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ELECTROLYSIS PERFORMANCE IMPROVEMENT CONCEPT STUDY (EPICS) FLIGHT EXPERIMENT PHASE C/D

FINAL REPORT

by

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by

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Cleveland, OH 44122

for the

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

FOREWORD

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

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CCDS	Command, Control and Display Subsystem
CDR	Critical Design Review
C/M I	Control/Monitor Instrumentation
CMC	Computer Monitor Circuit
DRD	Data Requirements Description
DRL	Data Requirements List
DTS	Diagnostic Test Software
ECLSS	Environmental Control and Life Support System
EMCC	Eight-Man Capacity Configuration
EPICS	Electrolysis Performance Improvement Concept Study
EPROM	Erasable Programmable Read Only Memory
EVA	Extravehicular Activity
FCA	Fluids Control Assembly
GSE	Ground Support Equipment
ICD	Interface Control Document
IEU	Integrated Electrolysis Unit
ISSA	International Space Station Alpha
JSC	Johnson Space Center
KSC	Kennedy Space Center
LED	Light Emitting Diode
M/EA	Mechanical/Electrochemical Assembly
MET	Mission Elapsed Time
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
OAET	Office of Aeronautics, Exploration and Technology
OGA	Oxygen Generation Assembly
ORU	Orbital Replaceable Unit
PCA	Pressure Control Assembly
PDR	Preliminary Design Review
PDU	performance display unit
PIP	Payload Integration Plan
PRD	Program Requirements Document
PSR	Pre-Ship Review
RTD	Resistance Thermal Detector
SDSU	Sensor Dedicated Shutdown Unit
SFE	Static Feed Electrolyzer
SFWEM	Static Feed Water Electrolysis Module
TCA	Thermal Control Assembly
TCP	Thermal Control Plate
TSA	Test Support Accessories
WVE	Water Vapor Electrolysis

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 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 the 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 extends to two consecutive days of testing for approximately eight hours of testing each day. The test plan basically consists of two current variations, 2 and 7 A (equivalent to 37 and 129 A/ft^2), over the two-day period. The experiment was conducted on STS-69 Endeavor. Since the Electrolysis Performance Improvement Concept Study flight experiment is fully automated, the only requirement for the crew is the initial actuation of the experiment and deactivation at the end of a two-day experiment. Each repetition of the two-day experiment requires the activation and deactivation by the crew. 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 are needed.

The flight experiment, 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.

Since the causes of the shutdowns have been clearly identified and the upgrading and recertification of the experiment can be completed with minimal efforts, reflight of the Electrolysis Performance Improvement Concept Study Flight Experiment at the earliest possible opportunity is strongly recommended.

INTRODUCTION

The Electrolysis Performance Improvement Concept Study (EPICS) is a flight experiment that demonstrated and validated in a microgravity environment the Static Feed Electrolyzer (SFE) concept which was selected for the use aboard the Space Station Freedom for oxygen (O_2) generation. It also investigated the impact of microgravity on electrochemical cell performance. Electrochemical cells are important to the space program because they provide an efficient means of generating oxygen (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 of these components by generating these gases in space.

The scope of experiment included variations in microstructural characteristics of electrodes and current densities. The analyzed results can be used to identify ways for improving the performance of the Static Feed Electrolysis process and other electrochemical regenerative life support processes. Specific technologies that will benefit include water electrolysis for propulsion, energy storage, life support, extravehicular activity (EVA), in-space manufacturing, and in-space science in addition to electrochemical regenerative life support technologies such as electrochemical carbon dioxide (CO_2) and O_2 separations, electrochemical O_2 compression and water vapor electrolysis (WVE).

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 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 and results of a flight experiment which investigated the effect of low gravity on the performance of an electrochemically-based subsystem which provides these utilities. The experiment focuses on the 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.

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. The static feed concept has evolved over the last 25 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.

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.

