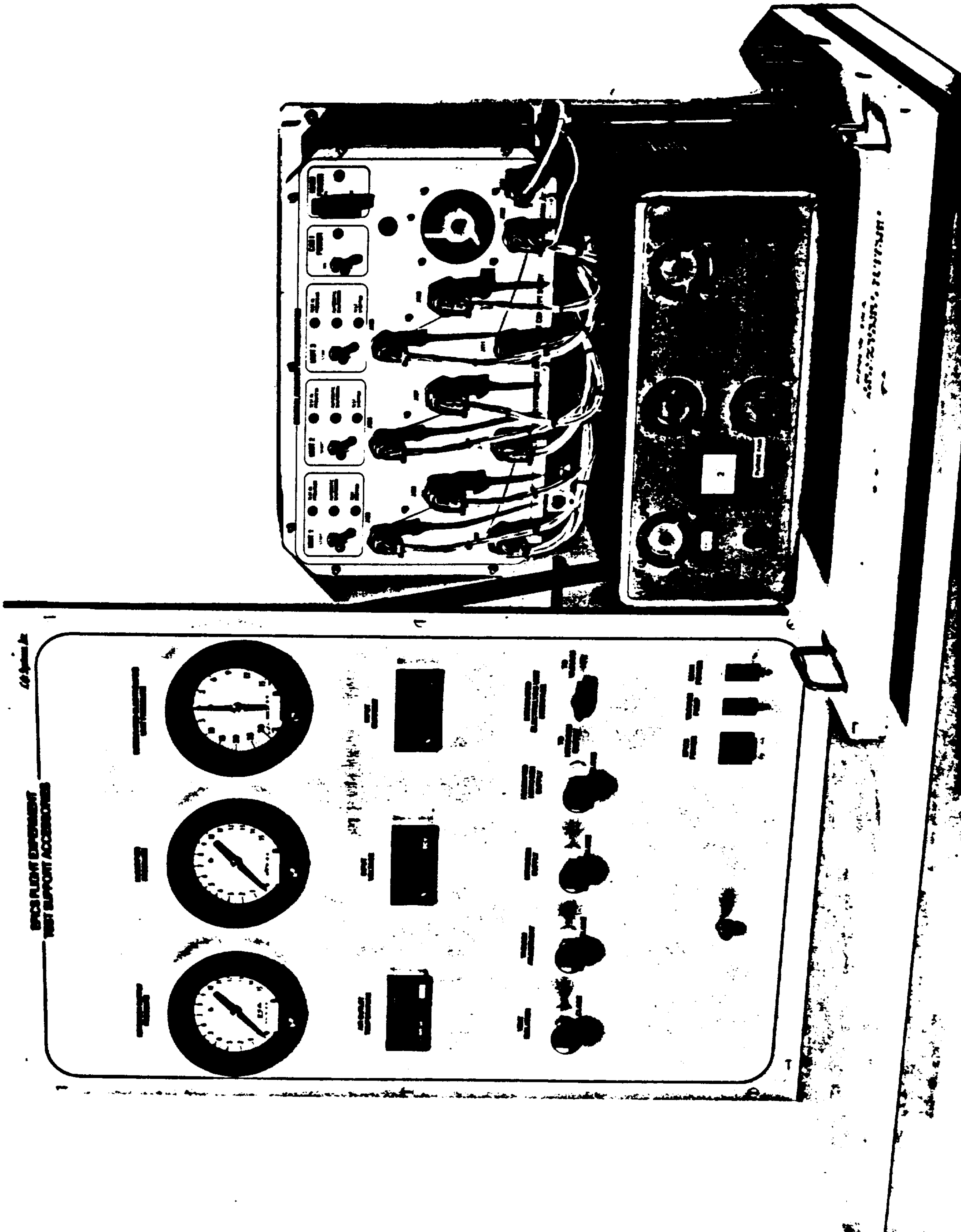


FIGURE 6 EPICS FLIGHT HARDWARE (M/EA AND C/M I) SHOWN WITH TSA

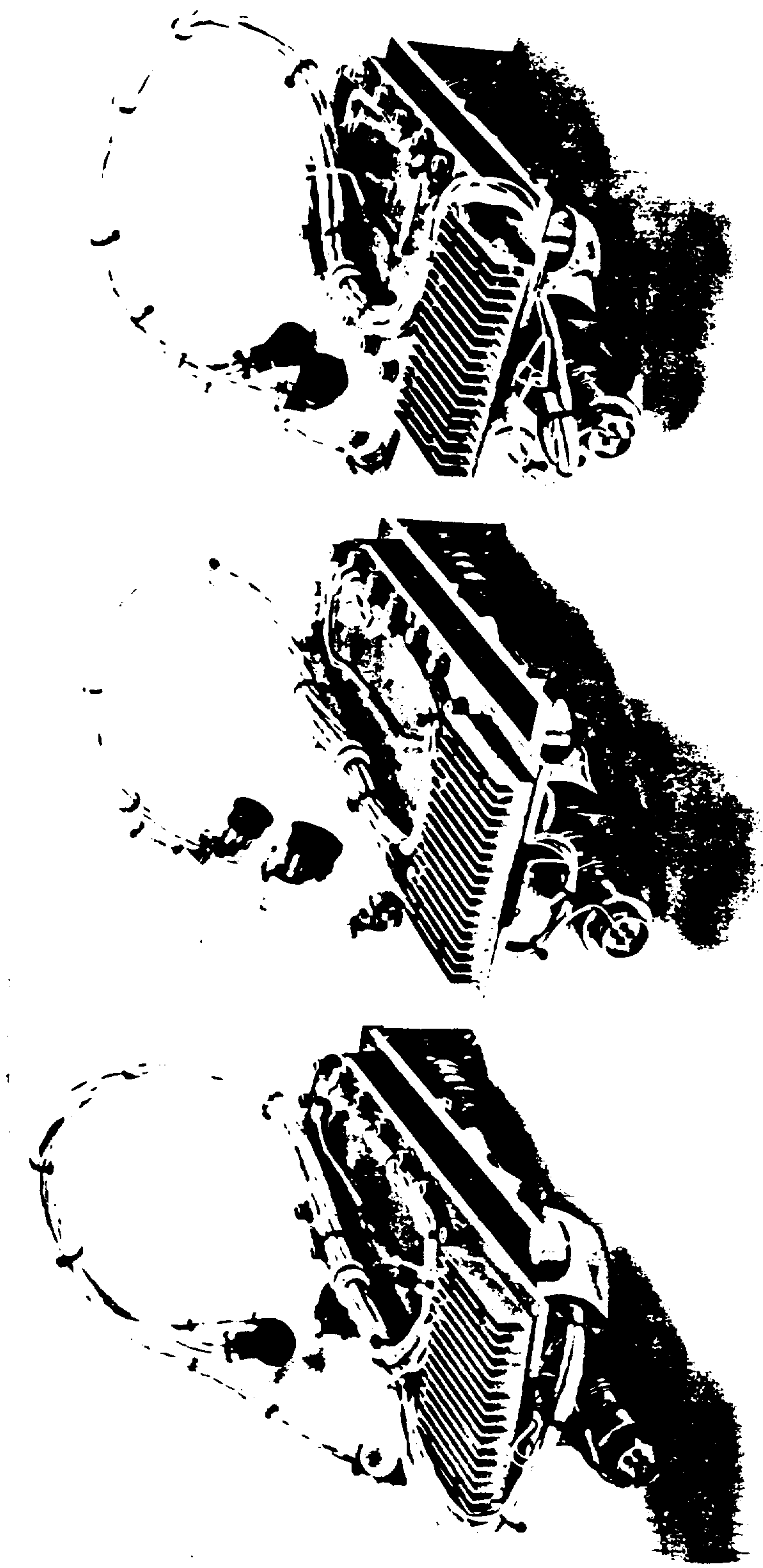
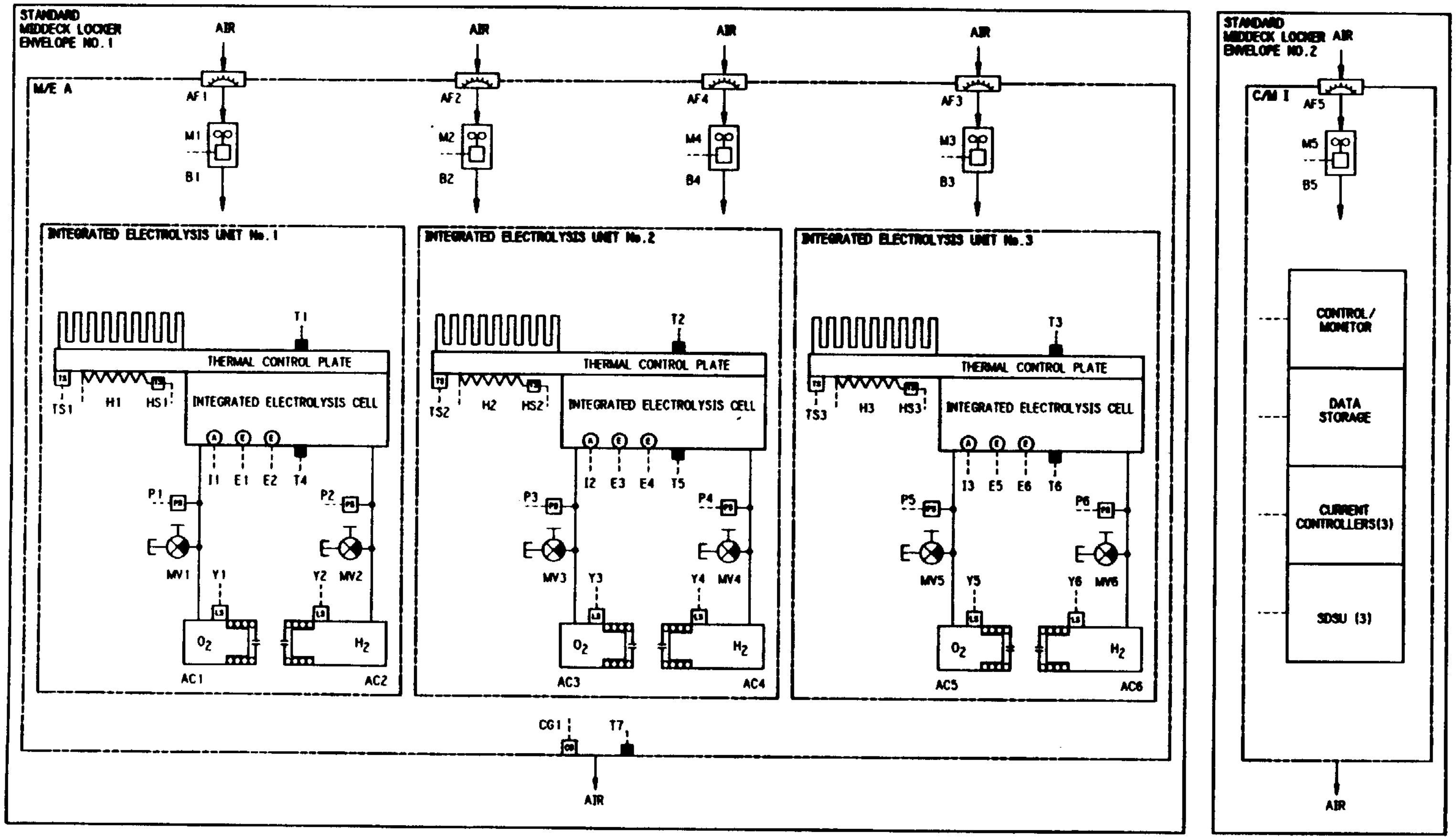


FIGURE 7 THREE INTEGRATED ELECTROLYSIS UNITS FLOWN IN STS-69

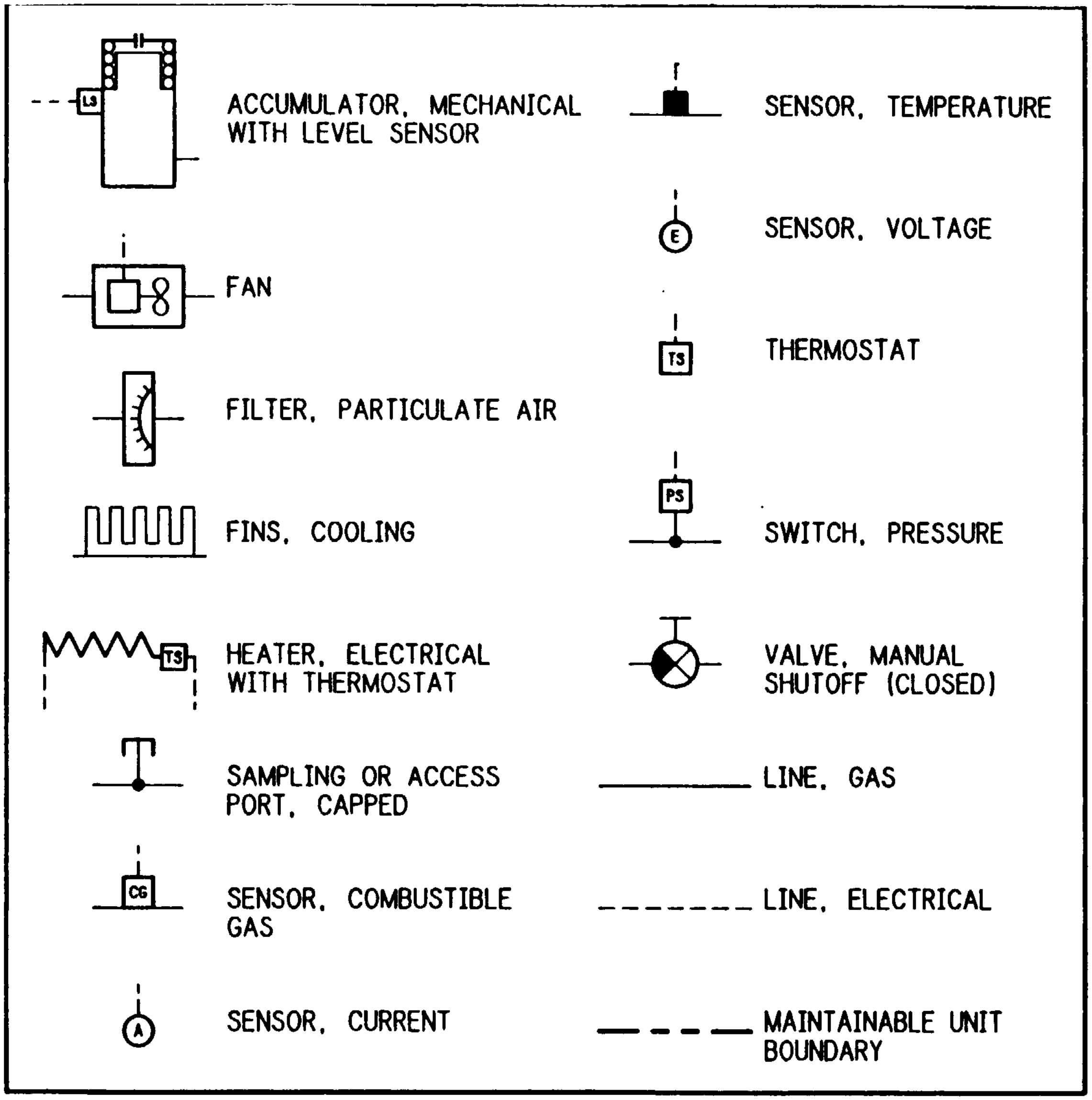


(a) M/E A: Mechanical/Electrochemical Assembly
C/M I: Control/Monitor Instrumentation

FIGURE 8 EPICS M/EA AND C/M I

Life Systems
CLEVELAND, OHIO

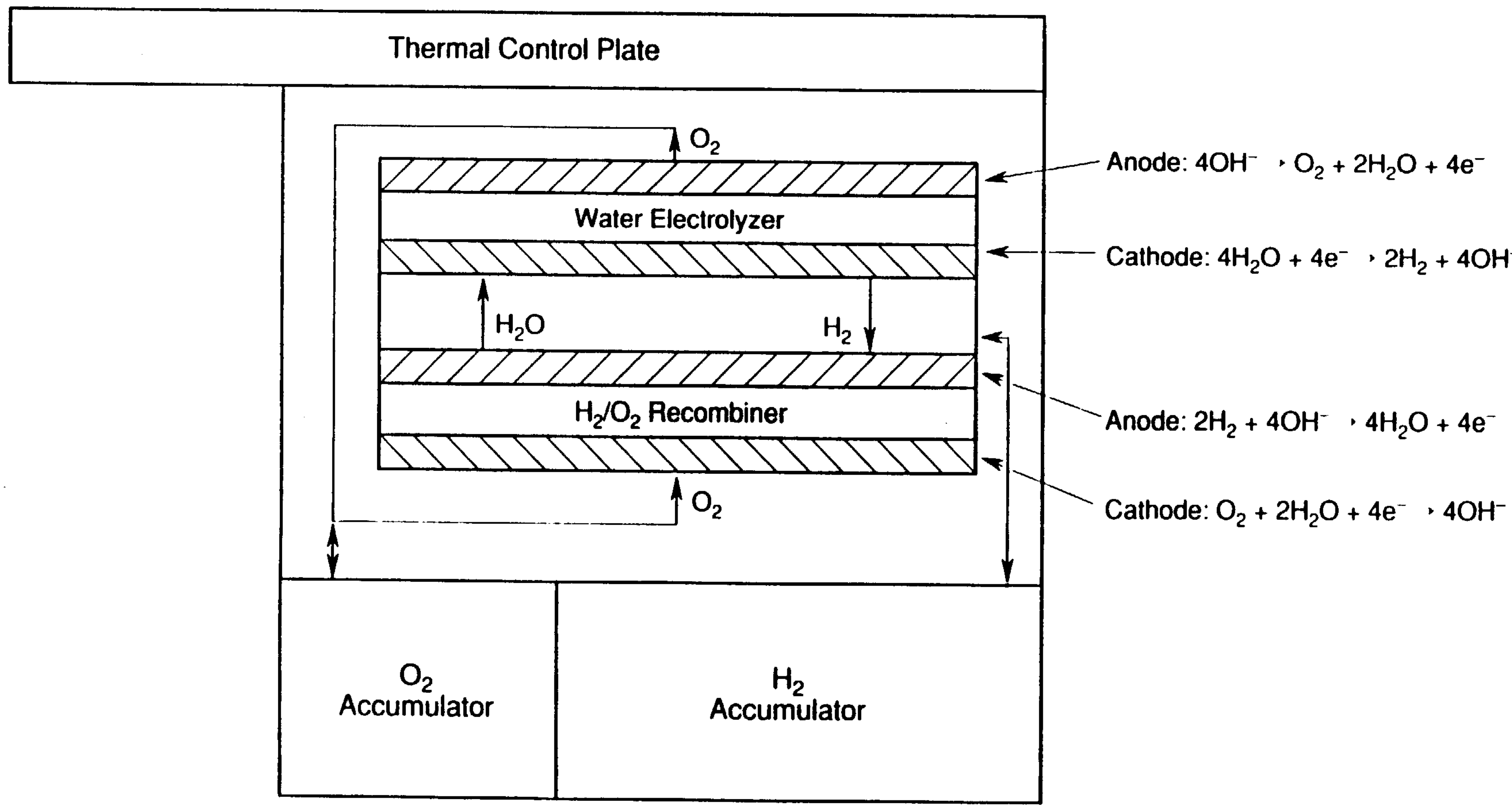
4561C



Life Systems
CLEVELAND, OHIO

Figure 8 - continued

4561A-1



Life Systems
CLEVELAND OHIO

4693A

FIGURE 9 FUNCTIONAL SCHEMATIC OF INTEGRATED ELECTROLYSIS UNIT (IEU) AND ELECTRODE REACTIONS

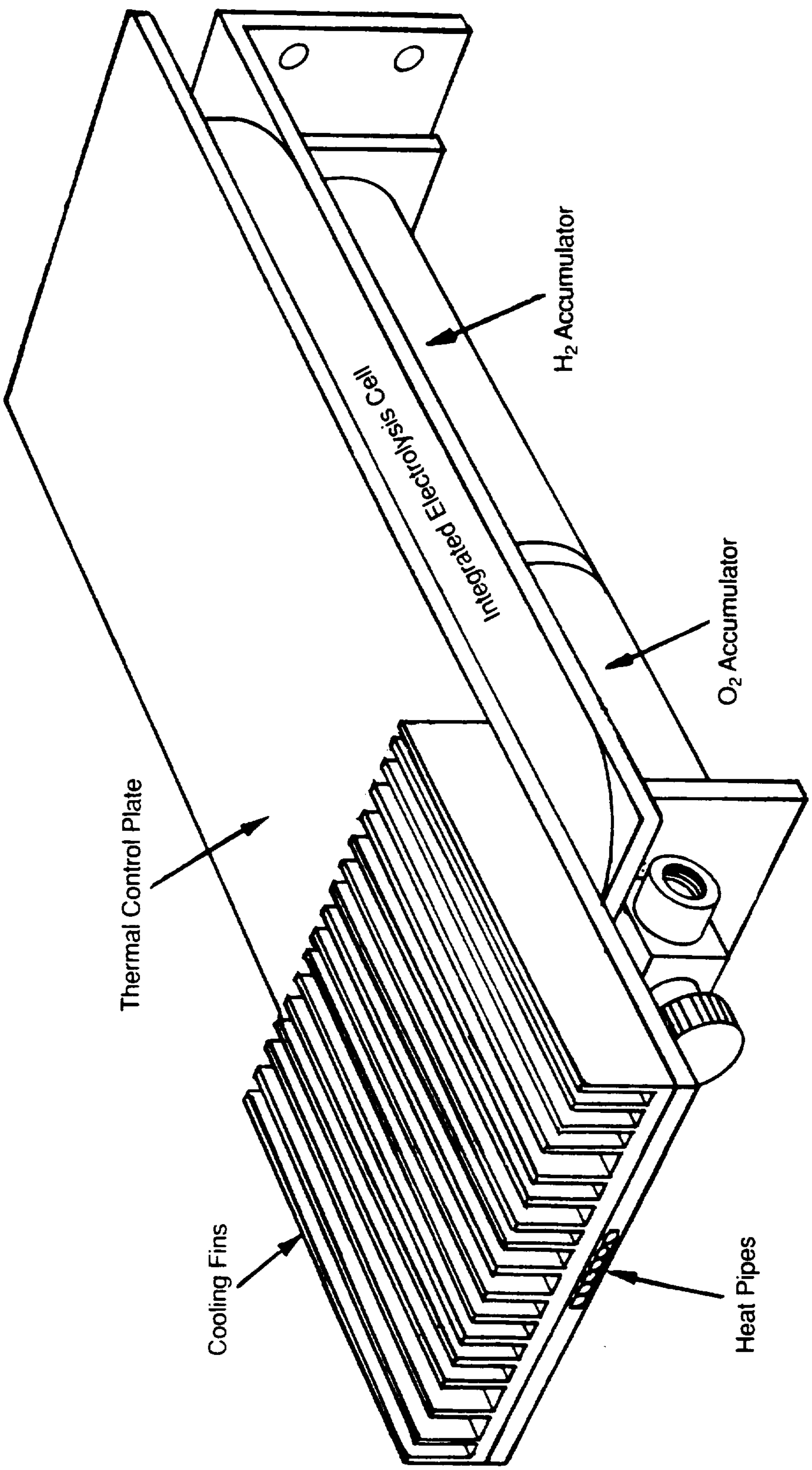


FIGURE 10 INTEGRATED ELECTROLYSIS UNIT

02/12/93

Ancillary Components

The M/E Aancillary components consists of four fans with filters, an outlet air temperature sensor and a combustible gas sensor. Three of the fans are thermal control fans. The thermal control fans circulate middeck air over the cooling fins on the TCP to provide cooling. Each fan operates independently on an on/off basis as needed to keep the IEU at the desired temperature.

The fourth fan is a continuously operated purge fan. The function of this fan is to continuously circulate middeck air throughout the enclosed volume to dilute any H_2 that may leak out of the IEUs. This fan operates independently of the C/M I and is on when the EPICS main power is on.

The air outlet temperature sensor is a Resistance Temperature Device (RTD) temperature sensor. This temperature sensor is located in the outlet air flow path. The purpose of this temperature sensor is to monitor the air outlet temperature.

The combustible gas sensor is a solid state gas sensor that is mounted within the outlet air flow path. The purpose of this sensor is to monitor H_2 levels around the EPICS system. This sensor is a check to ensure that the purge fan is operating properly and that the IEUs are not leaking H_2.

Control/Monitor Instrumentation

The EPICS C/M I consists of microprocessor-based instrumentation that is responsible for controlling the experiment and collecting the experimental data. The hardware and software of the C/M I are discussed below.

Hardware

The EPICS C/M I layout is illustrated in Figure 11. An EPICS electrical block diagram is shown in Figure 12. As indicated in this figure, the major functional blocks are as follows:

- Computer
- Power Conversion
- Data Storage
- Generic Sensor Signal Conditioning
- Actuator Signal Conditioning
- Current Controllers
- Sensor Dedicated Shutdown Units (SDSUs)
- Front Panel

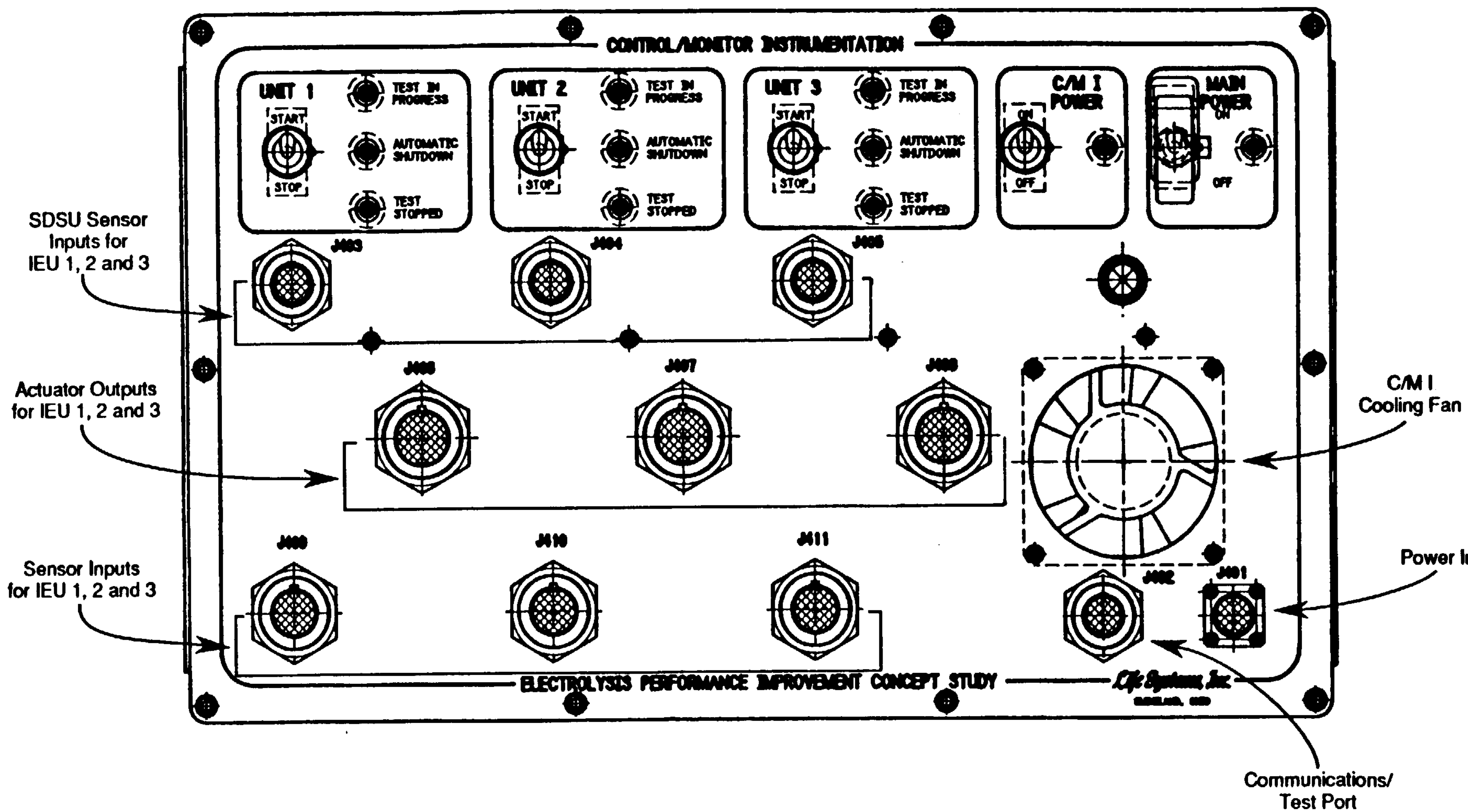
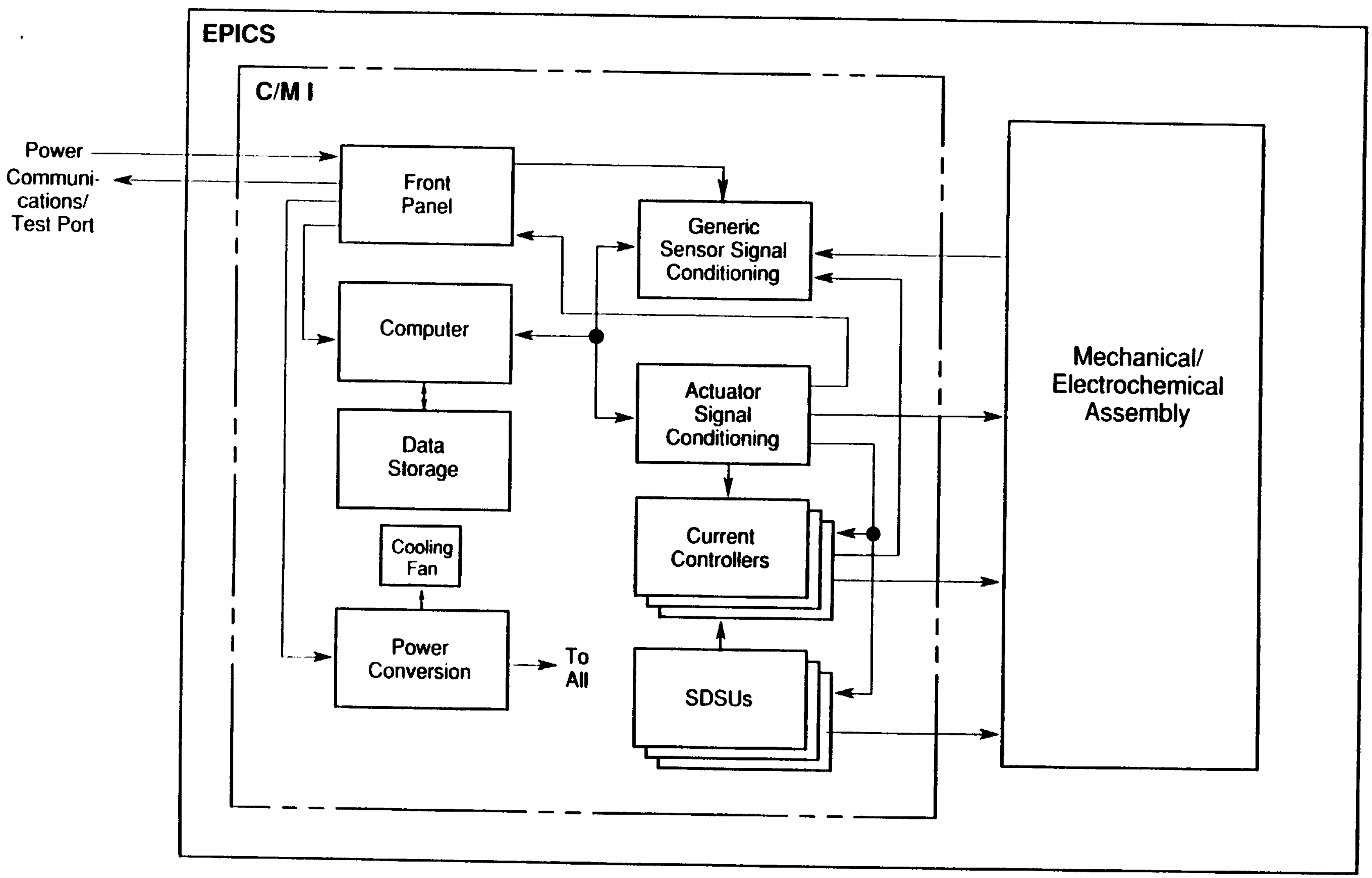


FIGURE 11 EPICS C/M I LAYOUT

Life Systems
CLEVELAND, OHIO

4710C



Life Systems
CLEVELAND OHIO

4424F

FIGURE 12 EPICS ELECTRICAL BLOCK DIAGRAM

The EPICS sensor ranges and accuracies are shown in Table 1.

Software

The C/M I software is stored in Erasable Programmable Read Only Memory (EPROM) within the Computer. The EPICS has three basic modes: Normal, Shutdown and Unpowered. These modes and the allowable mode transitions are illustrated in Figure 13 and described in Table 2.

During Normal mode, the software controls the test sequence, monitors sensors and manipulates actuators. The test sequence control consists of enabling current and temperature control loops with predetermined setpoints. The current control loop maintains cell current at proper levels by sending setpoint information to the Current Controller and monitoring performance. The temperature control loop maintains the IEU at the desired temperature by manipulating heat input or cooling air flow based on the setpoint deviation. During temperature ramping, only the heater is enabled. During electrolysis-recombination periods, both the heaters and the fans are enabled. The heaters and fans are controlled such that either one or the other is on but not both depending on whether the temperature is above or below the setpoint.

Simultaneously, while the test sequence is being controlled, the software is also monitoring the sensors for high or low limit alarms. The sensor limits that will initiate a shutdown are shown in Table 3.

EPICS Operation

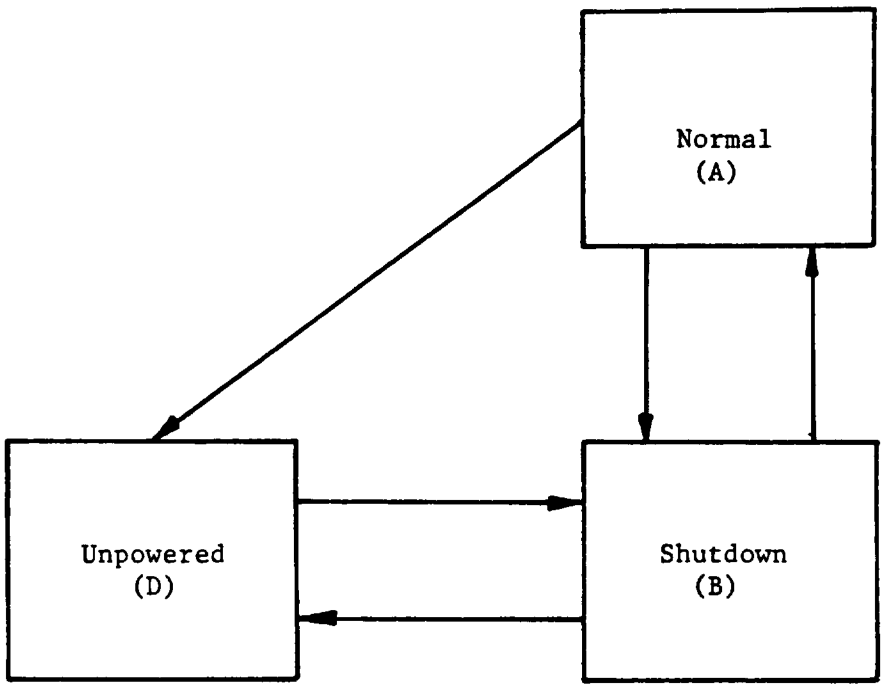
The EPICS experiment begins operation when activated by a crew member. A generalized test sequence for a given day is shown in Figure 14. The C/M I actions are described in Tables 4 and 5. The operating conditions are presented in Table 6.

The EPICS experiment initially starts out with all of the IEUs evacuated. Upon experiment activation by a crew member, each IEU begins heating up to the operating temperature. At the end of the temperature ramp, the current controller applies a specified current to the electrolysis cell only. This generates H_2 and O_2 and starts pressurizing each IEU. When the internal pressure reaches approximately 16.6 psia, each accumulator expands to about one half of its available travel range. This volume of gas provides a buffer for the recombiner cell to account for electrochemical inefficiencies. The current controller then switches over to combined electrolyzer/recombiner operation. The identical current then flows through the electrolyzer and the recombiner thus matching the gas generation rate with the gas consumption rate. The EPICS remains in this state for approximately 6.5 hours.

TABLE 1 EPICS SENSOR RANGES AND ACCURACY

No.	Description	Symbol	Normal Range	Accuracy
1	Cell Voltage	E1, E3, E5	1.4 to 2.1 V	±0.002 V
2	Cell Voltage	E2, E4, E6	0.4 to 1.0 V	±0.002 V
3	Cell Current	I1, I2, I3	0 to 7 A	±0.1 A
4	Cell Temperature	T1, T2, T3	65 to 140 F	±1.0 F
5	Cell Temperature (SDSU)[d]	T4, T5, T6	150 F[a]	±1.0 F
6	Air Outlet Temperature	T7	65 to 113 F	±1.0 F
7	Combustible Gas Sensor	CG1	0	±0.1% H_2 in Air
8	Accumulator Level	Y1 to Y6	20 to 80%	±5%
9	Pressure Switch[d]	P1 to P6	20.2 psia[a]	±0.5 psi
10	Heater Thermostat[e]	HS1 to HS3	160 F[a,b]	(b)
11	IEU Thermostat[d]	TS1 to TS3	150 F[a,c]	(c)

(a) Setpoint values.
(b) Shall open on increasing temperature at 160 ± 5 F and close on decreasing temperature at 145 ± 5 F.
(c) Shall open on increasing temperature at 150 ± 5 F and close on decreasing temperature at 135 ± 5 F.
(d) This sensor is connected to the SDSU. It is not connected to the Generic Sensor Signal Conditioning Subassembly.
(e) This sensor is used for overtemperature protection and will interrupt current flow to the heater if the setpoint is exceeded. It is not connected to the Generic Sensor Signal Conditioning Subassembly.



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

FIGURE 13 EPICS MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 2 EPICS OPERATING MODES AND UNPOWERED MODE DEFINITIONS

Mode (Code)	Definition
Normal (A)	The Integrated Electrolysis Units (IEUs) are performing their function as specified by the test sequence being performed by the controller. The units are in the desired temperature range as specified by the controller. Normal Mode is initiated by: • Manual actuation
Shutdown (B)	No current is being supplied to the IEUs. The experiment is powered and all sensors are active. The Shutdown Mode is initiated by: • Manual actuation • Low Recombiner Cell Voltage (E2, E4, E6) on each IEU[(a)] • High or Low Electrolysis Cell Voltage (E1, E3, E5) on each IEU[(a)] • High or Low Cell Current (I1, I2, I3) on each IEU[(a)] • High or Low IEU Temperature (T1, T2, T3) on each IEU[(a)] • High Air Outlet Temperature (T7) • High or Low Accumulator Level (Y1, Y2, Y3, Y4, Y5, Y6) on each IEU[(a)] • High Combustible Gas Level (CG1) • Power on reset from Unpowered Mode (D) • Mode transition from Shutdown Mode (B) to Normal Mode (A) was not successful
Unpowered (D)	No electrical power supplied to the EPICS unit. The Unpowered Mode is initiated by: • Manual request • Power failure • CMC alarm

(a) It is possible for an individual IEU to be shut down while the other two operate normally. These parameters can initiate this along with SDSU cell temperature, H_2 or O_2 pressure switch, and IEU thermostat.

TABLE 3 EPICS NUMERICAL SHUTDOWN PARAMETERS FOR NORMAL MODE OPERATION

Parameter	Schematic Symbol	Shutdown Level Low[a]	Shutdown Level High
Electrolyzer Cell Voltage, V	E1,E3,E5	1.3	2.3
Recombiner Cell Voltage, V	E2,E4,E6	0.1	-
Cell Current, A	I1, I2, I3	Variable[b]	Variable[b]
Accumulator Level, %	Y1-Y6	5	95
Cell Temperature, F	T1,T2,T3	110	145
Air Outlet Temperature, F	T7	-	120
Combustible Gas Sensor, Vol. %	CG1	-	1.5
Accumulator Position Rate of Change,[c] %/min	N/A	0.33	-
Accumulator Position Differential,[d] %	N/A	-	35
Heater Thermostat, F	HS1,HS2,HS3	-	160 ± 5
IEU Thermostat (SDSU), F	TS1,TS2,TS3	-	150 ± 5
Cell Temperature (SDSU), F	T4,T5,T6	-	150
Pressure Switch (SDSU), psia	P1-P6	-	20.2 ± 0.5

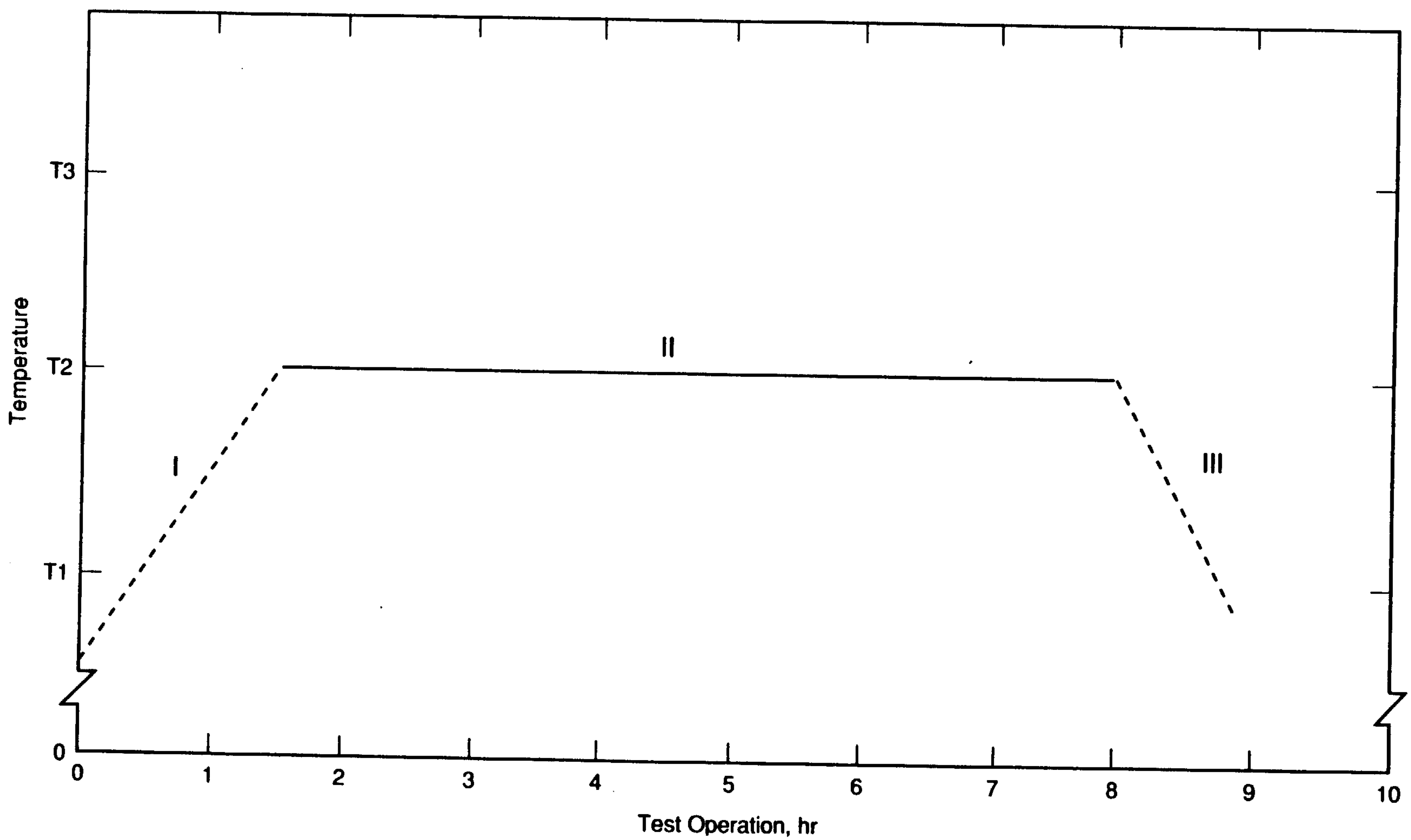
(a) The low shutdown limit is disabled during the 1.5-hour warmup and 16-hour quiescent periods each day except the cell temperature which is enabled after it reaches 115 F.

(b) The shutdown level depends upon the nominal setpoint as follows:

Low Current Experiment (Day 1) or during Electrolysis-Only Operation	High Current Experiment (Day 2)
Low Level Shutdown = 1.5A	Low Level Shutdown = 6.5A
High Level Shutdown = 2.5A	High Level Shutdown = 7.5A

(c) This parameter is calculated from the difference in accumulator positions (applicable to electrolysis-only)

(d) The parameter is the absolute value of the difference in accumulator position measurements (applicable to electrolysis-only).