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 of Static Feed Electrolyzer

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:

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

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

At the anode:

$$2\ OH^- = \frac{1}{2}\ O_2 + 2e^- + H_2O \tag{2}$$

These result in the overall reaction of:

$$H_2O = H_2 + \frac{1}{2}\ O_2 \tag{3}$$

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 1 is a functional schematic of the 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.

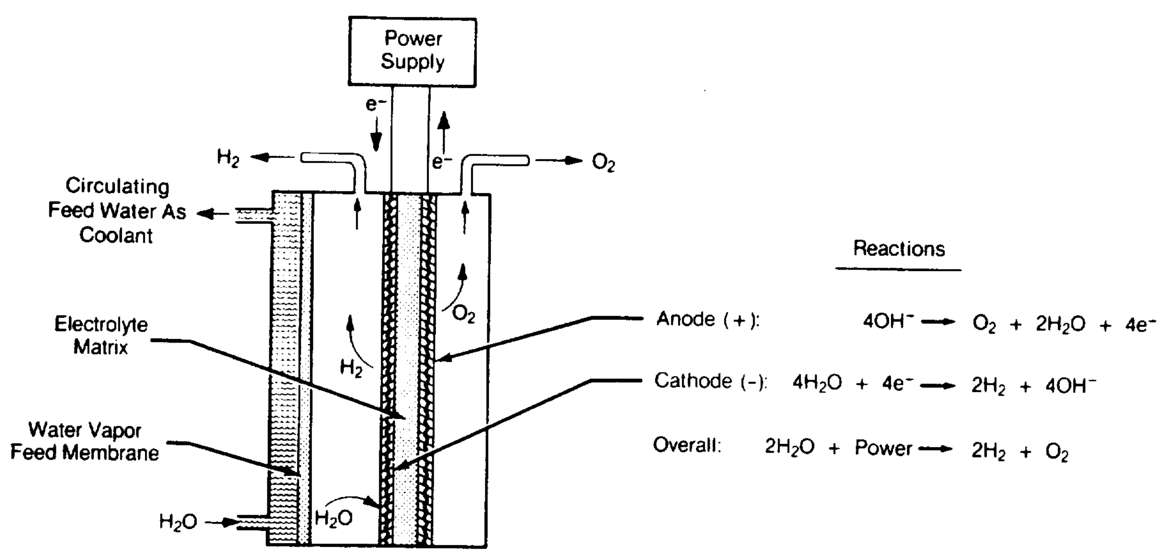


FIGURE 1 ELECTROLYZER CELL SCHEMATIC AND REACTIONS

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 2. 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 Fluids 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.

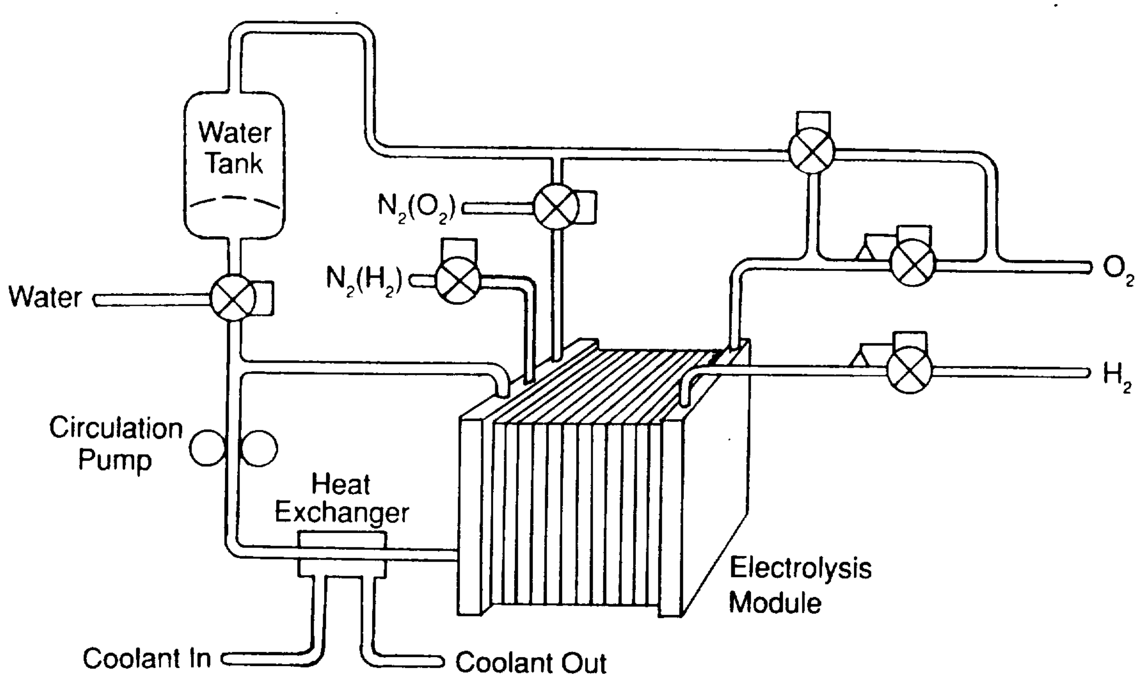


FIGURE 2 SIMPLIFIED SFE PROCESS SCHEMATIC

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 of 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).

Objectives

The overall objectives of the EPICS flight experiment 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, 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. In addition, other electrochemical regenerative life support technologies can also be improved using the flight experiment results.

The specific objectives of the experiment include:

1. Demonstrate and validate the Static Feed Electrolysis concept in microgravity.
2. Investigate the impact on cell performance of varying electrode characteristics, porosity and thickness, in microgravity.
3. Evaluate performance improvement in microgravity at two different current densities.
4. Develop flight experiment hardware which is 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.
7. Develop flight experiment hardware which requires minimal National Space Transportation System (NSTS) integration efforts.

8. Bring attention to the potentiality that low-gravity may have a positive effect on performance of space systems.

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) Environmental Control and Life Support System (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 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

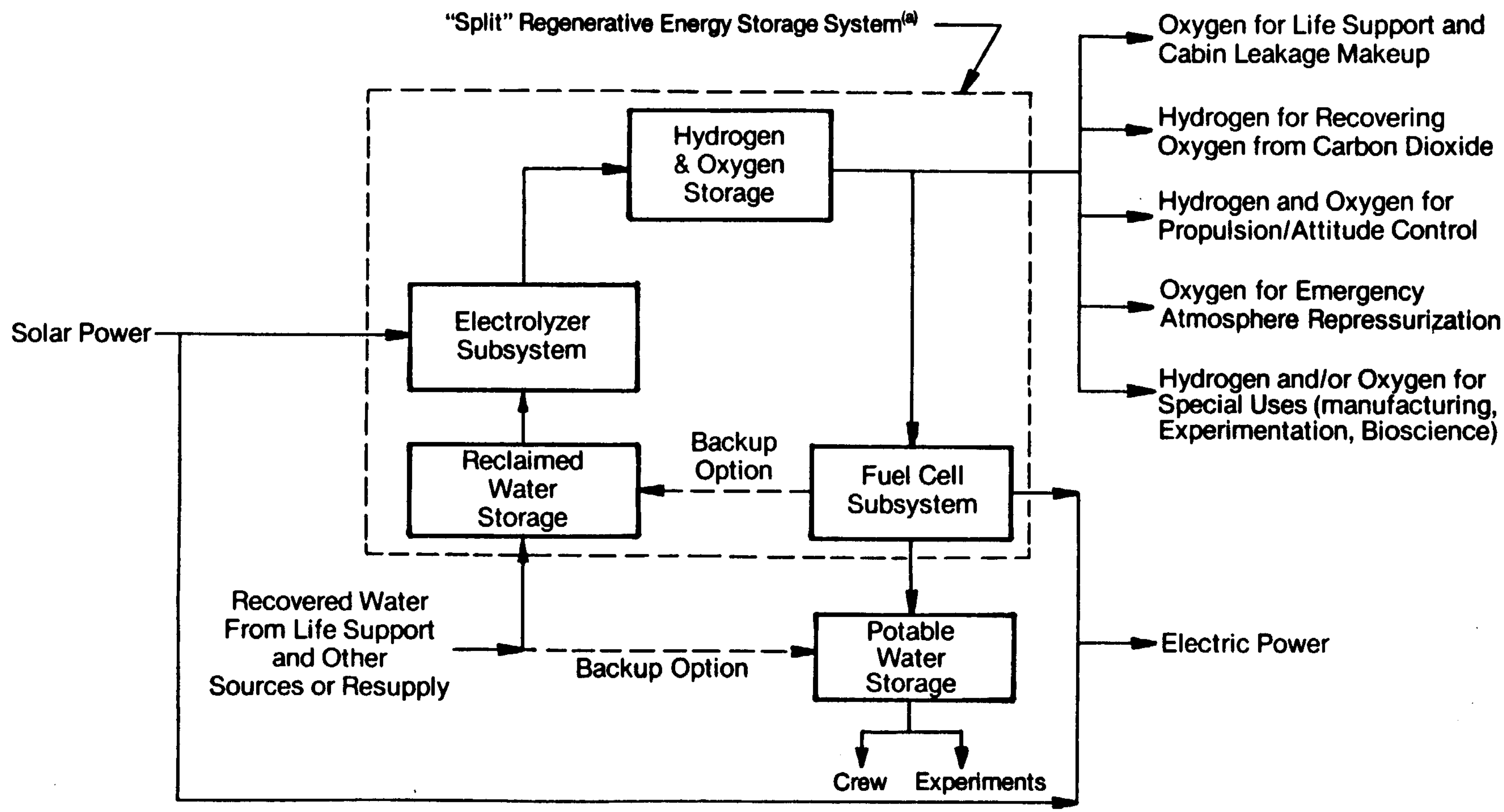
The results of the EPICS flight experiment can be very timely for NASA goals. The EPICS flight experiment results would be obtained in sufficient time for Life Systems to incorporate design improvements into the OGA for the International Space Station Alpha (ISSA) Program. The OGA is being considered to supply O_2 required for the crew of the ISSA. In addition, the EPICS results could be utilized for other applications in the ISSA such as the U.S. Laboratory Module Centrifuge project or in future manned missions to the moon or Mars.