Life Systems
CLEVELAND, OHIO

FIGURE 14 EPICS EXPERIMENT TEST SEQUENCE

A5104

TABLE 4 EPICS TEST SEQUENCE DESCRIPTION

Sequence	Description
I.	- The feedback temperature control algorithm is enabled that utilizes the combination of heaters and fans to raise the cell temperatures to the setpoint without exceeding maximum temperature limits. - The current controllers are disabled, i.e., no currents flow. - The sensors are monitored for alarm levels. - Data is recorded at 30-second intervals. - The total time allowed for this transition period is 1.5 hours.
II.	- The current controller is activated in the electrolysis mode only. - When either O_2 or H_2 accumulator position indicators indicate a predetermined position, the IEUs are switched to combined current mode (i.e., current through both electrolyzer and recombiner). - Accumulator position monitoring is enabled. If proper positions of any accumulator has not been reached, an automatic shutdown of respective IEU is initiated. - The current controller's setpoint is specified by a master test sequence control algorithm. - The thermal control fans (B1, B2, B3) are activated intermittently depending on the active IEU setpoint deviation. - Data is recorded at 30-second intervals. - The sensors are monitored for alarm levels. If a given IEU has an alarm, then that IEU is disabled. Other IEUs remain active. - If air outlet temperature (T7) exceeds 120 F, then the thermal control fans (B1, B2, B3) are activated regardless of the IEU setpoint deviations. If the temperature does not return to safe levels in four minutes then the controller will initiate a shutdown.
III.	- The current controllers are disabled. - The heaters are deactivated. - The thermal control fans (B1, B2, B3) are turned on (continuous). - The sensors are monitored for alarm levels - Data is recorded at 10-minute intervals. - When all IEU temperatures reach 100 F or below, then the thermal control fans (B1, B2, B3) are disabled. - The total allowed time for this transition is 16 hours.

The above sequence will repeat the next day of the mission with a different current setpoint.

TABLE 5 EPICS EXPERIMENT SEQUENCE

Sequence[a]	I	II	III
Temperature, F	Amb→135	135	135→Amb
Heater Cntl	Enable[b]	Enable[b]	Disable
Fan B1 (Thermal)	Enable	Enable	Enable
Fan B2 (Thermal)	Enable	Enable	Enable
Fan B3 (Thermal)	Enable	Enable	Enable
Fan B4 (Purge)	On	On	On
Cur Cntl I1	Off	Active	Off
Cur Cntl I2	Off	Active	Off
Cur Cntl I3	Off	Active	Off
Alarm Monitor	Yes	Yes	Yes
Record Data per	30 sec	30 sec	10 min
Time of Phase	1.5 hr	6.5 hr	16 hr
Accum. Time	1.5 hr	8.0 hr	24 hr

(a) Sequence:
I - Initialization
II - Operation at 135 F
III - Quiescent

(b) Full power (i.e., 28 W) available to each IEU heater.

TABLE 6 EPICS OPERATING CONDITIONS

Vehicle Conditions	
Middeck Total Pressure, psia	14.7 ± 0.2
Middeck Temperature, F	65 to 80
Nominal Operating Conditions	
Number of Units	3
Current Density, ASF	37 to 129
Operating Pressure, psia	16.6 ± 1.7
Operating Temperature, Nominal, F	135

During this electrolysis/recombination period, all sensors are continuously monitored for fault conditions. Thermal control of the integrated electrolysis cell is accomplished by adding or removing heat using the IEU heater or circulating middeck air over the cooling fins on the TCP.

At the completion of the electrolysis/recombination operating period, the Current Controllers are deactivated and the IEUs cool back down to ambient temperature. The EPICS remains at this condition until the next day when testing resumes. Note that the C/M I controls each 48 hour test sequence and no further action by the crew members is needed.

EPICS Ground Support Equipment

The EPICS flight experiment was designed to be a self-contained experiment that does not require plumbing interfaces, extensive crew interfaces or special data links. As a result, GSE is not required to support the experiment during the mission. However, some GSE is needed to prepare the EPICS flight hardware for the flight experiment. A summary of these GSE operations is shown in Table 7.

Mission Scenario

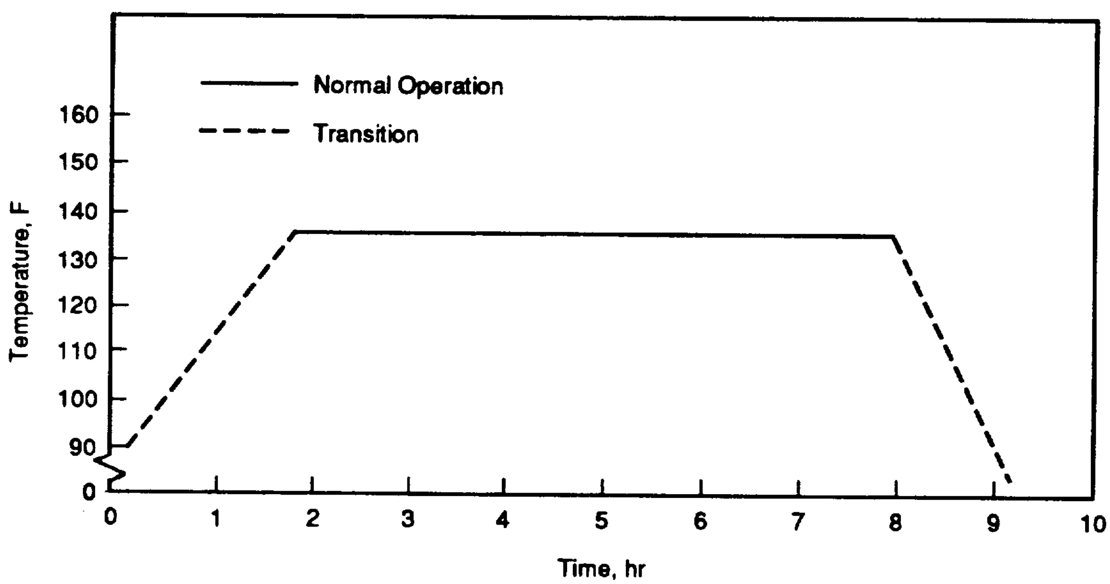
The mission for the reflight of the experiment extends, as a minimum, to two consecutive 24-hour days of testing for a typical two days of operation. The test plan is represented in Figure 15 and contains two current variations, 2 and 7 A. For the reflight aboard STS-84 more than one, with a maximum of three, two day test sequences were planned. Since the EPICS flight experiment is fully automated, the only requirement for the crew is the initial actuation of the experiment and deactivation and reactivation between each two day sequence. Final deactivation is optional. The C/M I is designed to handle each complete experiment sequence and its storage of data. No special data links or audio visual equipment are needed. The crew can manually terminate power to the experiment at anytime without creating a hazard.

TABLE 7 SUMMARY OF EPICS GROUND SUPPORT OPERATIONS

Activity	GSE Operation
At Life Systems	
Pre-Acceptance Test	• Evacuate and Purge IEUs with N_2 • Evacuate and Isolate IEUs • Check Instrumentation Calibration • Conduct a 2-day Test
Acceptance Test	• Conduct Acceptance Test
Post-Acceptance Test	• Evacuate and Purge IEUs with N_2 • Evacuate and Isolate IEUs
At NASA-KSC	
Pre-Flight	• Assemble M/EA • Check Instrumentation Calibration • Orbiter Fit Check • Orbiter Integration • Post-Integration Power-Up Checkout
Post-Flight	• Orbiter Deintegration • Check Instrumentation Calibration

Experiment Schedule

Day	1	2	3[a]	4[a]	5[a]	6[a]
Current, A	2	7	2	7	2	7
Test Duration, hr						
IEU1	8	8	8	8	8	8
IEU2	8	8	8	8	8	8
IEU3	8	8	8	8	8	8



Each eight-hour period consists of one and one half hours of startup, followed by six and one half hours of operation at 135 F.

(a) The experiment may be repeated during the mission at the discretion of NASA

FIGURE 15 REFLIGHT TEST PLAN FOR EPICS EXPERIMENT

POST FLIGHT (STS-69) HARDWARE AND SOFTWARE UPGRADES

Prior to re-flight of the EPICS, both hardware and software upgrades were incorporated into the unit. These upgrades were based on the findings and recommendations of a NASA JSC review team formed after the STS-69 flight experiences. The team findings and recommendations and subsequent hardware and software upgrades are presented below.

Review-Team Findings and Recommendations

The NASA JSC review team defined the following findings and recommendations:

Findings

At approximately 22 minutes into the warm-up phase on the first day of the STS-69 flight, Cell No. 1 went into a safe shutdown. Post-flight testing determined that the calibration of Resistance Temperature Device (RTD) T4 on Cell No. 1 had shifted to cause an incorrect temperature measurement. This temperature measurement falsely indicated that the cell had exceeded the high cell temperature limit of 150 F, when it was actually 116 F. The SDSU detected this incorrect temperature measurement and terminated power to the heater. The unit then went into a safe shutdown due to a preprogrammed low-temperature shutdown.

Cells No. 2 and 3 successfully completed the first 1.5 hour warm-up and six hour electrolysis operation at 2 A (37 ASF). Following the normal cool down and 16 hour standby modes, the units started the second warm-up phase. At approximately 24 minutes into the second warm-up, both units shutdown. Post-flight data analysis determined that the shutdown occurred when the electrolyzer open cell voltage decreased to a level below 1.3 volts, a voltage which is normal for open circuit mode. Inspection of the computer software code determined that this shutdown was caused by a missing line of software code. The missing code would have disabled the electrolysis mode low voltage shutdown during the warm-up phase. The low voltage limit of 1.3 volts was not reached during any pre-flight ground testing, and the missing software code was not detected. The shutdown was recreated during post-flight testing by simulating a low-cell voltage input during the second warm-up phase.

Recommendations

The review team made the following recommendations:

1. Refly the EPICS experiment at the earliest opportunity.

2. Replace failed temperature sensor on IEU No. 1.

3. Re-evaluate the existing operational and shutdown limits based on the acceptance test data and flight data and adjust if necessary.

4. Modify the existing application code to correct the known low voltage "enable" error and insert new application code into the EPICS firmware.

5. Re-run an Acceptance Test and compare results with previous data.

6. Conduct more extensive software verification procedure to verify corrected software function, as well as all other software functions.

7. Re-evaluate the rationale and impacts of adding operational enhancements which allow for on-orbit diagnostics, data downloading, and restart by the crew.

8. Consider conducting an independent audit of the EPICS software application code.

9. Assess the need to replace all temperature sensors and thermostats.

Hardware Upgrades

The hardware upgrades of the EPICS included replacement of temperature sensors T1 and T4 located in IEU No. 1. Both sensors had to be replaced since they are epoxied into a common slot on the IEU thermal control plate. An assessment was made to evaluate replacement of all temperature sensors and thermostats. It was concluded replacement was not required based on the performance of the sensors and thermostats during post-flight (STS-69) testing. More physically rugged temperature sensors however were selected for replacement of T1 and T4.

Another hardware change made to the EPICS was the replacement of the M/EA mounting plate with an identical remake. The replacement was deemed wise since the self-locking helical inserts used to mount both the IEUs and the M/EA cover to the plate were near their limit (5) of allowable loosening and tightening cycles. These same inserts had once been replaced in the original plate. It was judged that they could not be replaced again without potentially damaging the substrate aluminum of the mounting plate.

One added hardware modification was made to the electrical portion of the M/EA. This modification consisted of the addition of a connector to the cable assemblies that could allow for on-orbit diagnostics, data downloading and/or restart of the system by the crew (reference Recommendation 7 by the review team). This connector also simplified connecting the diagnostic computer during ground testing for both control and data monitoring.

In concert with the potential on-orbit diagnostics and data downloading concept, a study was completed that would provide the crew with on-orbit diagnostic capabilities to address various anomaly conditions should they arise. Table 8 summarizes potential events and corrective actions that could be taken without the use of the onboard diagnostic computer.

TABLE 8 POSSIBLE EPICS ANOMALY CONDITIONS AND ACTIONS TO BE TAKEN

Event	Action to Be Taken
During Activation	
Step 1: 1. Main Power Light Emitting Diode (LED) does not come on AND purge fan does not come on.	1. Turn off main power switch and check power interface.
2. Main Power LED does not come on AND purge fan does come on.	2. No Action - Assume LED out. Continue activation procedure.
3. Main Power LED does not come on AND purge fan does not come on.	3. No Action - Purge fan operation not required for safety or mission success. Continue activation procedure.
Step 2: 1. C/M I Power LED does not come on AND C/M I fan does not come on.	1. Cycle C/M I power switch off and on again.
2. C/M I Power LED does not come on AND C/M I fan does come on.	2. No Action - Assume LED out. Continue activation procedure.
3. C/M I Power LED does come on AND C/M I fan does not come on.	3. No Action - Continue activation procedure[a].
4. LED lights do not blink in correct sequence.	4. Cycle C/M I power switch off and on again.
Step 3: 1. Test in Progress LEDs do not come on.	1. Cycle C/M I power switch off and on again.
During Operation	
1. A red LED on a single IEU is on.	1. No Action - IEU locked out and cannot be restarted.
2. All 3 red and all 3 yellow LEDs are on.	2. No Action - The test is terminated and cannot be restarted.
3. All 3 red LEDs are on and all 3 yellow LEDs are off (Global Shutdown)	3. Test can be restarted by cycling the C/M I switch off and on again. (Test will continue where it left off.) Note: The teletemp label on the top of the M/E A enclosure can be used to verify that an overtemperature condition existed.
During Deactivation	
1. Test Stopped LEDs not on.	1. Verify that it has been 48 hours and one minute[b] since experiment initiation. If so, continue with deactivation. If not, wait until 48 hours and one minute are complete.
2. Purge fan not running.	2. No Action - Purge fan operation not required for safety or mission success.

Flight Rules: (1) Prior to cabin depression to less than 14.5 psia, the EPICS C/M I should be powered off.
(2) No action is required in case of power interruption.

(a) If overtemperature occurs on any components of the C/M I, the C/M I will stop current supply to the M/EA and EPICS will shutdown safely due to low or no current to IEU.

(b) Additional one minute is required for the data acquisition system to register the lighting of Test Stopped LEDs.

Software Upgrades

Based on the review teams' recommendations the EPICS software was modified and upgraded for the following requirements:

- Disabling of fault detection for low electrolyzer cell voltages during the 1.5 hour warm-up and during quiescent periods.

- Continuing data acquisition and storage for up to 20 minutes after a shutdown of the last IEU to aid in possible shutdown diagnostics by analyzing parameter trends after a shutdown.

- Retain restart capability after a global shutdown, i.e., a shutdown either caused by the combustible gas sensor CG1 or high temperature T7.

Also, as recommended, an independent audit of the EPICS software application code was performed using an outside vendor. Three changes were recommended as follows:

1. Recommendation: Update data logging application software.

   Rationale: Since two timers were added to support continuation of data logging for a specified time after a system shutdown to ensure that all relevant data surrounding the shutdown is properly logged before ceasing data logging, the application software should be updated to reflect this change.

2. Recommendation: Correct the sequence of switching the relays controlling current to the IEU'S.

   Rationale: The software should ensure one current relay is off before switching another current relay to on. The software code, as implemented, does not accomplish this since the actuator hardware is updated simultaneously. In order to properly implement the intent and avoid simultaneous or overlapping switching of the various actuators, the code should be modified to perform one action during each of several consecutive 100 msec update cycles.

3. Recommendation: Correct the handling of heaters to restore actuator Pulse Width Modulation (PWM).

   Rationale: The heaters are currently being exercised by a "bang-bang" control around the high control setpoint, rather than by the use of a proportional control between the high and low setpoints. Incorporating such a PWM capability or modifying the control logic, however, must weigh the possibility of introducing new problems against any marginal performance improvement of the proposed PWM approach.

The three recommendations were evaluated and recommendation 1 and 2 incorporated into the EPICS software. Since the "Bang-Bang" heater control was not a problem either in flight or during ground testing, the modification of using PWM control was not selected for incorporation. Also, the potential of introducing errors into a system that performed properly supported that decision. The recommendations and implementation selections were jointly reviewed and agreed to with the NASA JSC Co-Principal Investigator.

PRE-FLIGHT, FLIGHT AND POST-FLIGHT TESTING AND DATA ANALYSIS

Three test phases were completed as part of the EPICS Reflight Program. The phases are: Pre-Flight, Flight and Post-Flight.

Pre-Flight Tests

Following the hardware and software modifications incorporated into the EPICS for reflight a pre-flight test program was completed. It included functional verification testing and pre-acceptance and acceptance tests.

Functional Verification Tests

Following incorporation of the hardware and software changes a functional verification test was conducted with the EPICS. The test was conducted at the 2 A level and showed that the hardware incorporation, such as Temperature Sensors T1 and T4 and the diagnostic port connector functioned properly.

Verification of the software changes were completed at the end of 24 hours of operation. The Combustible Gas Sensor CG1 and Temperature Sensor T7 were sequentially overridden resulting in the desired global shutdowns. Restarts after each of the two shutdowns were successfully demonstrated.

Also, during the warmup period, the electrolyzer cell voltage of the IEU 1 was overridden to 1.29 V and, as now designed, no shutdown occurred. To verify that data acquisition will continue for 20 minutes after a shutdown of the last, or third, IEU, the three IEUs were shutdown by overriding a temperature for IEU 1, a voltage for IEU 2 and an accumulator position for IEU 3. The EPICS successfully continued to collect data for 20 minutes, as designed, after the third IEU shutdown.

Initial Pre-Acceptance and Acceptance Tests

Following successful demonstration of the hardware and software modification a Pre-Acceptance Test was completed and an Acceptance Test initiated.

Results. A planned 48 hour Pre-Acceptance Test phase was successfully completed. The test data was reviewed and none was considered unusual based on past observations. As a result, the Formal Acceptance Test was scheduled nine days after completion of the Pre-Acceptance Test.

One hour and thirty-six minutes into Acceptance Testing, IEU 3 shut down resulting in the termination of the Acceptance Test. The shutdown was caused by the difference between the H_2 and O_2 accumulator positions being greater than 35%, a planned automatic shutdown condition.

Analysis. A review of the data showed that at the time of shutdown the accumulator positions for IEU 3 were 39% and 4% for the H_2 and O_2 accumulators, respectively. In comparison, respective accumulator positions for IEU 1 were 26% and 9% and for IEU 2 14% and 3%, indicating that the IEU 3 hydrogen accumulator indicated a much higher position than the other two hydrogen accumulators. Reviewing the accumulator position data at test startup showed that the hydrogen accumulators for IEU 1 and IEU 2 were each at a 2% position while IEU 3 was at 6%. The O_2 accumulator positions for IEU 1, 2 and 3 were 2, 2 and 1% respectively.

Figure 16 is a plot showing the difference at shutdown of Y5 and Y6 the O_2 and H_2 accumulator positions for IEU 3. Similar data was then investigated for Y5 and for Y6 for the Pre-Acceptance Test conducted just 10 days prior to the Acceptance Testing. This data is shown in Figure 17. It indicates that already an O_2 accumulator position decay was evident, especially compared to the Pre-Flight Acceptance Test for STS-69 which is shown in Figure 18.

Suspected causes of the IEU 3 shutdown included: 1) erroneous readout of Y5, the O_2 accumulator position reading, 2) faulty signal conditioning circuitry, 3) potential inward and/or outward leakage, or 4) excessive diffusion of gases.

A check of the accumulator position reading mechanism, as well as associated signal condition circuitry proved that the readings were true. Also, using helium leak detection, no internal to external leaks were found. The leak testing showed that the leakage rate was less than 10^{-9} standard cm^3 of helium per second compared to the acceptance criteria of 10^{-5} standard cm^3 helium per second.

Based on the above, the most logical cause was assumed to be that of a very low leakage, i.e., lower than detectable by the leak detector, and/or slow diffusion of external air into the H_2 compartment of IEU 3. It should be noted that at the time of this test phase the three IEUs have been stored for over 10.5 months with their internal cavities at subatmospheric condition. As a result, a weak leak in any of the seals in IEU 3, not detectable by helium leak detection, but effective over a 10.5 months period could cause air to leak inward. As a result, nitrogen would accumulate in the H_2 compartment of IEU 3, which would be supported by the initially higher starting reading of the H_2 accumulator (6% versus 2% of the other IEUs).

To pursue this line of reasoning, the O_2/H_2 cavities of IEU 3 were evacuated to return them to a known gas composition condition, i.e., pure water vapor at the ambient temperature and electrolyte concentration within the cells. Test results verified that accumulator behavior was restored to that previously observed by rerunning a complete 48 hour mission test profile. The accumulator positions for IEU 3 are shown in Figure 19 which indicates behavior almost identical to that shown in Figure 20 for an initial pre-flight operation conducted at a later time.

Based on this observation it was concluded at that time that long storage should be followed by an evacuation of all gas cavities for all IEUs prior to any re-flight. This of course would not be required for any future Electrolyzer since they would not be operated in a closed system with recombiners.