Program Organization

To meet the objectives mentioned above, the program (Phase C/D) was divided into 11 tasks, 10 original and 1 added-on task as listed below:

Design, Fabrication, Testing and Flight (Phase C/D) Tasks

1. Preliminary Design



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

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

2. Payload Integration Plan (PIP), PIP Annexes and Interface Control Document (ICD)

3. Engineering Model Development

4. Final Design

5. Engineering Analysis

6. Fabrication and Assembly

7. Testing, Data Reduction, and Analysis

8. Pre- and Post-Flight Support

9. Program Documentation

10. Program Management and Control

11. Technical Improvement and Additional Tasks Required

For simplicity, the added activities due to the mid-program incorporation of the Program Requirements Document (PRD), JSC-37757, consisting of added technical requirements, added program documentation efforts and added program management, were incorporated into the existing task structure.

End Products

The end products of Phase C/D of this contractual effort are:

1. Drawings. Delivered to NASA Johnson Space Center (JSC) the following sets of drawings.

    a. A reproducible set of preliminary design drawings prior to the Preliminary Design Review (PDR).

    b. A reproducible set of final design drawings prior to the Critical Design Review (CDR).

    c. A reproducible set of as-built drawings prior to the Pre-Ship Review (PSR).

2. Space Shuttle-Related Documentation. Delivered to JSC all documentation required for Space Shuttle safety and integration activities.

3. Project Documentation. Delivered to JSC all required documents, including this Final Report, as listed in the Data Requirements List (DRL).

4. Flight Hardware. Delivered the flight hardware and software and any necessary support equipment to the Kennedy Space Center (KSC) for flight aboard the Space Shuttle STS-69.

5. Flight Data. Delivered to JSC:

   a. A magnetic tape containing all the data gathered during the space flight, reduced to engineering units.

   b. Summary data plots and tables.

Report Organization

The following sections include separate discussions on the EPICS flight experiment hardware, Ground Support Equipment (GSE), test results, followed by conclusions and recommendations.

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.

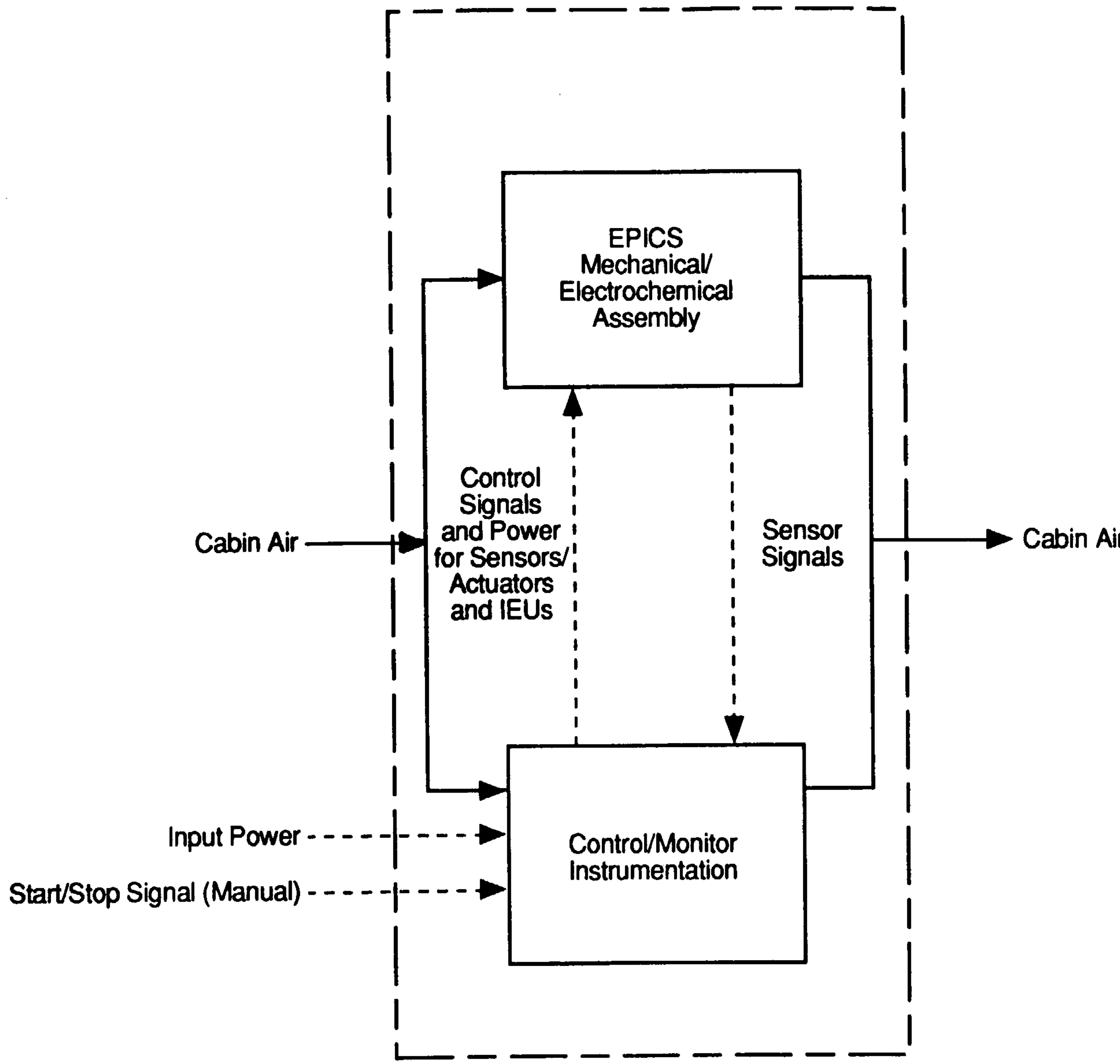

FIGURE 4 EPICS INTERFACE BLOCK DIAGRAM

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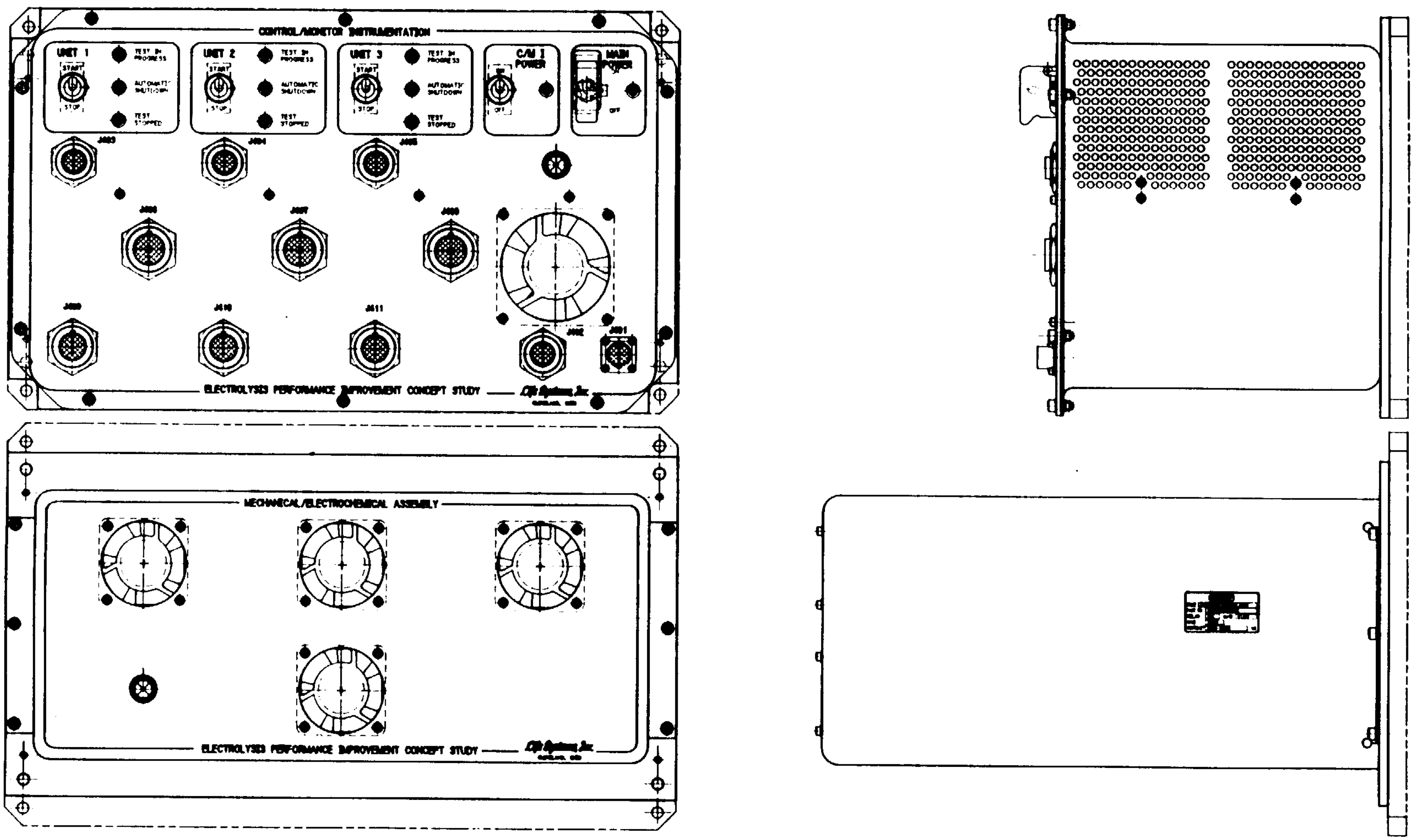