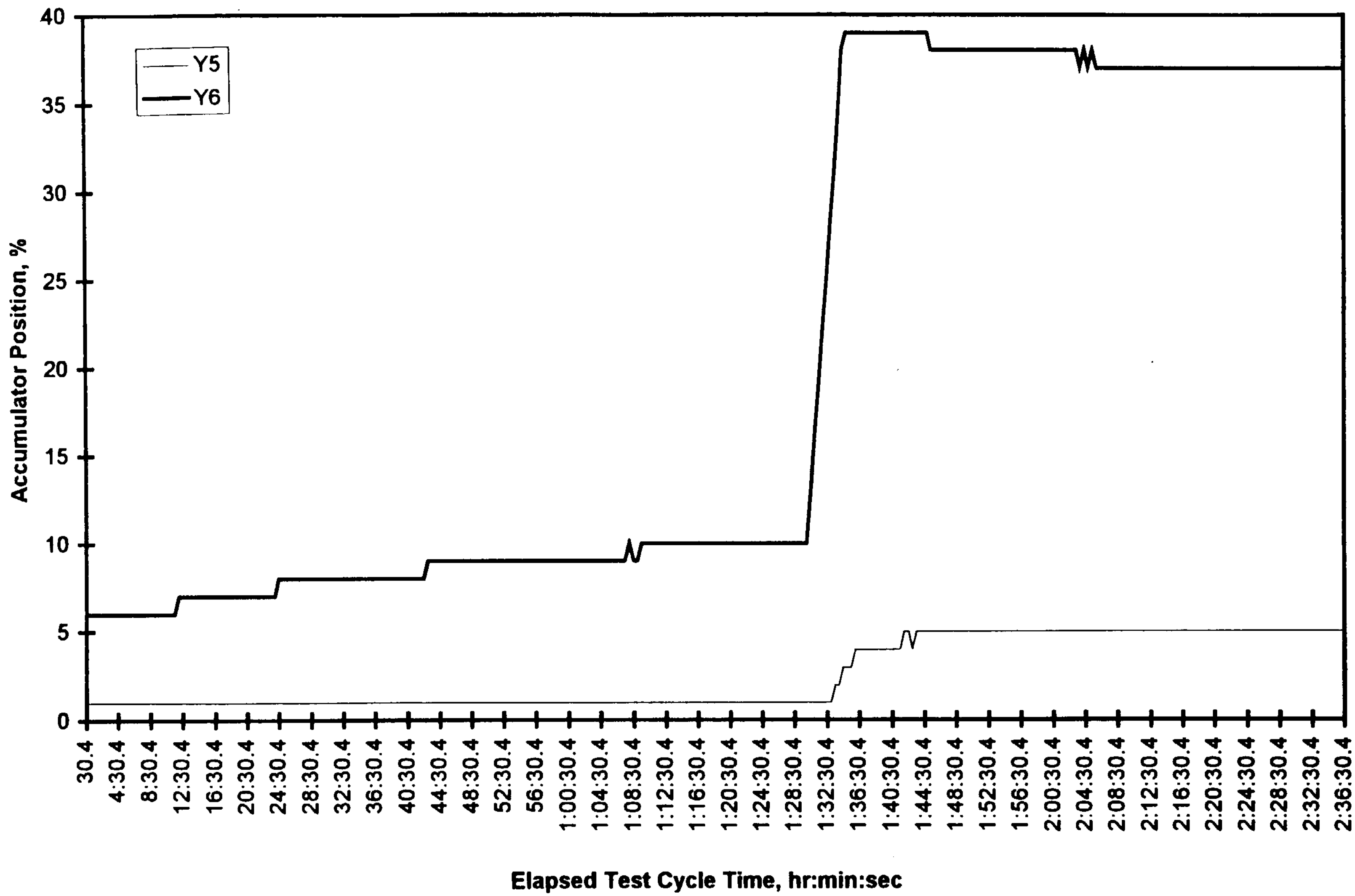


FIGURE 16 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU3
(INITIAL ACCEPTANCE TEST, 09/09/96)

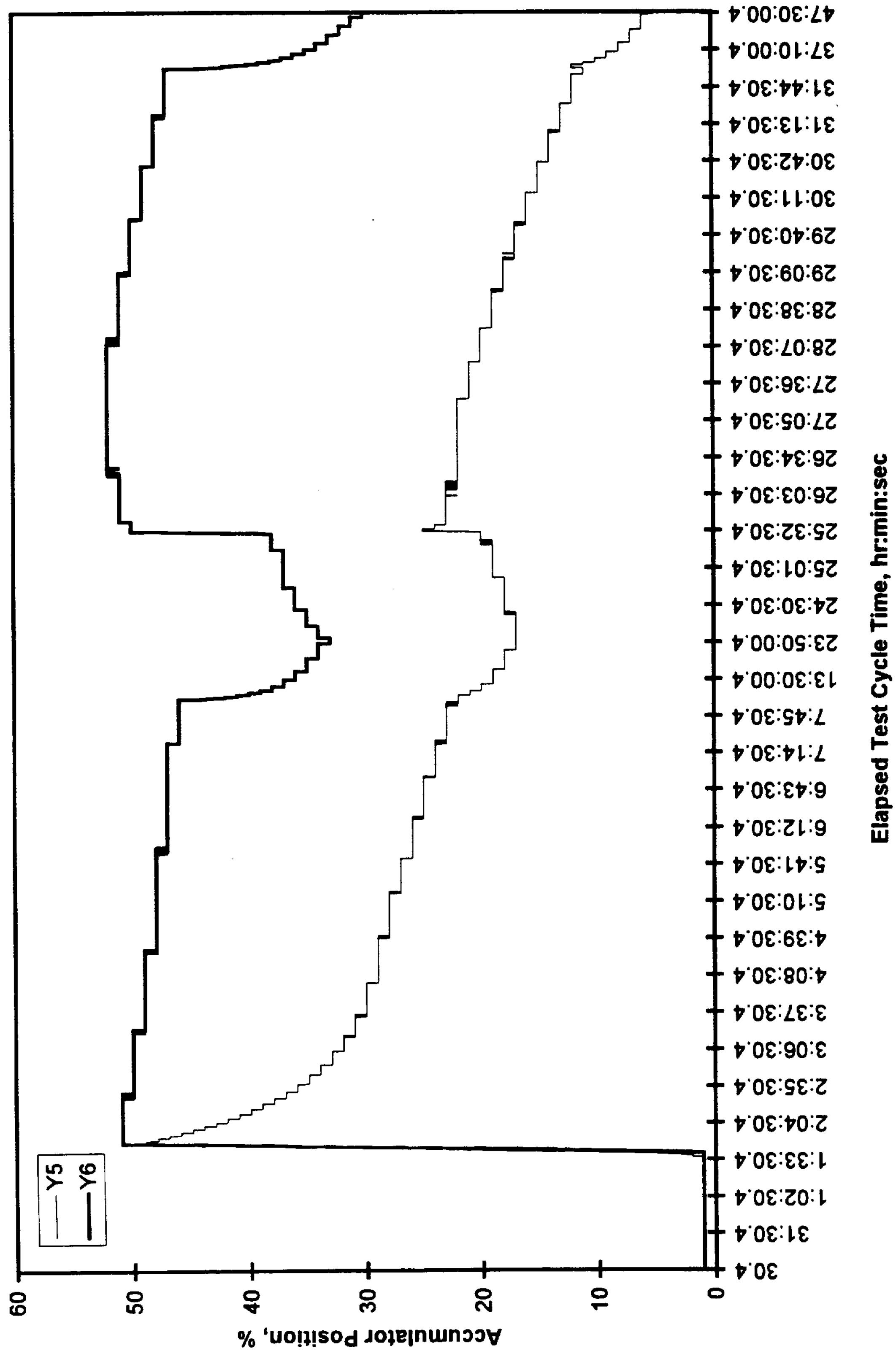


FIGURE 17 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU3 (INITIAL PRE-ACCEPTANCE TEST 08/28/96)

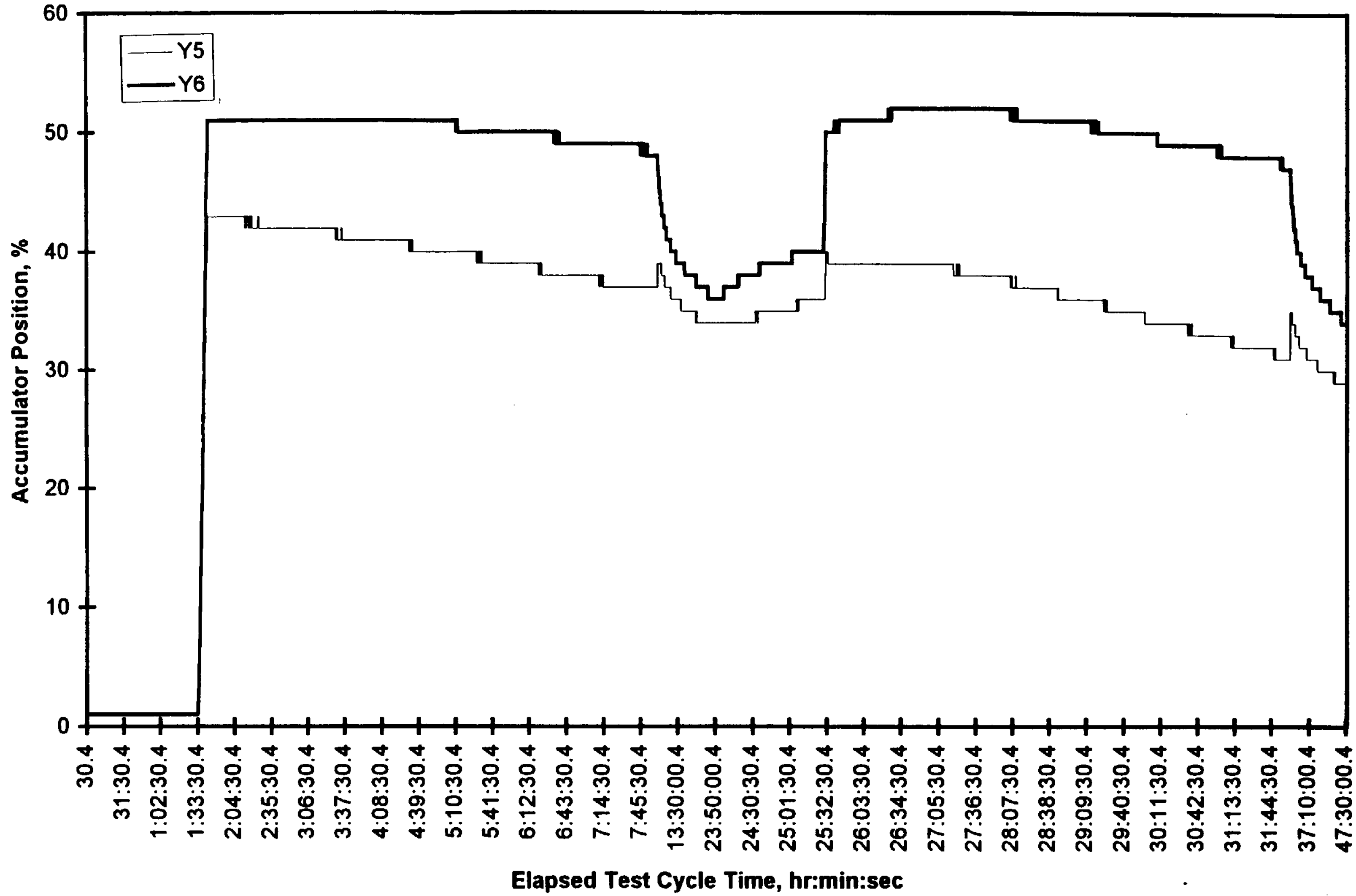


FIGURE 18 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU3
(ACCEPTANCE TEST FOR STS-69, 05/04/95)

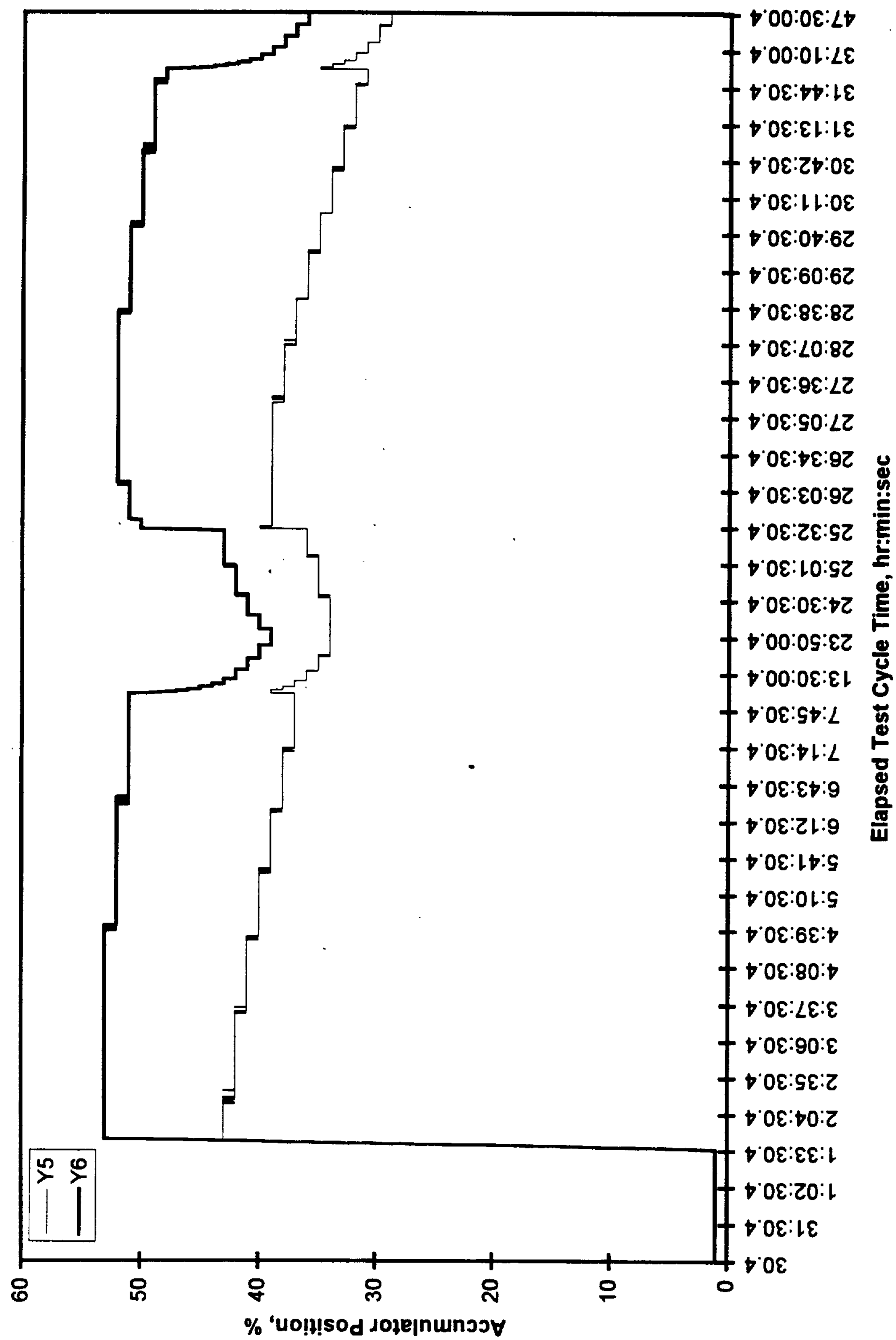


FIGURE 19 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU3
(POST EVACUATION, 10/15/96)

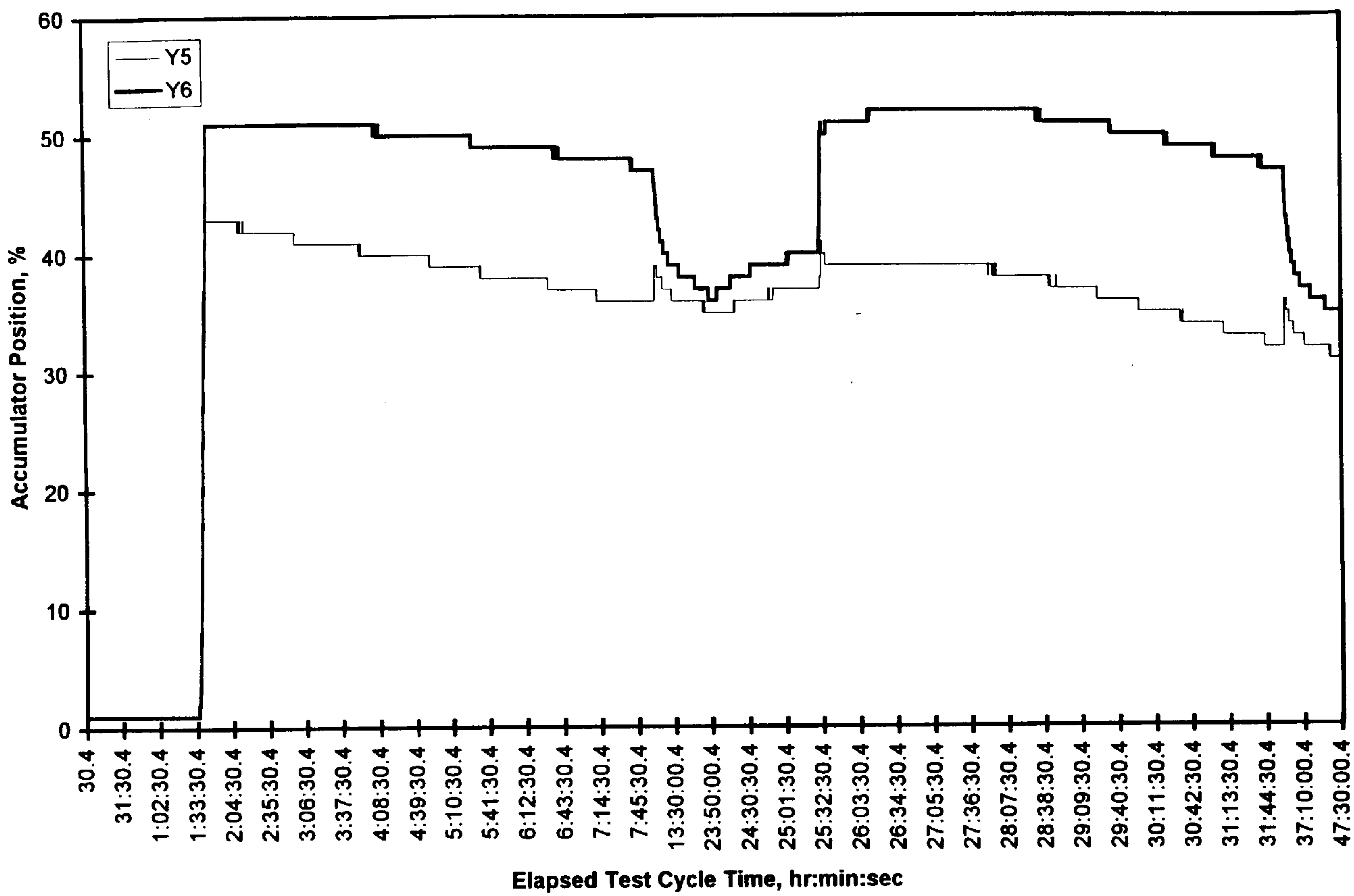


FIGURE 20 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU3
(REFLIGHT PRE-ACCEPTANCE TEST, 03/13/97)

Following this successful test the EPICS was stored for final pre-flight testing for flight aboard STS-84.

Final Pre-Acceptance and Acceptance Tests

Approximately three months prior to anticipated launch aboard STS-84, and five months after last operation of the EPICS, the three IEUs were evacuated for Pre-Acceptance and Acceptance Testing. Pre-Acceptance and Acceptance Testing were successfully completed following the evacuation of all three IEU's prior to these tests. The O_2/H_2 accumulators performed without any shutdown although Y3 of IEU 2 was lower than usual. Their positions vs time are shown in Figure 21. Electrolyzer voltage performance was typical when compared to past data, with the three voltages shown in Figure 22.

Following the Acceptance Test the EPICS was packaged and shipped to KSC for processing and installation into STS-84.

Flight (STS-84) Test

Following delivery of the EPICS and its checkout and formal turnover at KSC, the unit was installed aboard Shuttle Orbiter Vehicle OV104 for Flight STS-84. The middeck locker location for the EPICS hardware was MF71G and MF71H.

Three 48-hour mission profiles were planned with the EPICS hardware. Activation of Run No. 1 was on May 15, 1997, for Run No. 2 on May 17, 1997 and for Run No. 3 on May 19, 1997. Final deactivation occurred on May 21, 1997.

The IEU No. 3 of the EPICS successfully completed all three 48 hour mission profiles, while IEU No. 1 and No. 2 underwent a safe and automatic shutdown during the 2 A operation of Run No. 1. The results obtained with IEU No. 3 are discussed first, followed by the discussions of the observations with IEUs No. 2 and 3.

IEU No. 3 Results

Figures 23 through 27 show five key parameters of the IEU tests superimposed for the three runs on a single graph for each parameter. Figure 23 shows the electrolyzer voltages for the three runs for both the 2 and 7 A operation. Slight increases in cell voltage, more dominant at the 7 A operation, were observed when progressing from Run 1 through Run 3.

Figure 24 shows the recombiner cell voltage E6 as a function of elapsed test cycle time for the three runs completed. Slight, but insignificant variations were observed between the three runs, but otherwise no unusual or unexpected behavior was evident.

Figure 25 shows the IEU 3 temperature T3 for the three runs as well as the collective exit temperature T7 from the M/EA. Temperature levels of T3 are repetitive and consistent within

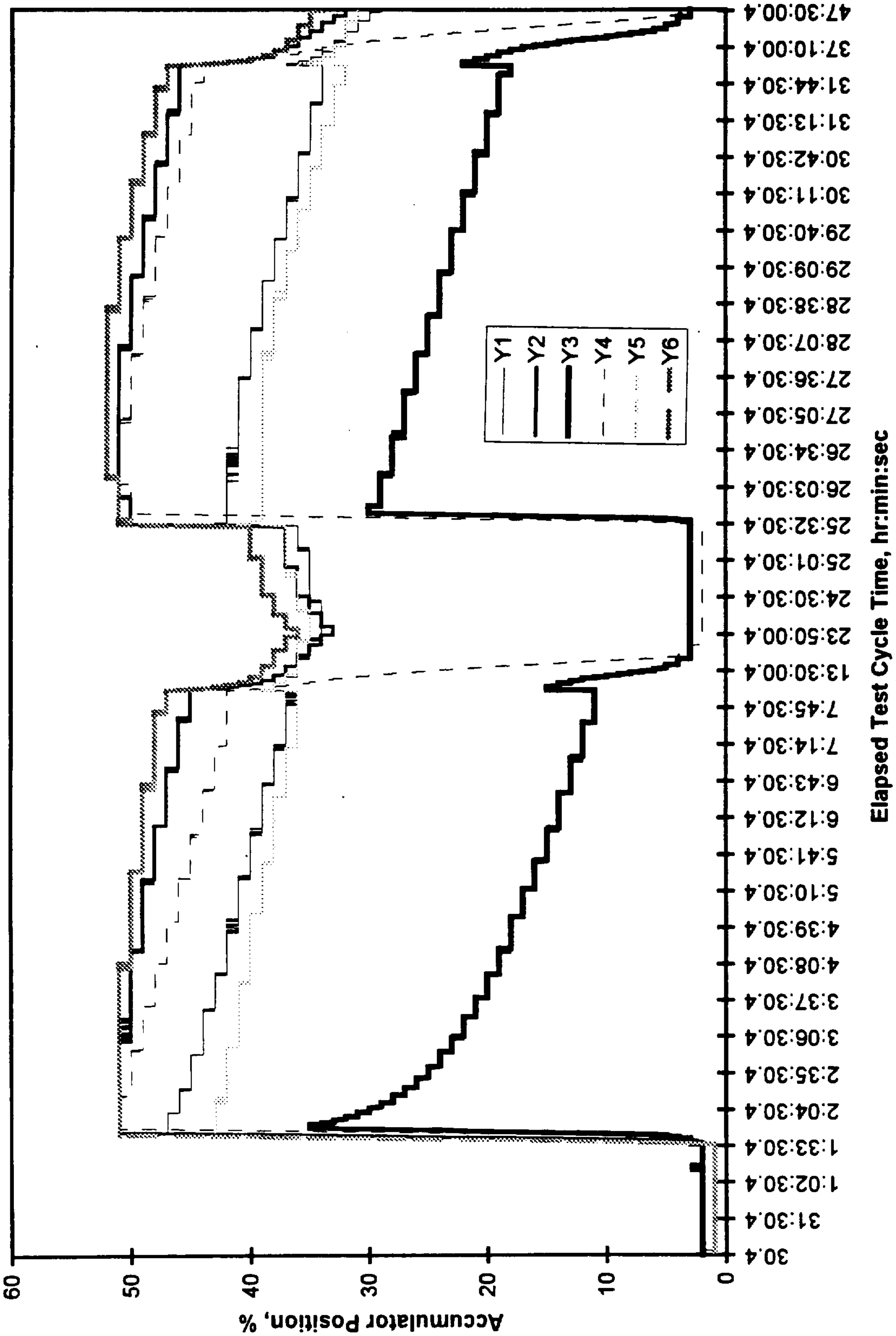


FIGURE 21 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU 1, 2 AND 3
(REFLIGHT PRE-ACCEPTANCE TEST, 03/13/97)