FIGURE 5 EPICS FLIGHT EXPERIMENT HARDWARE PACKAGING

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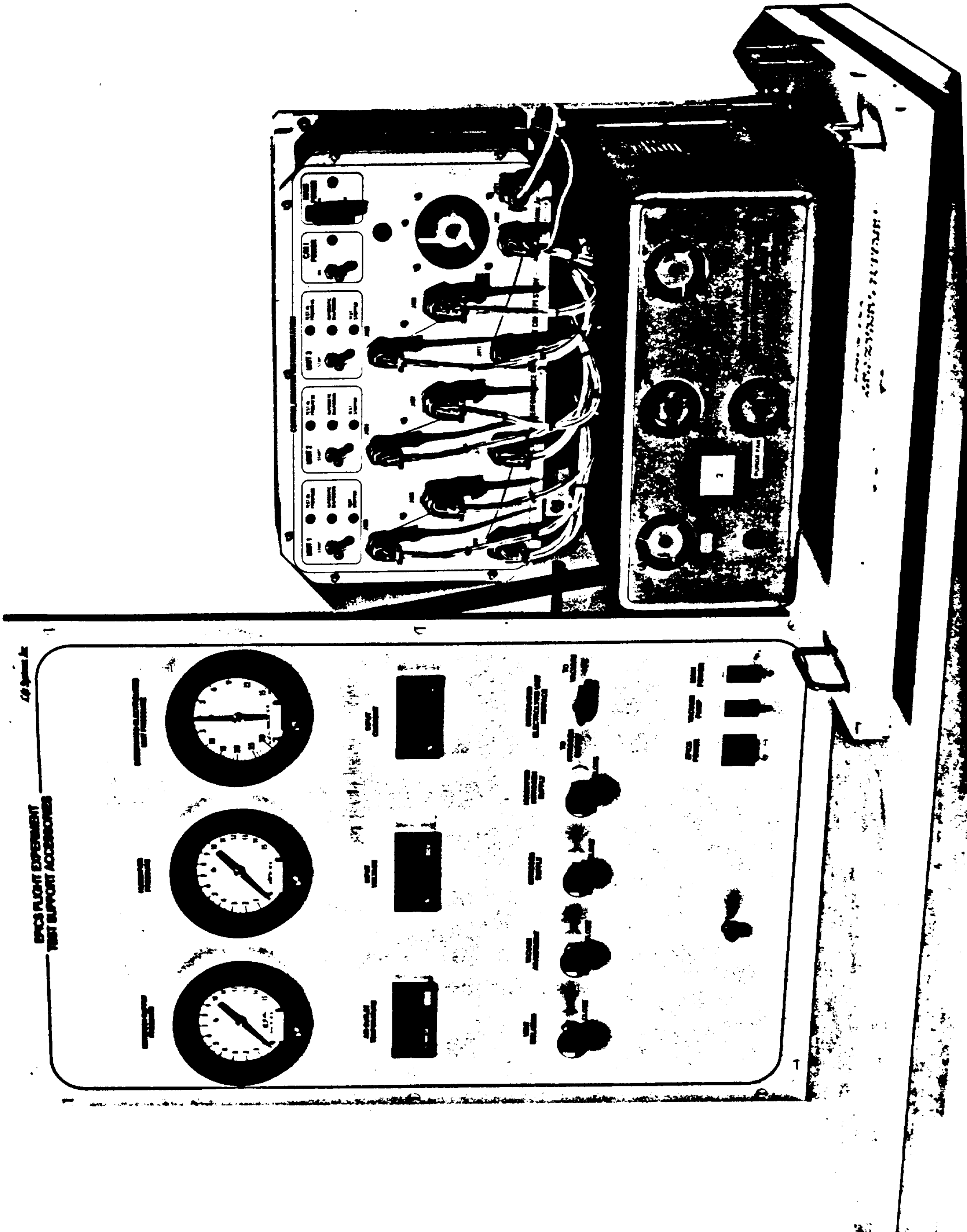