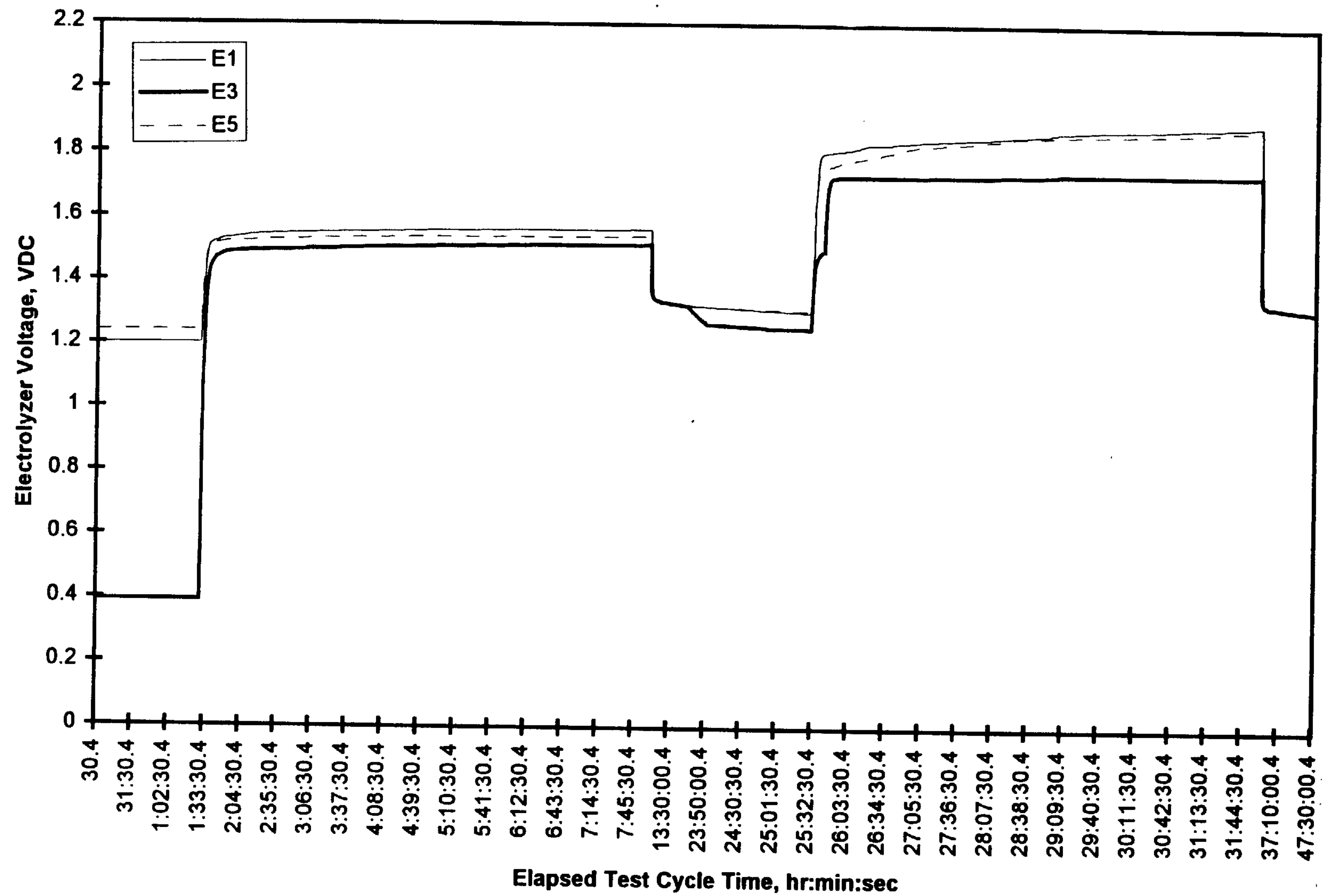


FIGURE 22 ELECTROLYZER VOLTAGES VS. TIME FOR ALL THREE IEUS
(PRE-ACCEPTANCE TEST 03/13/97)

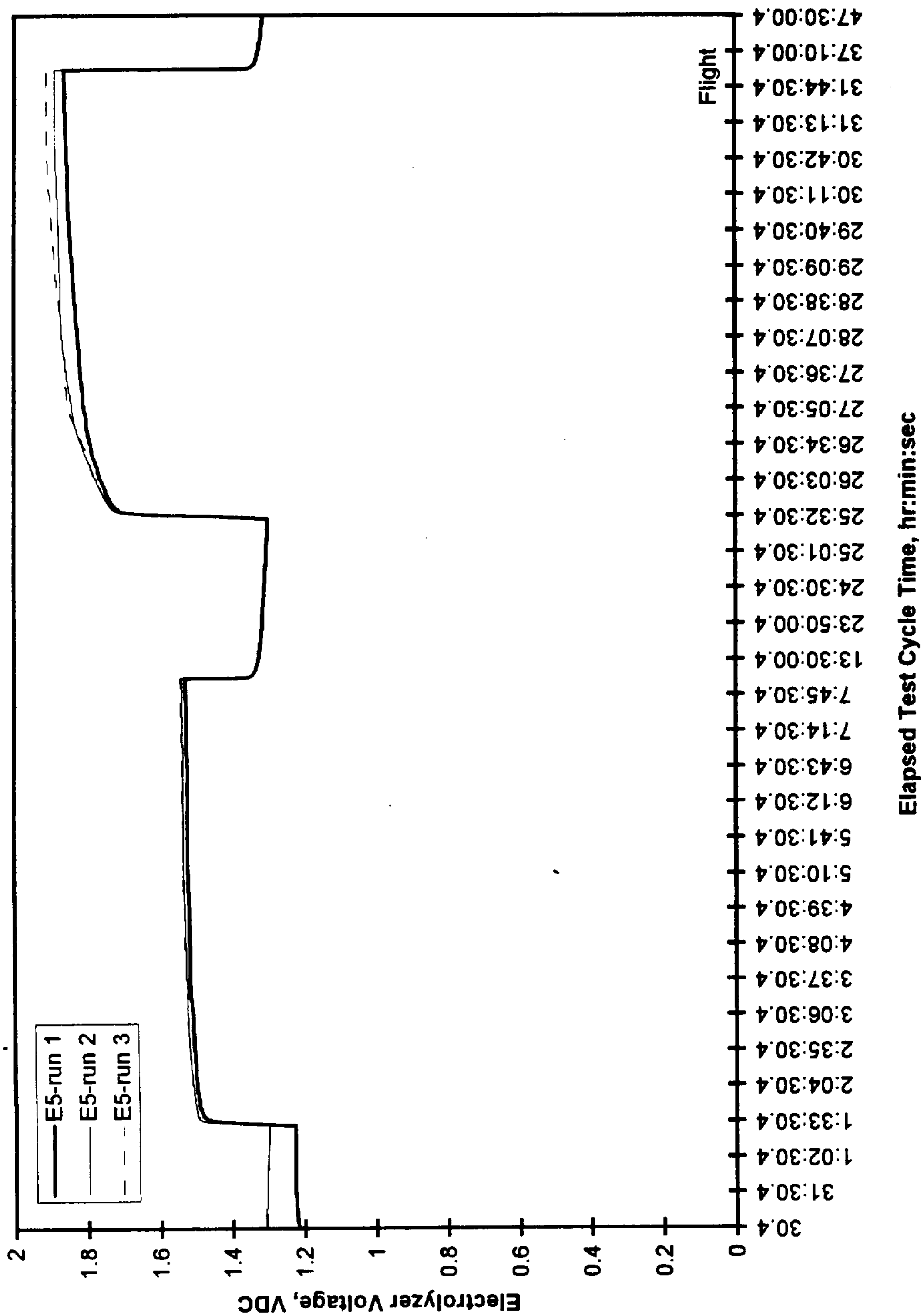


FIGURE 23 ELECTROLYZER VOLTAGE VS. TIME (THREE CYCLES), IEU3
(FLIGHT DATA, 05/15/97)

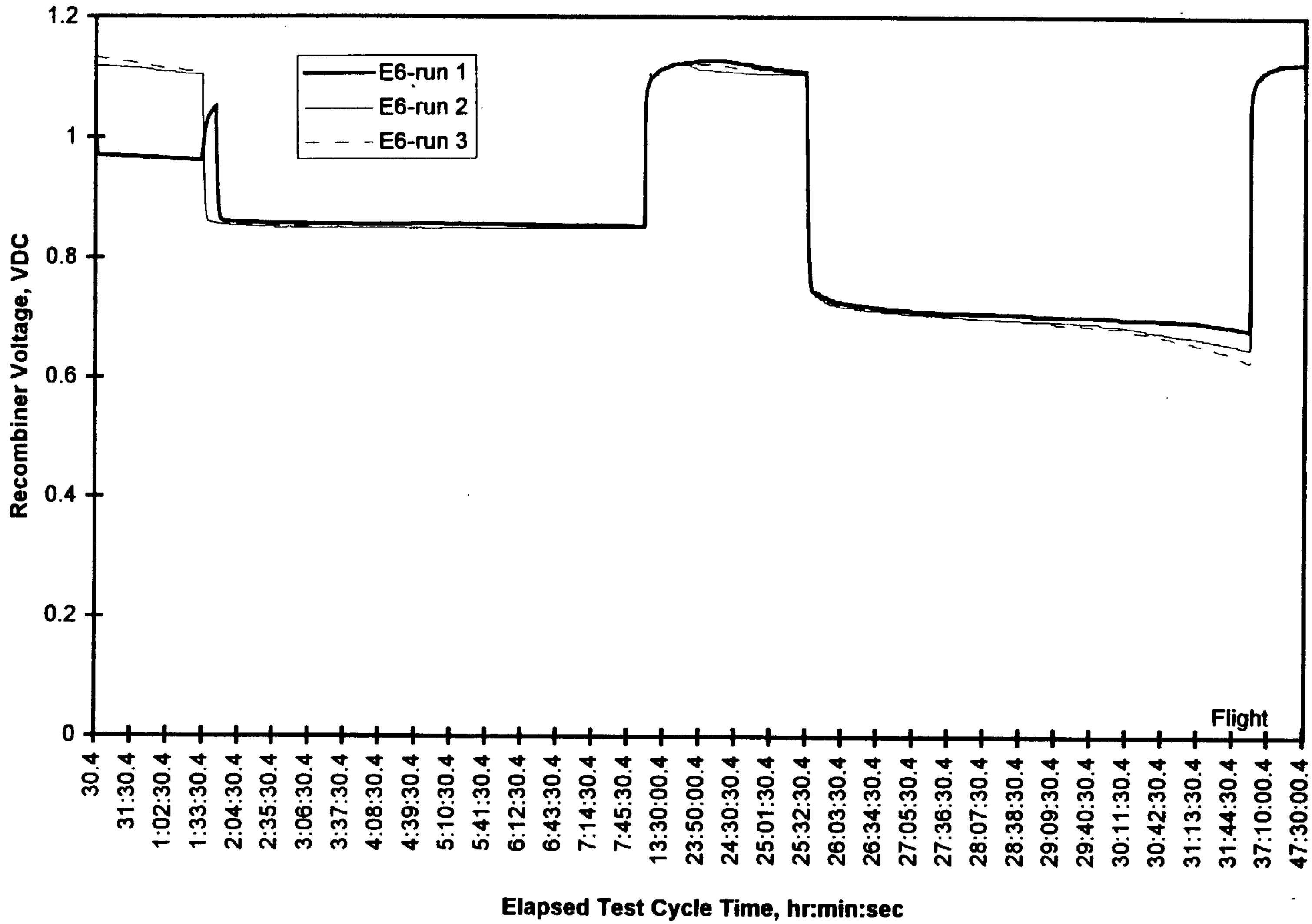


FIGURE 24 RECOMBINER VOLTAGE VS. TIME (THREE CYCLES), IEU3
(FLIGHT DATA, 05/15/97)

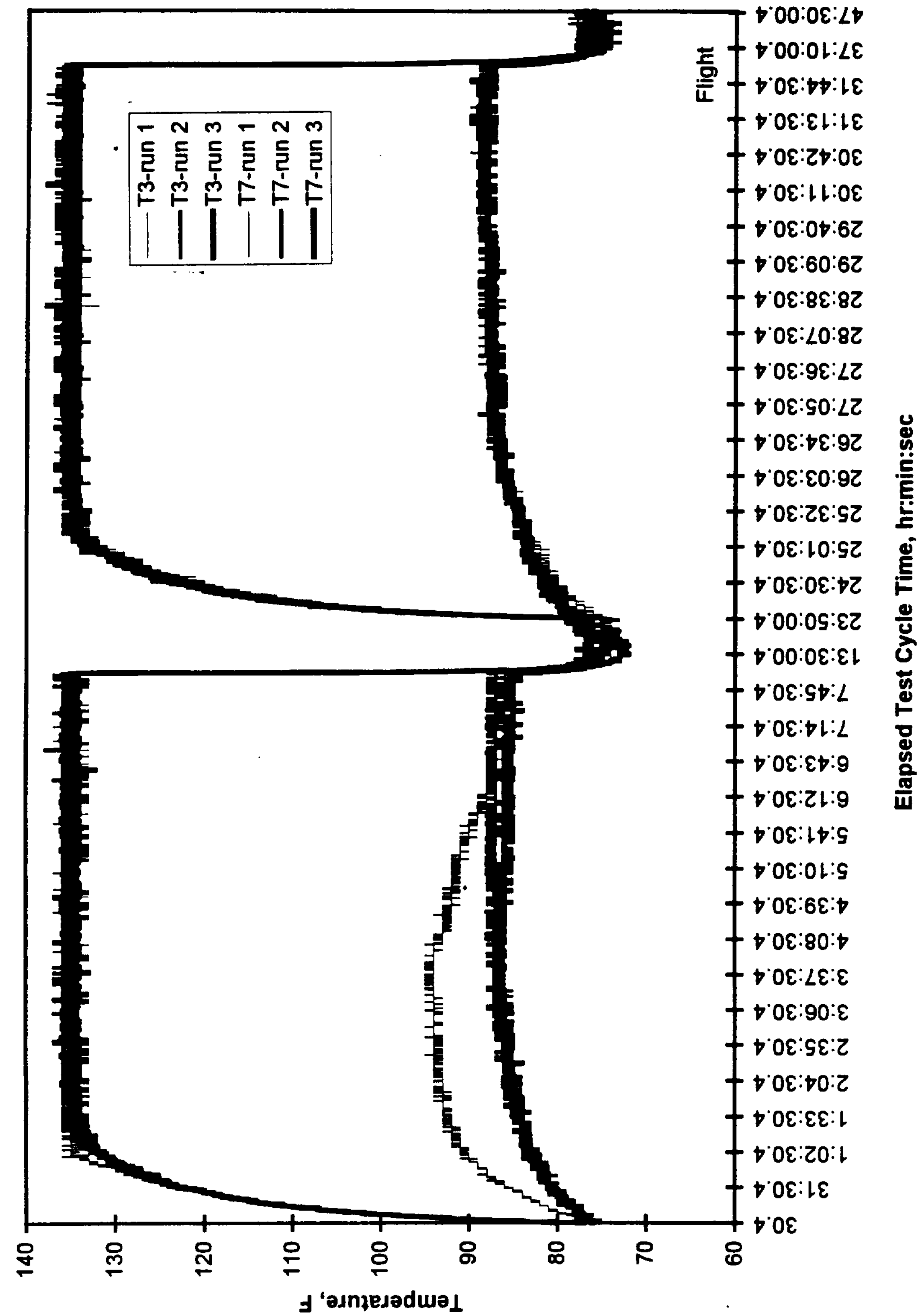


FIGURE 25 TEMPERATURES VS. TIME (THREE CYCLES), IEU3 AND M/EA EXIT
(FLIGHT DATA 05/15/97)

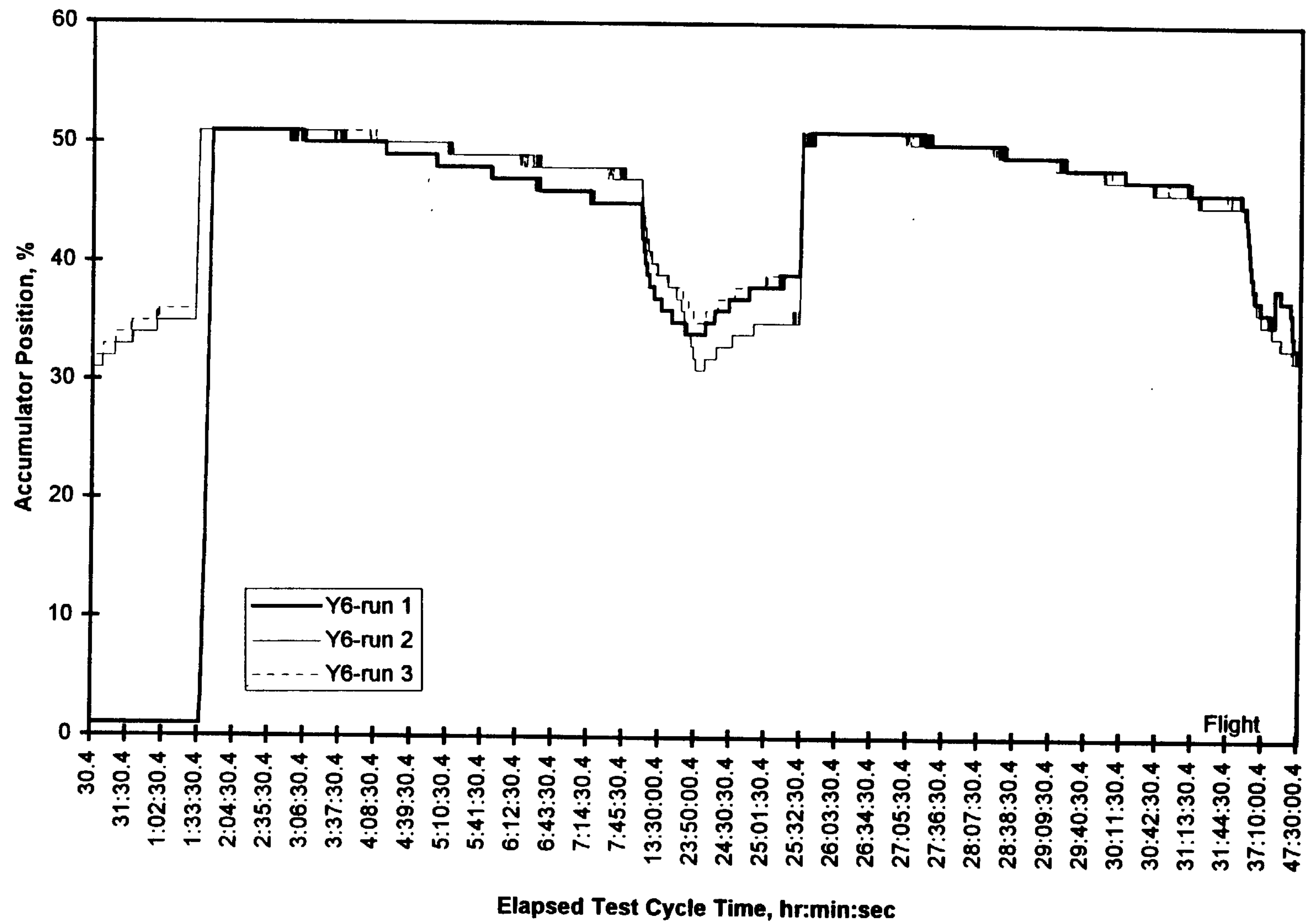


FIGURE 26 H_2 ACCUMULATOR POSITION VS. TIME (THREE CYCLES), IEU3
(FLIGHT DATA, 05/15/97)

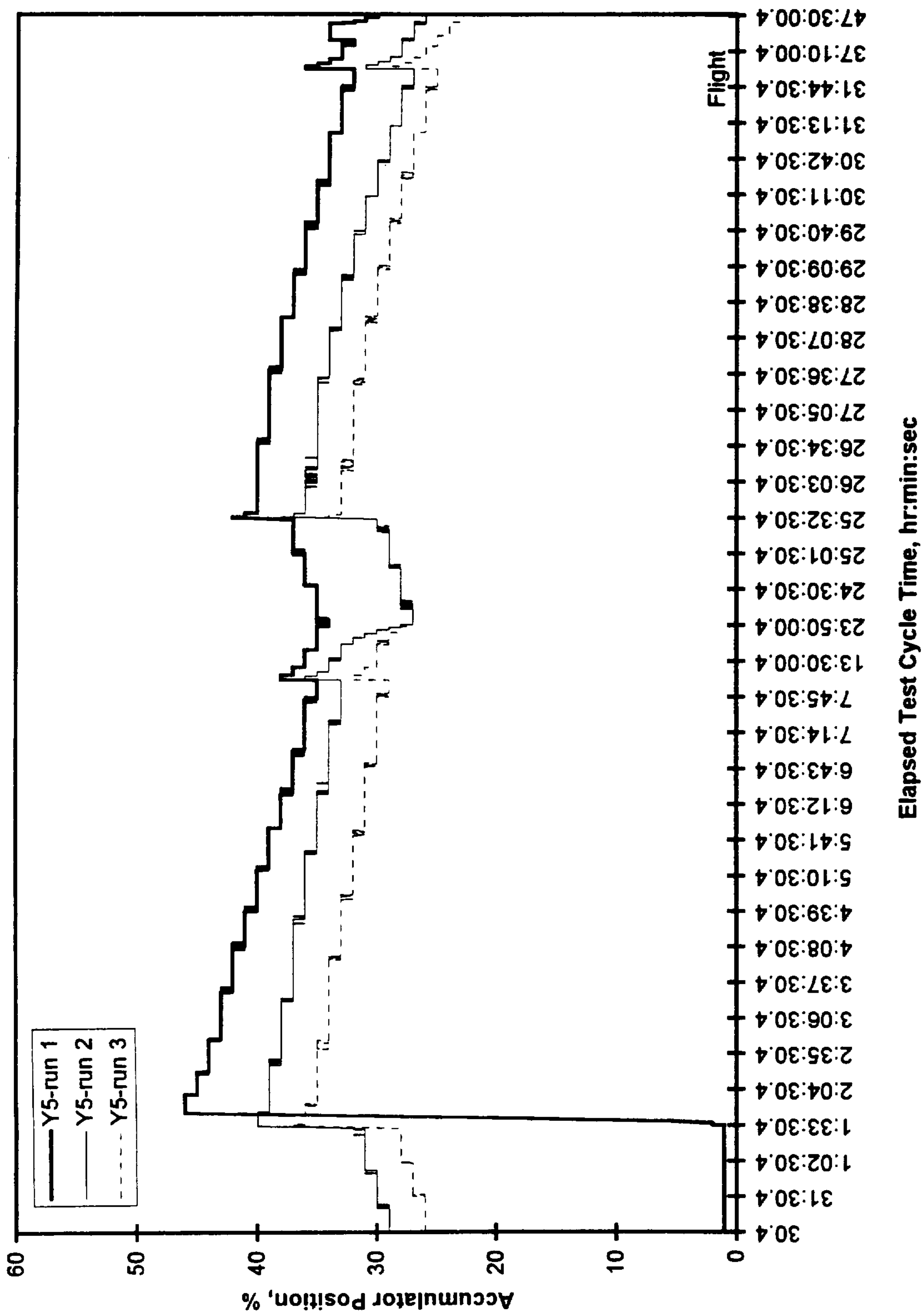


FIGURE 27 O_2 ACCUMULATOR POSITION VS. TIME (THREE CYCLES), IEU3
(FLIGHT DATA, 05/15/97)

the control band of 134 to 136 F. T7 shows a higher value which then declines during the initial run. The higher T7 resulted from the heat load that initially included the heat from IEU 1 and 2 prior to their shutdowns at approximately the three to four hour mark of the initial run. Subsequently, T7 is repetitive but at a lower value reflective of the lower heat load from one IEU only. Initial heat up of IEU 3 for Run No. 1 appears also to be quicker than for Runs 2 and 3, again, attributed to the total heat load and high air temperature within the M/EA resulting from all three IEUs starting up during Run No. 1.

Figure 26 shows the accumulator position for the H_2 accumulator as a function of elapsed test cycle time for IEU No. 3. The initial position for Run No. 1 was near zero, reflective of the evacuated state of the IEUs prior to test initiation. Subsequent starting points for Runs 2 and 3 are equal to the stopping point from the previous mission profile test. Similar observations are made for the O_2 accumulator position shown in Figure 27. While the accumulator positions as function of time for the H_2 accumulator were nearly repetitive (see Figure 26), a slow decay in accumulator position for the O_2 accumulator is noted in Figure 27. Its behavior will be discussed as part of the analysis section of the Flight and Post-Test results.

IEU No. 1 Results

At approximately 4 hour and 15 minute of elapsed test time of the first mission profile, IEU No. 1 automatically and safely shut down. The shutdown cause was traced to loss of heater power to IEU 1 at the 3 hour and 52 minute mark. The additional 23 minutes of operation following the heater loss was the time required for the IEU temperature to reach its lower shutdown limit of 110 F.

Figure 28 shows electrolyzer cell voltage E1 of IEU 1 versus elapsed time. The cell voltage at the 2 A level is steady until the 3 hr and 50 min mark. Then a slight rise is observed followed by a decay to open circuit voltage. The slight rise is due to the loss in temperature as the unit cooled from 135 F to the 110 F shutdown limit. The temperature profile verifying this scenario as depicted in Figure 29. Cause of the heater loss is discussed in the Post-Flight Test and Analysis Section below.

IEU No. 2 Test Results

At approximately 5 hours and 20 minutes of elapsed test time of the first mission profile, IEU No. 2 safely and automatically shutdown. The shutdown was caused by the O_2 accumulator position Y3 reaching its low shutdown limit of 5%. This is shown in Figure 30 which also indicates that the H_2 accumulator showed no signs of abnormal behavior. For comparison a typical H_2 and O_2 accumulative position profile (that for IEU No. 3) for a similar time period, is shown in Figure 31. Up to the point of shutdown, both IEU 1 and 3 H_2 accumulator positions behaved similarly. Rationale for the decay in O_2 accumulator position will be presented in the Post-Test Analysis section. Electrolyzer cell voltage E3 versus time for IEU No. 2 is shown in Figure 32. The voltage was steady and at expected levels up to the shut down.

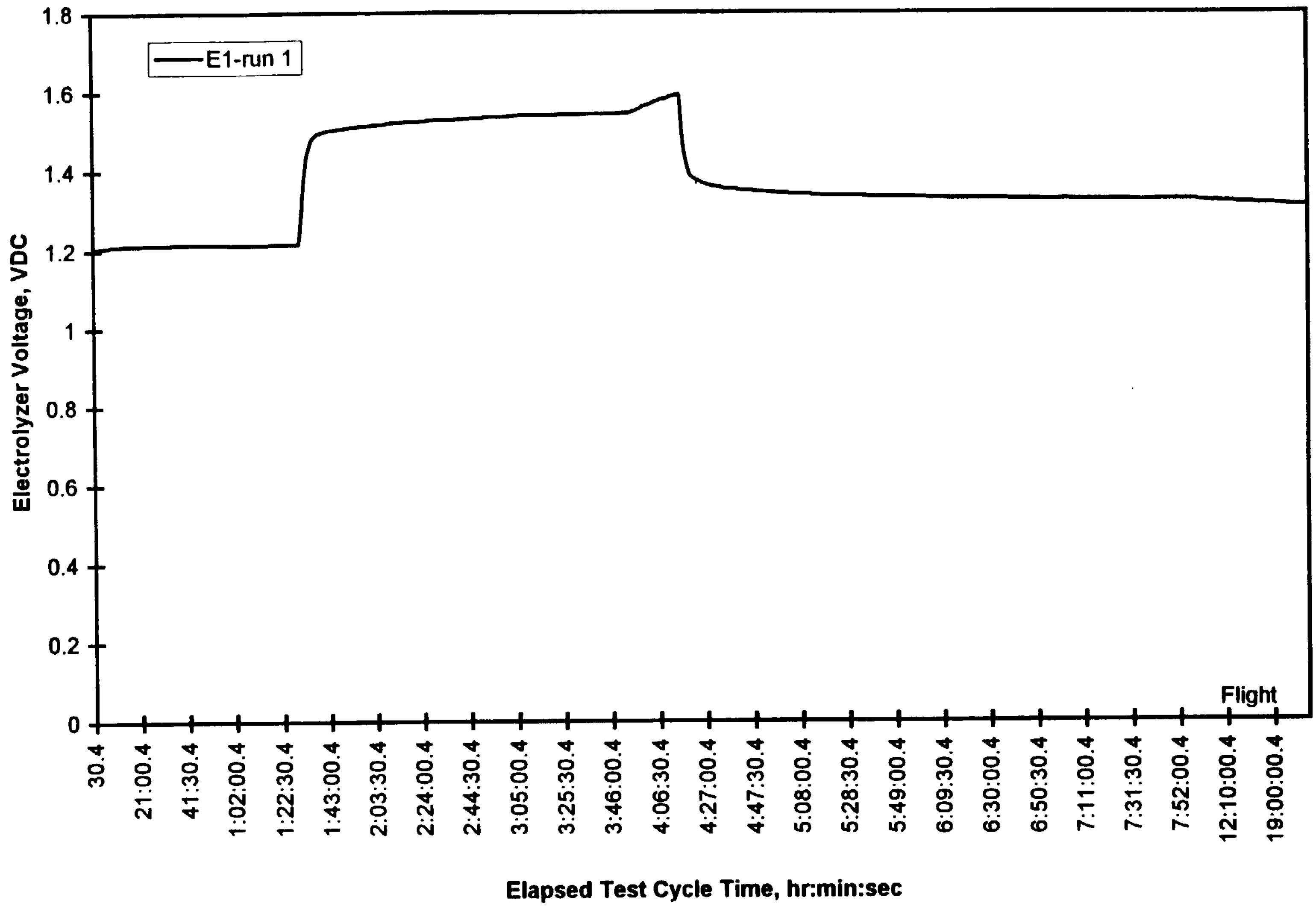


FIGURE 28 ELECTROLYZER VOLTAGE VS. TIME, IEU1
(FLIGHT DATA, 05/15/97)

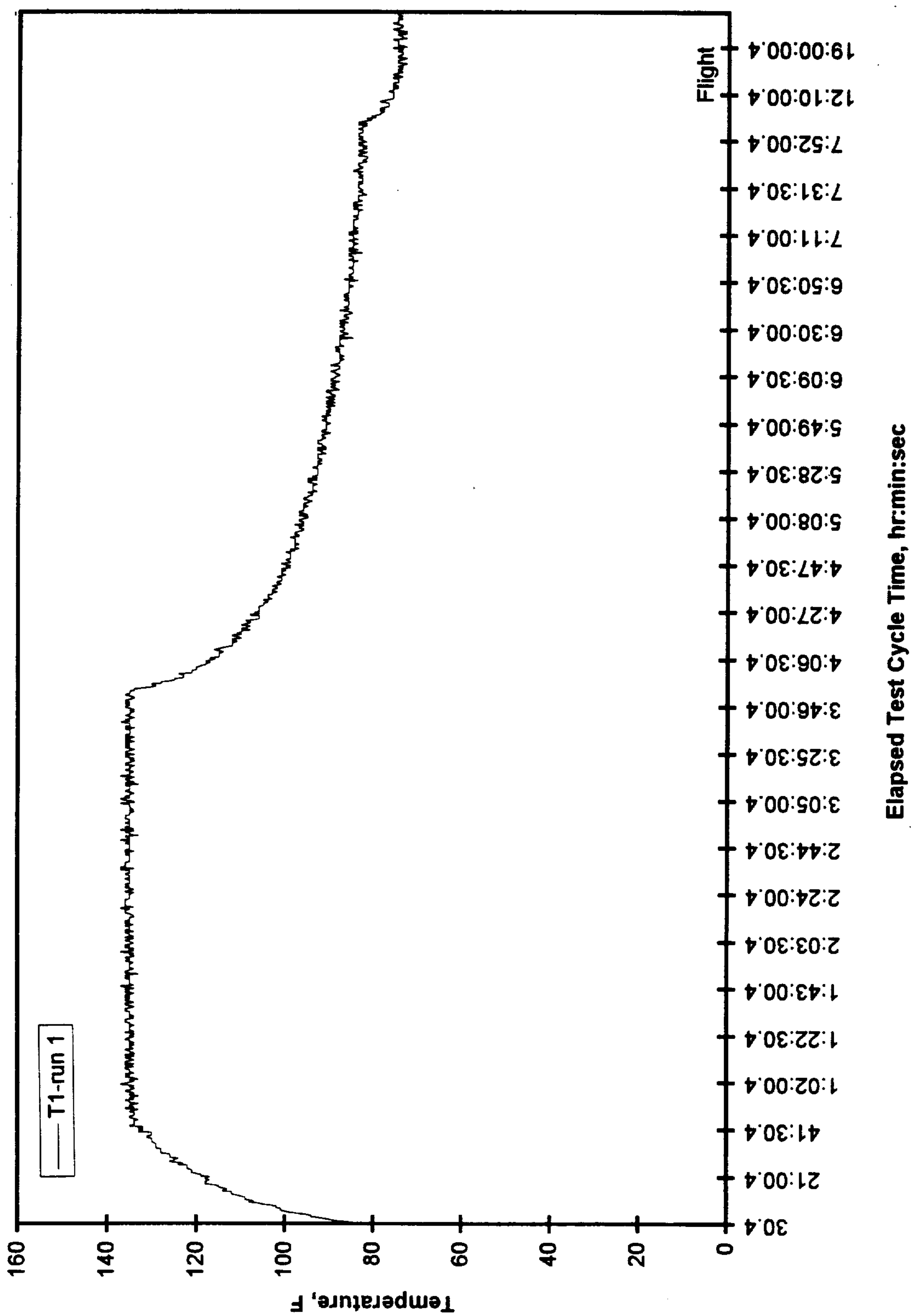


FIGURE 29 TEMPERATURE VS. TIME, IEU1
(FLIGHT DATA, 05/15/97)

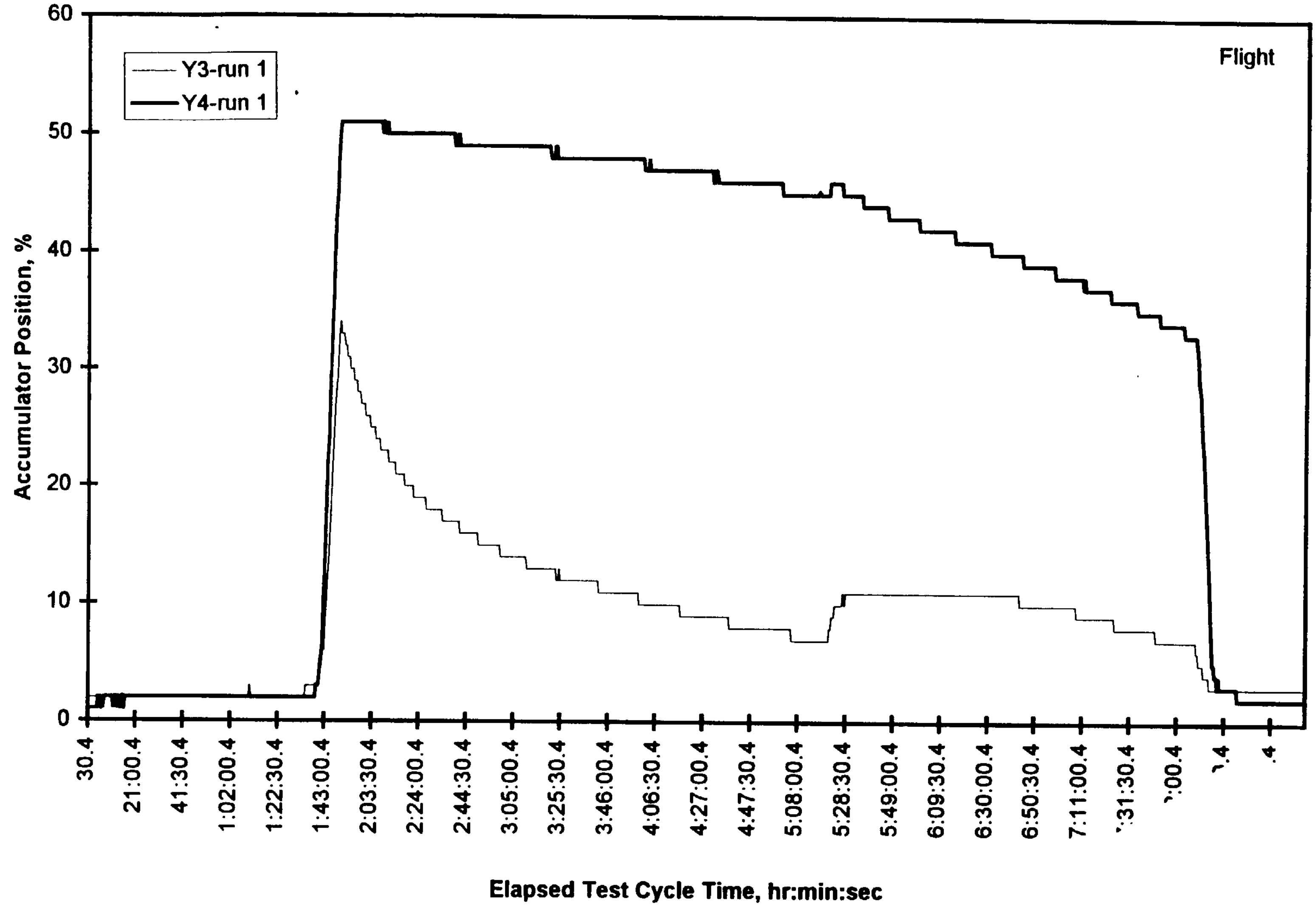


FIGURE 30 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU2
(FLIGHT DATA, 05/15/97)

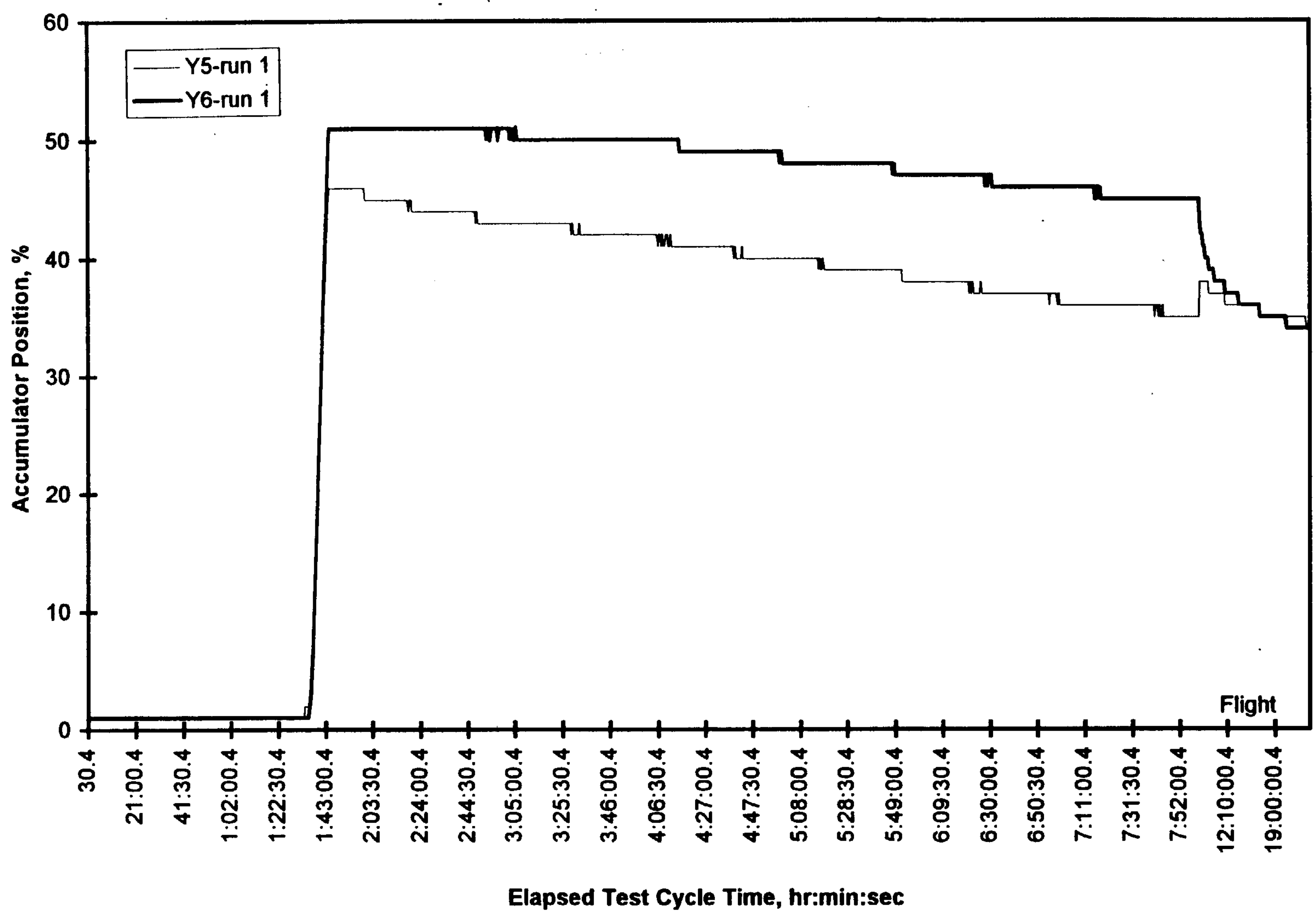


FIGURE 31 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU3
(FLIGHT DATA, 05/15/97)

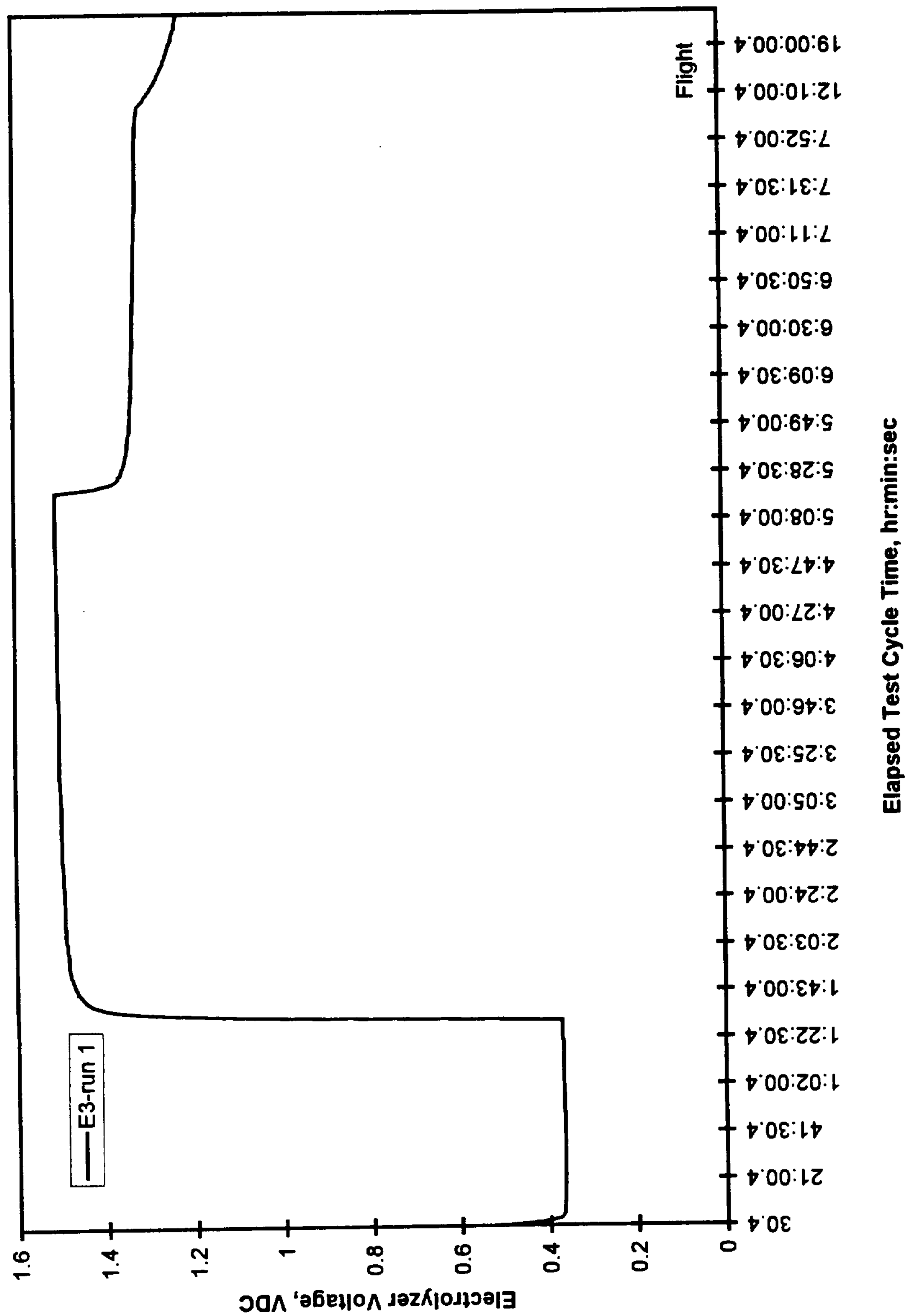


FIGURE 32 ELECTROLYZER VOLTAGE VS. TIME, IEU2
(FLIGHT DATA, 05/15/97)

Post-Flight Tests and Analysis

Following deactivation procedures and data retrieval at KSC, the EPICS was returned to Life Systems for Post-Test and Analysis. The goal was first to repeat the three 48 hr mission profile cycles similar to those completed on orbit, followed by specific troubleshooting and analysis activities to identify the shutdown causes of IEU 1 and IEU 2.

Post-Test Results

Following visual inspection of the EPICS hardware and unpowered continuity tests on the IEU No. 1 heater and heater leads, the EPICS was reassembled, all faults cleared and automatic startup reinitiated. As expected, IEU 1 automatically shutdown since no temperature rise occurred. Both IEU 2 and 3, however, initiated the heatup cycle, then the electrolysis-only phase, followed by electrolysis and recombiner operation. The results are discussed first for the IEU 3 operation followed by that for IEU 2.

IEU 3 Post-Flight Results. IEU 3 successfully completed three 48 hr mission profiles similar to those completed on orbit. The test results are presented in Figures 33 through 37 for similar key operating parameters investigated from the STS-84 flight data.

Figure 33 shows electrolyzer cell voltage E5 versus elapsed test cycle time for the three individual runs. While the profiles are similar to those observed during microgravity operation, it is noted that the overall voltage levels are higher, with the relative increase as a function of cycles greater than observed in space. Also, a change in voltage slope is a function of time at the 27 hour mark of each of the three cycles is noted.

Figure 34 shows the recombiner cell voltage E6 as a function of elapsed test cycle time. Its performance and shape is similar to that observed on orbit and no special observations are made other than a slight decrease in cell voltage during 7 A operation. No significance is attached to that observation.

Figure 35 shows both the IEU cell temperature T3 and the combined M/EA exit temperature T7 as a function of elapsed test cycle time. While the shapes of the curves are similar to those observed on orbit, significant differences exist. On-orbit heat up time proceeds more quickly reaching the controlled temperature level in about one hour versus the 2 to 3 hour mark for ground operation. The deviation of T7 during Run 1 for the initial cycle is similar to that observed on orbit, however, the lower level is attributed to the fact that only IEU No. 2 was contributing to the initial heat up compared to both IEU 1 and IEU 2 contributing on orbit.

The dip at about the 25 hour mark in the temperature profile of T3 for all three cycles at the 7 A operation is caused by the change-over from electrolysis-only operation for the initial 1-1/2 hour at 2 A to the 7 A operation. In microgravity aboard STS-84 the switchover point to electrolysis and recombiner at 7 A occurred after IEU 3 had reached the control temperature

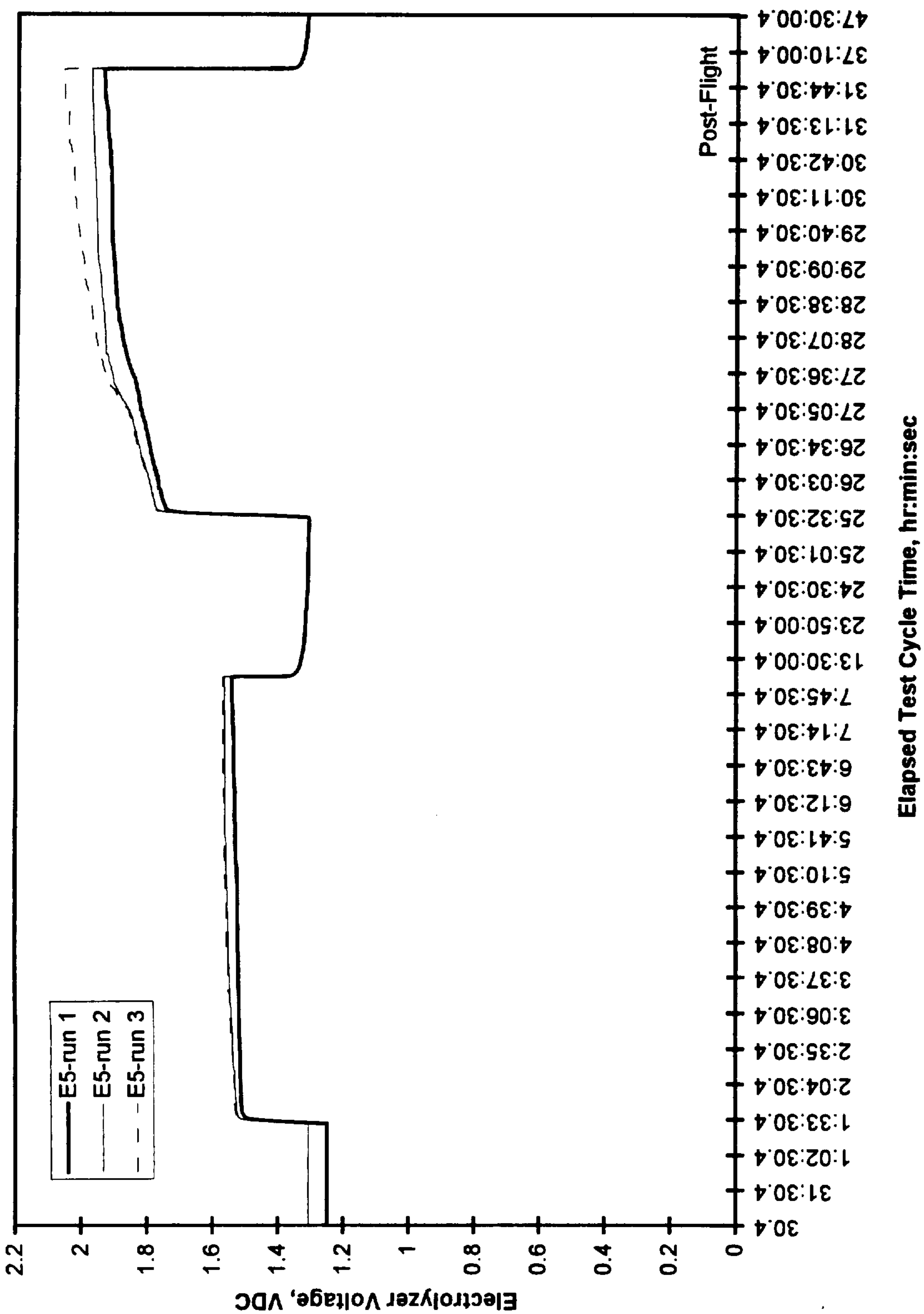


FIGURE 33 ELECTROLYZER VOLTAGE VS. TIME (THREE CYCLES), IEU3
(POST-FLIGHT, 06/16/97)

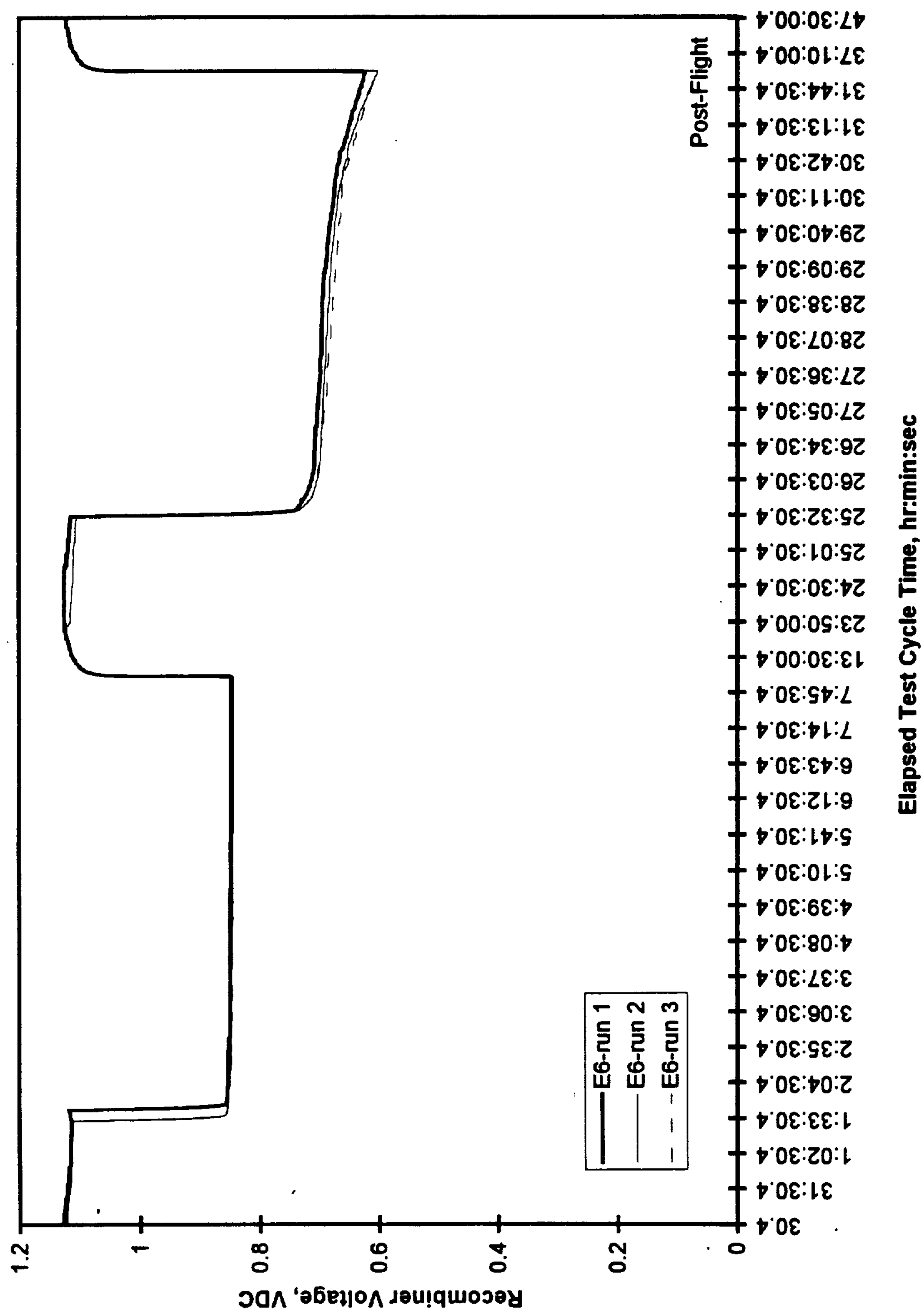


FIGURE 34 RECOMBINER VOLTAGE VS. TIME (THREE CYCLES), IEU3
(POST-FLIGHT, 06/16/97)

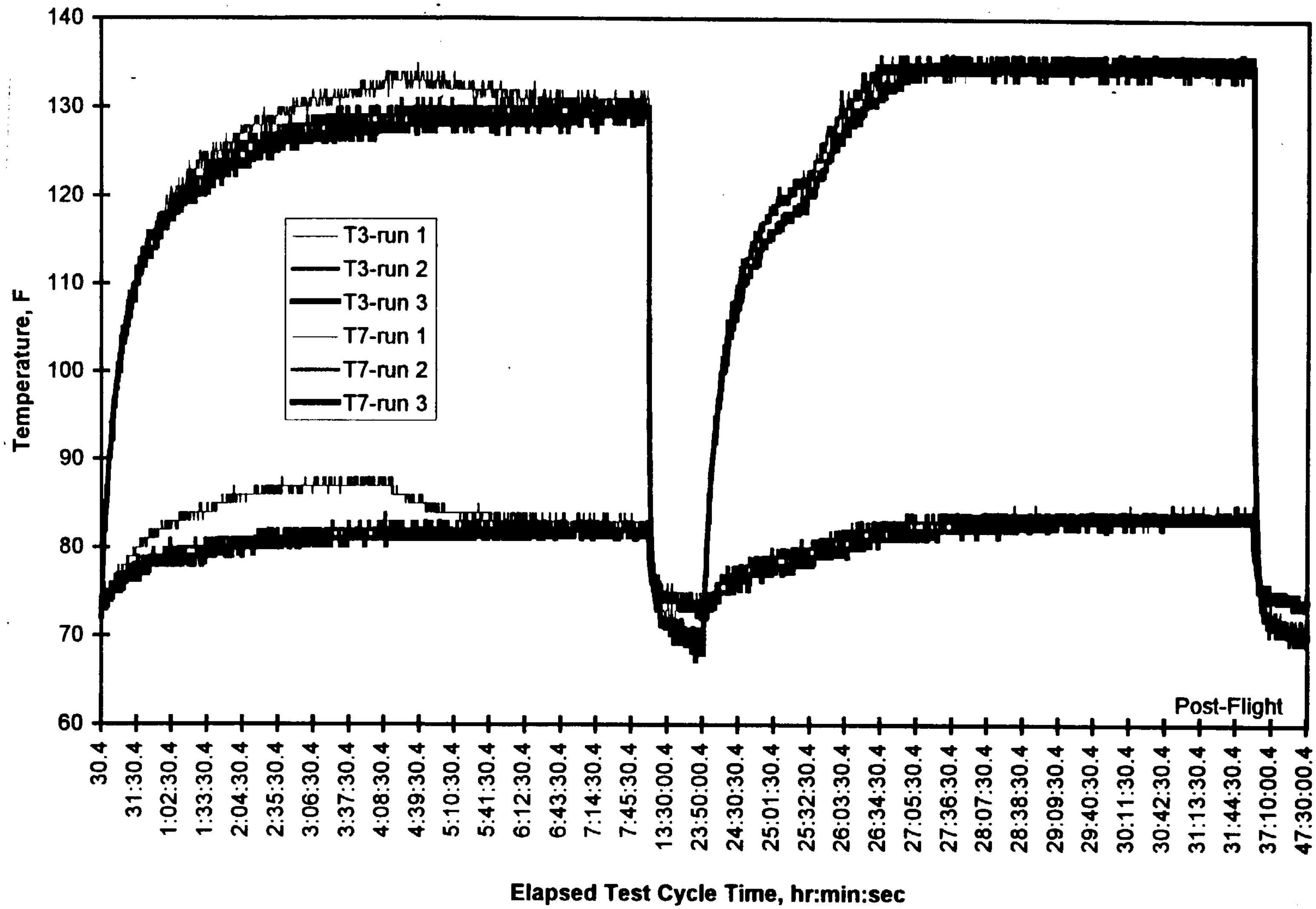


FIGURE 35 TEMPERATURES VS. TIME (THREE CYCLES), IEU3 AND M/EA EXIT
(POST-FLIGHT, 06/16/97)

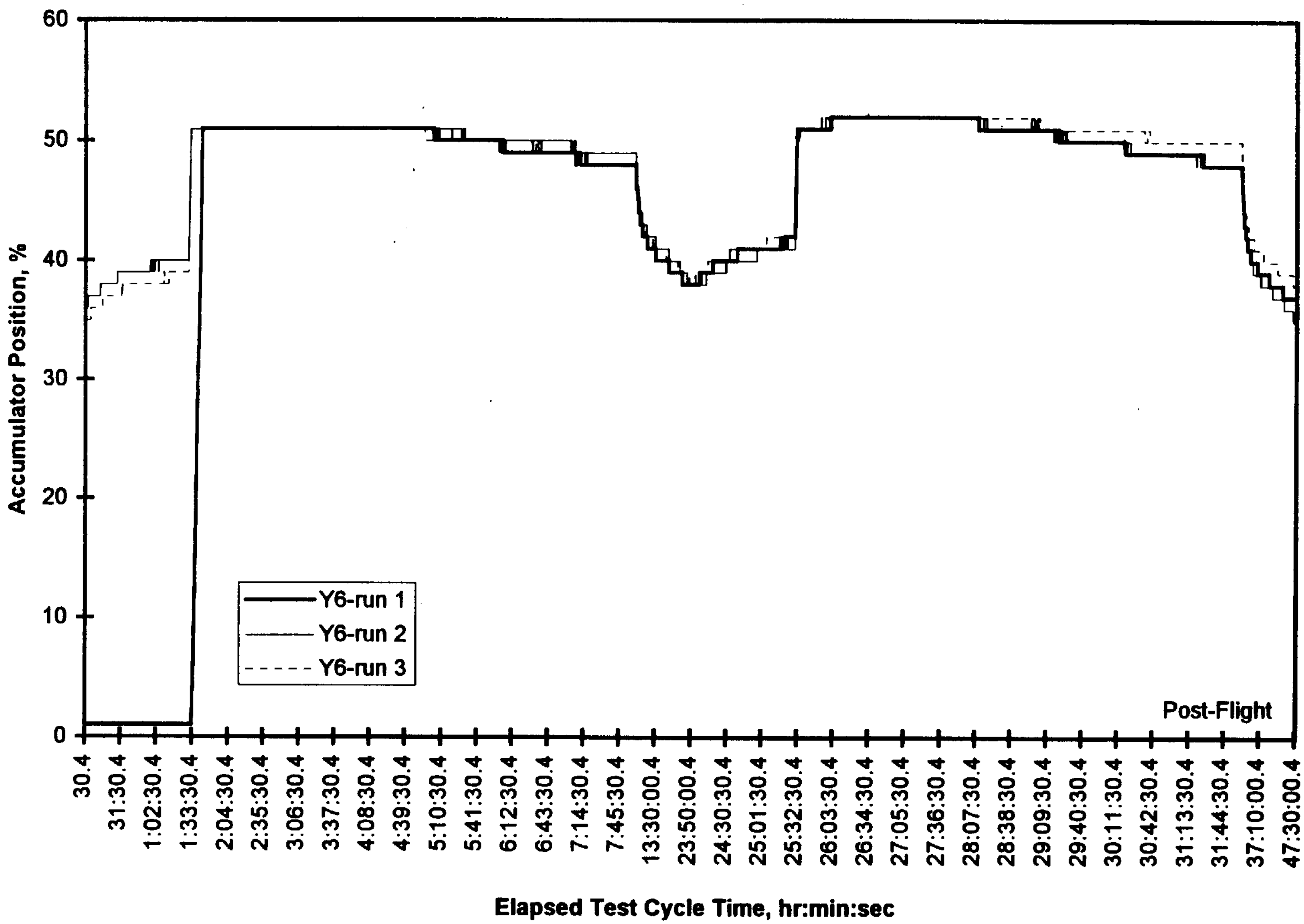


FIGURE 36 H_2 ACCUMULATOR POSITION VS. TIME (THREE CYCLES), IEU3
(POST-FLIGHT DATA, 06/16/97)

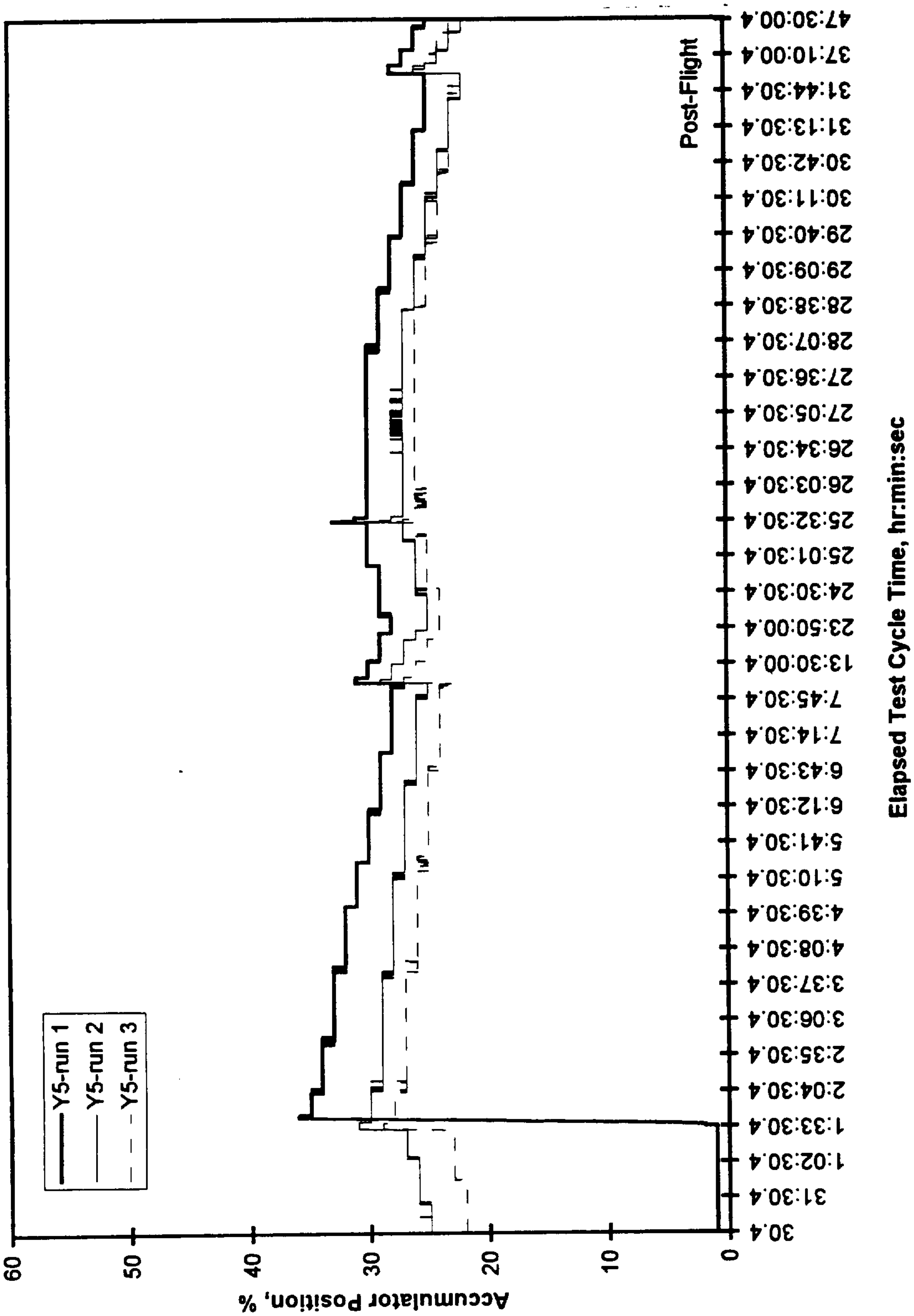


FIGURE 37 O_2 ACCUMULATOR POSITION VS. TIME (THREE CYCLES), IEU3
(POST-FLIGHT DATA, 06/16/97)

point of 135 F due to the much faster heat up time in orbit. The change in slope on the ground in temperature is due to the increased heat load when 7 A are flowing through the cells compared to 2 A. The 7 A causes a much faster heat up rate, hence the discontinuity.

Figure 36 shows H_2 accumulator position Y6 as a function of elapsed test cycle time for the three cycles. The shape and behavior of the H_2 accumulator for IEU 3 is very similar to that in orbit and no special comments are warranted.

Figure 37 shows O_2 accumulator position Y5 as a function of elapsed test cycle time for IEU 3 for each of the three 48 hour mission profiles. Again, as in microgravity, with each successive run a drop in O_2 accumulator position is noted. While the relative drops from one run to the next is not as pronounced as they were in space, there relative levels are a continuation of dropping from those observed in microgravity i.e., Run No. 1 on Earth is lower in O_2 accumulator position than the last run in space. This phenomenon will be further analyzed below.

IEU No. 2 Post-Flight Results. Retest of the EPICS showed that the same phenomenon occurred with IEU 2 as was observed in space. An automatic and safe shutdown occurred when the O_2 accumulator position Y3 dropped to 5%, however, the level of 5% was reached more quickly for the ground retest compared to the test in microgravity. The IEU 2 shutdown at approximately 4 hours and 6 minutes compared to the 5 hour and 20 minutes observed in space. Electrolyzer voltage E3 of IEU 2 as a function of elapsed time and H_2 and O_2 accumulator positions Y4 and Y3 for the same time frame are shown in Figures 38 and 39, respectively.

Analysis and Findings

Analysis and findings based on the on-orbit test results and those results obtained during post-flight testing and troubleshooting are discussed below. IEU No. 3 is addressed first followed by IEU 1 and 2.

IEU No. 3 Analysis and Findings. IEU 3 successfully completed all Pre-Flight, Flight and Post-Flight test cycles. Three observations, however, warrant discussion. The first is thermal behavior, the second is cell voltage levels and the third is O_2 accumulator position.

As was shown in Figures 25 and 35, thermal behavior is different, not as unexpected, in orbit as compared to ground operation. In the absence of natural convection cell heat up times are shorter and temperature control is more crisp and precise. Heat up times for IEU 3 were generally cut in half, a factor that could be considered for future thermal system designs for space application.

The rise in cell voltage, more evident at the 7 than at the 2 A level for IEU 3 in successive cycles on orbit with continued increases during the immediate post tests could be caused by several factors. Such factors include electrode degradation, increased contact resistance and/or lack of water feed. To explore this phenomenon further subsequent tests were run on the EPICS following its three mission profile cycles initially repeated on the ground. As can be seen, in Figures 40 and 41, two subsequent runs conducted 10 and 28 days after the

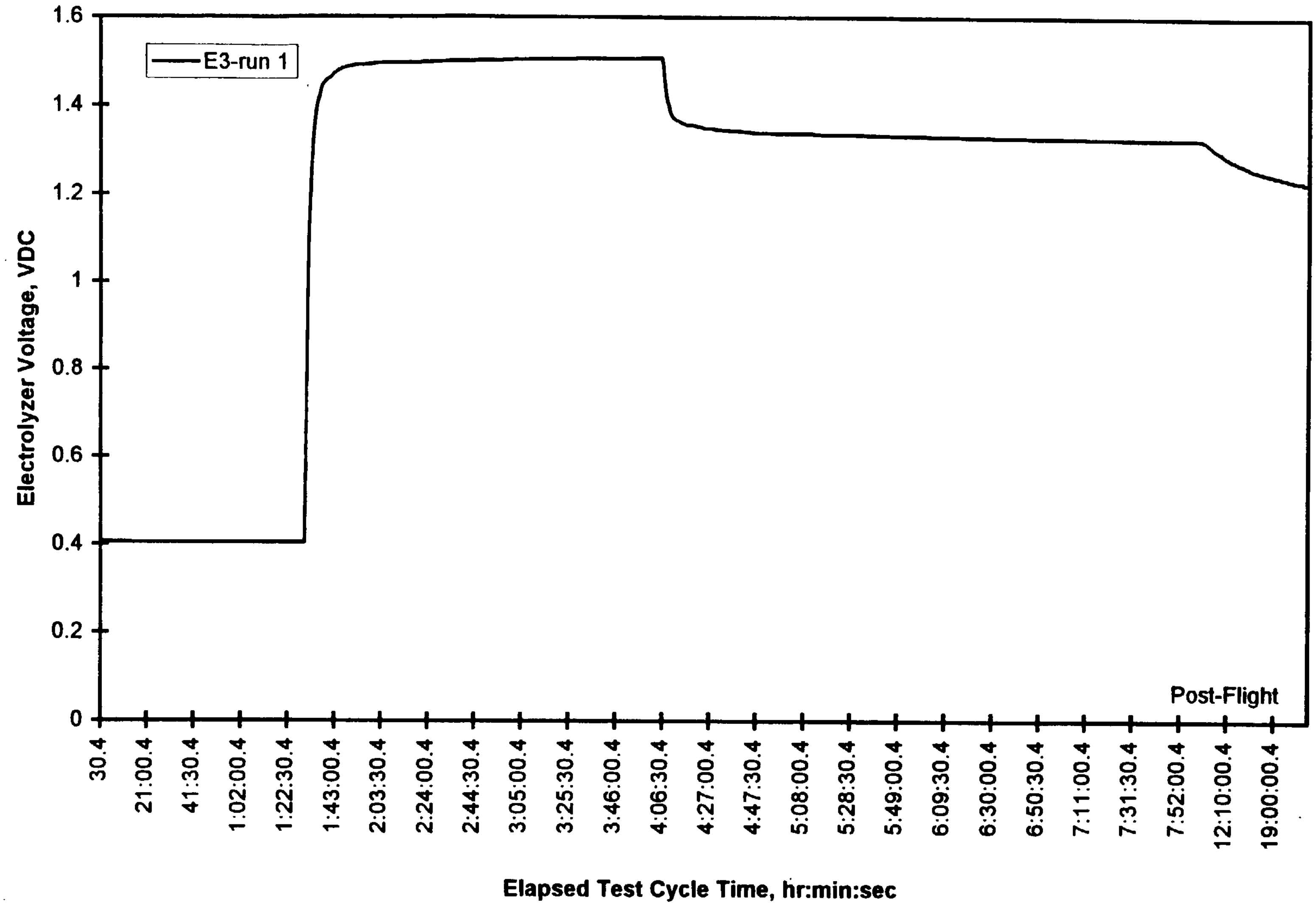


FIGURE 38 ELECTROLYZER VOLTAGE VS. TIME, IEU2
(POST-FLIGHT DATA, 06/16/97)

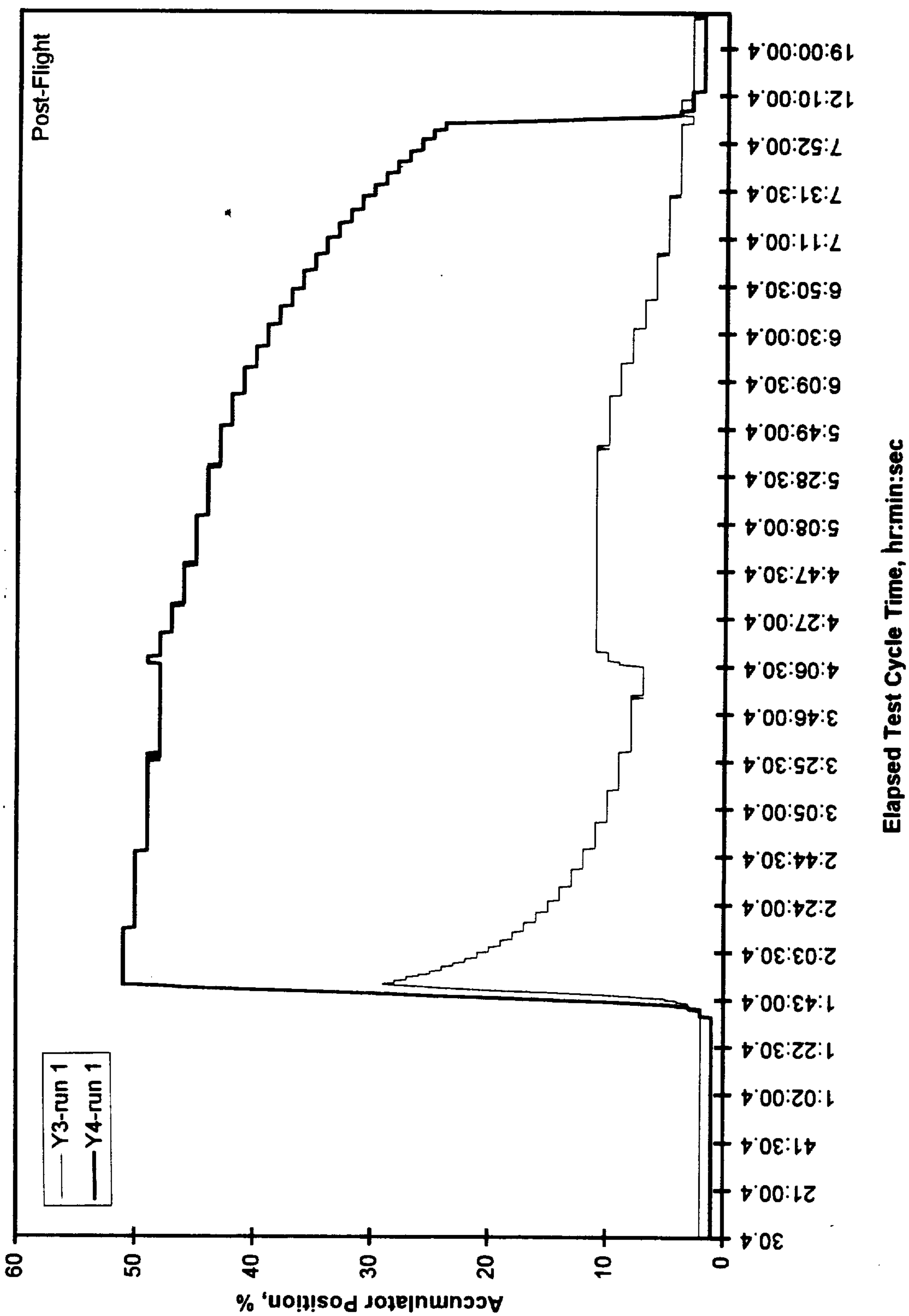


FIGURE 39 H_2 AND O_2 ACCUMULATOR POSITIONS VS. TIME, IEU2
(POST-FLIGHT, 06/16/97)

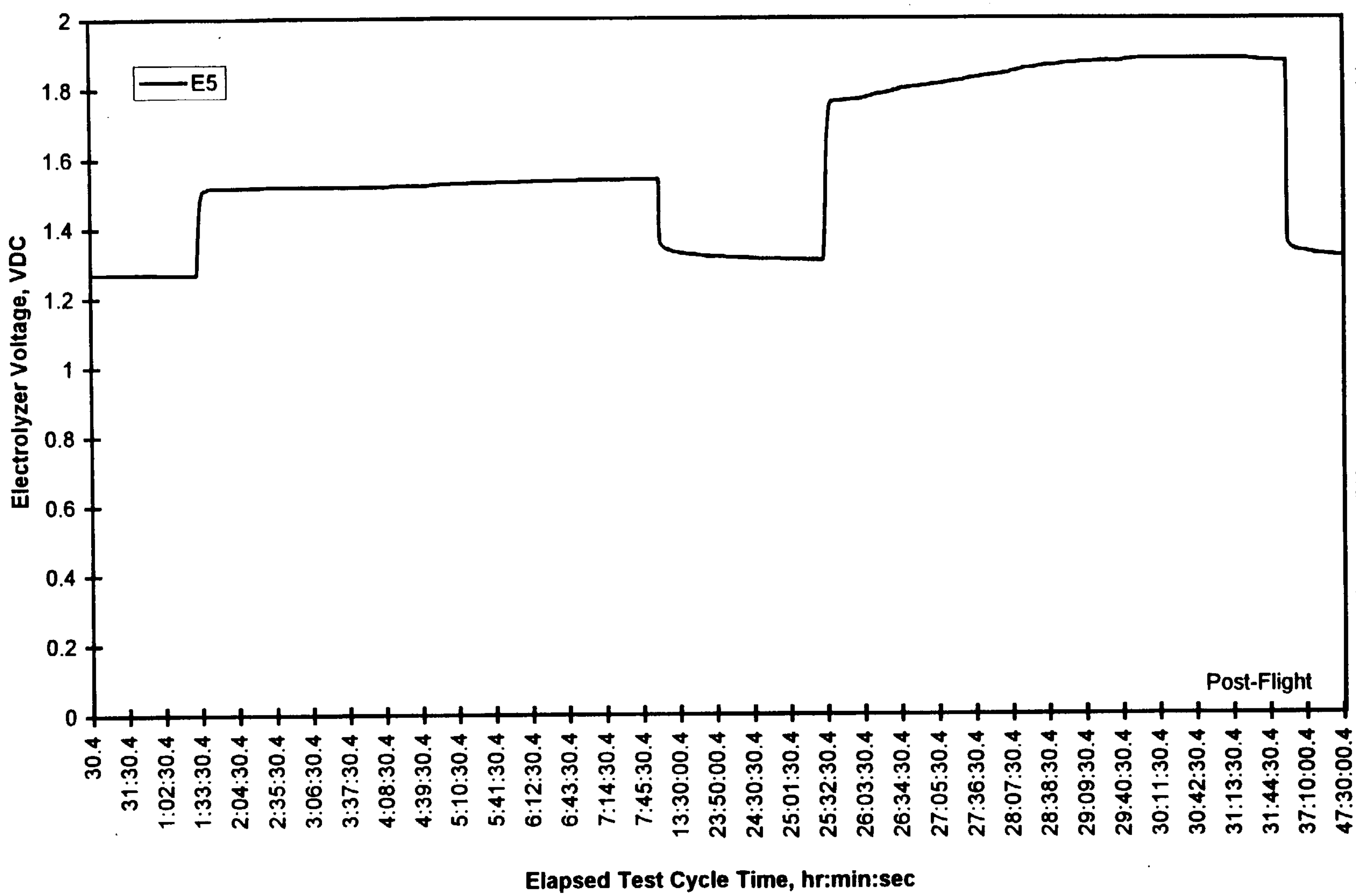


FIGURE 40 ELECTROLYZER VOLTAGE VS. TIME, IEU3
(DATA 10 DAYS AFTER THREE CYCLE RUN, 06/26/97)

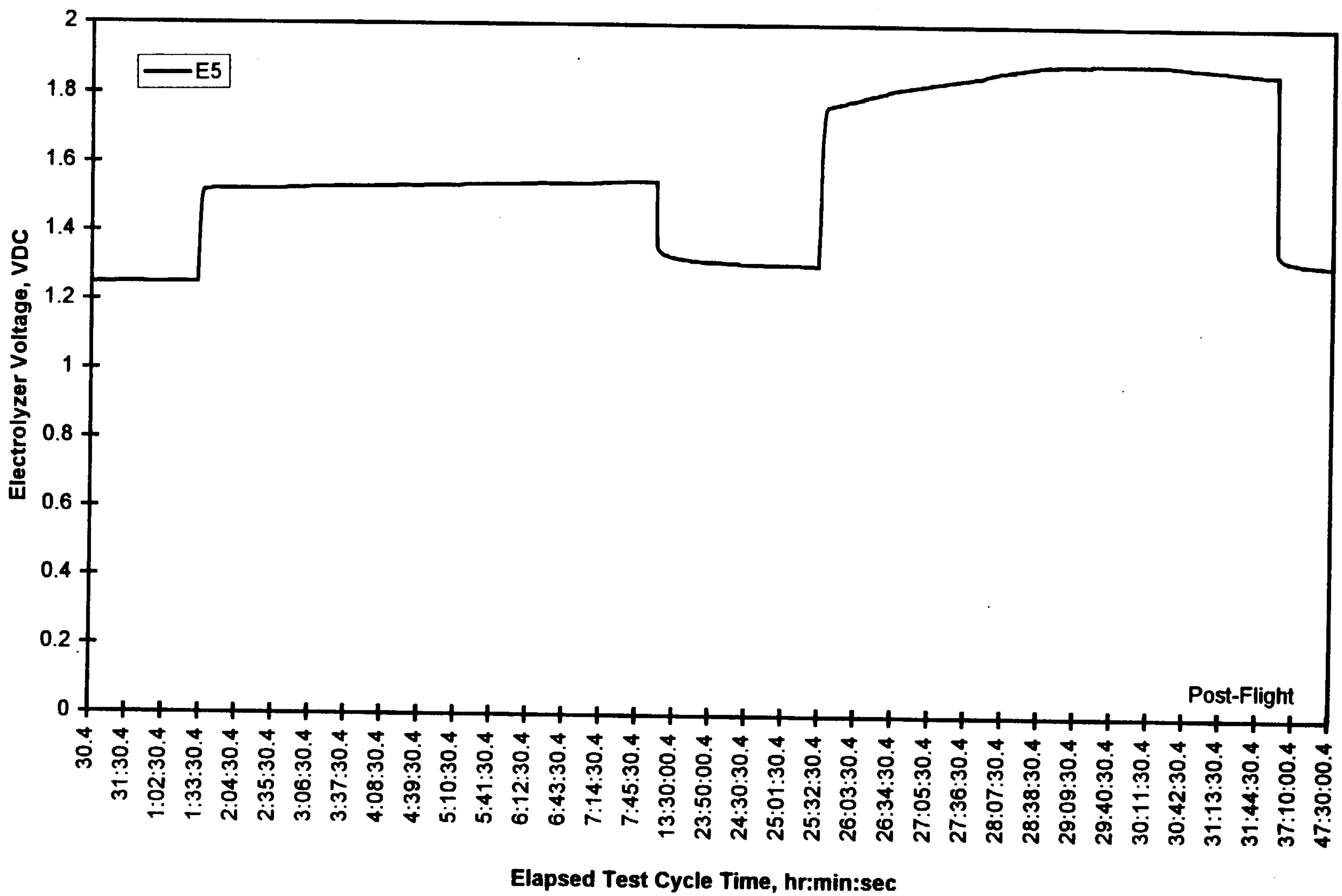


FIGURE 41 ELECTROLYZER VOLTAGE VS. TIME, IEU3
(DATA 28 DAYS AFTER THREE CYCLE RUN, 07/14/97)

consecutive three cycle post flight test, showed cell voltage improvements, with the level of the last run being equal to that observed in the pre-acceptance and acceptance tests of IEU 3. This observation rules out electrode degradation, increased contact resistance or any other physical changes. The most likely cause suspected is that of lower water vapor transport or lack of sufficient water feed as a function of time. End-of-cycle voltages from STS-69 pre-acceptance through STS-84 post-flight evaluation are shown in Table 9 for support.

It is postulated that the diffusion resistance from the recombiner to the electrolysis cell is greater than was anticipated and that for multiple successive runs over a short time, steady state conditions are not reached. Only after longer term storage will electrolyte concentrations equilibrate between the electrolysis and the recombiner cell cores. Confirmation of this again could be determined from subsequent testing, not part of the current effort.

Such a voltage rise phenomenon observed with IEU 3 of the EPICS over successive runs would not exist in a regulator electrolyzer where the water vapor source is constant compared to that from an aqueous solution of another electrochemical cell. Future experiments should explore providing a consistent water vapor pressure source to the EPICS electrolyzers to verify this phenomenon.

IEU 1 Analysis and Findings. Troubleshooting of the heater circuitry for IEU No. 1 showed that a fuse protecting the heater circuit was blown. The actual fuse in the circuit was a 1 A fuse, although design calculations and drawings indicated a 2.5 A fuse was required. Although the fuse had successfully operated for over 100 hours, including operation aboard STS-69, its 100% loading eventually caused degradation and failure. Subsequent operation following replacement of the fuse showed normal behavior of IEU 1.

IEU 2 Analysis and Findings. The most unusual behavior is observed for IEU 2 operation, similar to that corrected for IEU 3 during August 1996 operation. Essentially, all physical causes such as inward to outward leaks, incorrect accumulator readings, faulty electronic circuits, etc. have been ruled out by physical measurements and troubleshooting. The current conclusion reached is that during operation a small amount of O_2 is either not generated at the proper rate or is consumed at a rate greater than that required by the recombiner cell. During all tests, where O_2 accumulator decay was observed, H_2 accumulator positions remained consistent indicating that H_2 was generated and consumed equivalent to the currents assumed to flow through the active electrolyzer and recombiner cell cores.

Quantification of the "disappearing O_2" shows that approximately 40.9 cm^3 were "lost" during the 5.33 hour time period for IEU 2 on-orbit operation, which is equivalent to an electrochemical current of O_2 consumption of 0.056 A or, for an open circuit system, an O_2 production efficiency of 97.2% at 2 A and 99.2% at 7 A. Possible causes include:
1) formation of a by-product, such as corrosion, 2) changes in electrolyte composition due to leaching of O_2- combinable species from structural materials, and 3) other possible side reactions not yet identified.

TABLE 9 ELECTROLYZER END-OF-CYCLE VOLTAGE SUMMARY

TEST		ELECTROLYZER VOLTAGE, END-OF-CYCLE, VDL					
		2A			7A		
DESCRIPTION	START DATE	1	2	3	1	2	3
Pre-Acceptance	04/27/95	1.534	1.530	1.530	1.840	1.801	1.832
Acceptance	05/04/95	1.530	1.523	1.522	1.817	1.787	1.854
Flight (STS-69)	09/95	--	1.528	1.523	--	--	--
Post-Flight	10/05/95	--	1.542	1.534	--	1.833	1.815
Initial RF[a] Pre-Accept	08/26/96	1.541	1.514	1.506	1.874	1.755	1.823
Post Evac of IEU3	09/11/96	1.530	1.521	1.508	--	--	--
Post Evac All Items	10/15/96	1.544	1.530	1.520	1.871	1.808	1.795
RF Pre-Acceptance	03/13/97	1.563	1.514	1.541	1.898	1.742	1.885
RF Acceptance	03/20/97	1.565	1.512	1.549	1.903	1.731	1.891
Flight STS-84[b]	05/15/97	--	--	1.528	--	--	1.863
		--	--	1.541	--	--	1.891
		--	--	1.542	--	--	1.914
Post Flight	06/16/97	--	--	1.540	--	--	1.940
		--	--	1.570	--	--	1.980
		--	--	1.570	--	--	2.060
Post Fuse Replace	06/26/97	1.568	--	1.541	1.934	--	1.877
Post Final EVAC	07/14/97	1.563	--	1.548	1.929	--	1.867

(a) RF = Reflight
(b) For Successive Cycles

It is recommended that an analysis and test program be defined and initiated to identify the causes and solutions of "Disappearing O_2." Such an activity is beyond the scope of the current program.

CONCLUSIONS

Based on the work performed and reported herein the following conclusions have been reached:

1. The electrolysis cell concept of the SFE technology can successfully generate hydrogen and oxygen in a microgravity environment.

2. Thermal control and heat up times for electrochemical cells are easier and shorter to achieve in a microgravity environment.

3. No impacts on the Static Feed Electrolyzer design concepts were identified for microgravity application.

4. Direct water vapor feed from a fuel-cell type H_2 and 0_2 recombination cell to the electrolyzer does not present a steady source of water vapor pressure and can affect electrolyzer performance.

5. Relative performance comparisons of an electrolyzer being fed water by a recombiner cell are possible for equal operating condition, provided there is sufficient non-operating time between operating sequences for water vapor pressure equalization. Recovery after ten days of non-operation was demonstrated, but shorter times may be possible.

6. For equal conditions (except gravity) electrolyzer performance in microgravity is, as a minimum, equal to that for ground operations.

7. The "Loss" of O_2 first experienced with IEU 3, but corrected by evacuation and then experienced by IEU 2, which was not correctable by evacuation, is not fully understood at this time.

RECOMMENDATIONS

Based on the work performed and reported herein the following recommendations are made:

1. Initiate a program to define and implement the activities necessary to identify the cause(s) of apparent oxygen loss as observed with the EPICS.

2. Initiate a program to implement the findings of the recommendation of No. 1 above and refly the EPICS as a Shuttle Orbiter middeck flight experiment.

3. Define the activities necessary to expand the EPICS to a potential Regenerative Fuel Cell test bed for flight experimentation.

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. Lee, M. G. and Schubert, F. H.; "Electrolysis Performance Improvement Concept Study (EPICS) Flight Experiment Phase C/D," Final Report, Contract NAS9-18568, Life Systems, Inc., Cleveland, OH; November, 1995.

6. Powell, F. T.; Schubert, F. H.; Lee, M. G., "Electrolysis Performance Improvement Concept Studies (EPICS)," Preliminary Conceptual Design Report, Contract No. NAS9-17966, Life Systems, Inc., Cleveland, OH; May, 1989.