FIGURE 6 EPICS FLIGHT HARDWARE (M/EA AND C/M I) SHOWN WITH TSA

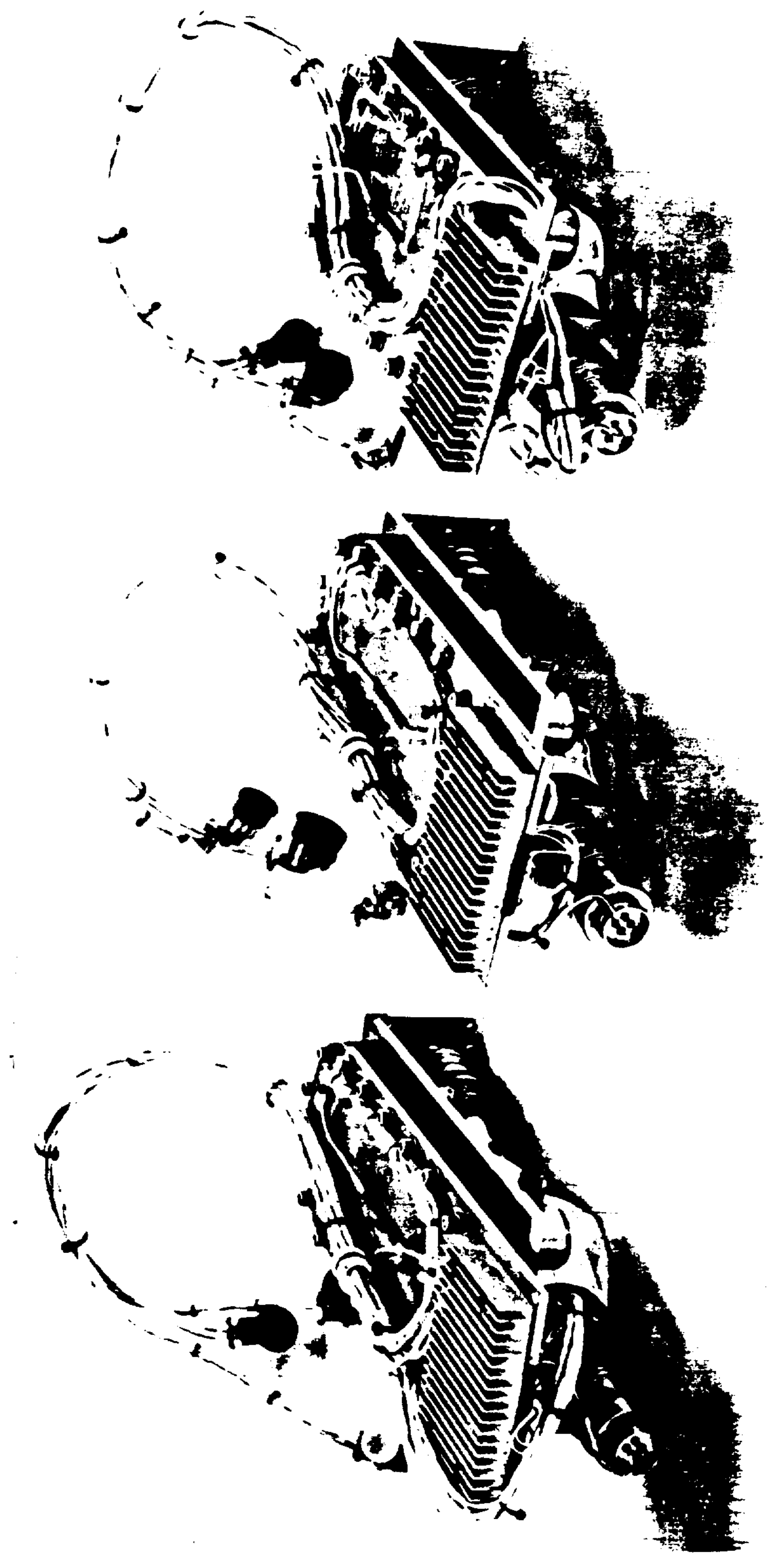


FIGURE 7 THREE INTEGRATED ELECTROLYSIS UNITS FLOWN IN STS-69

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

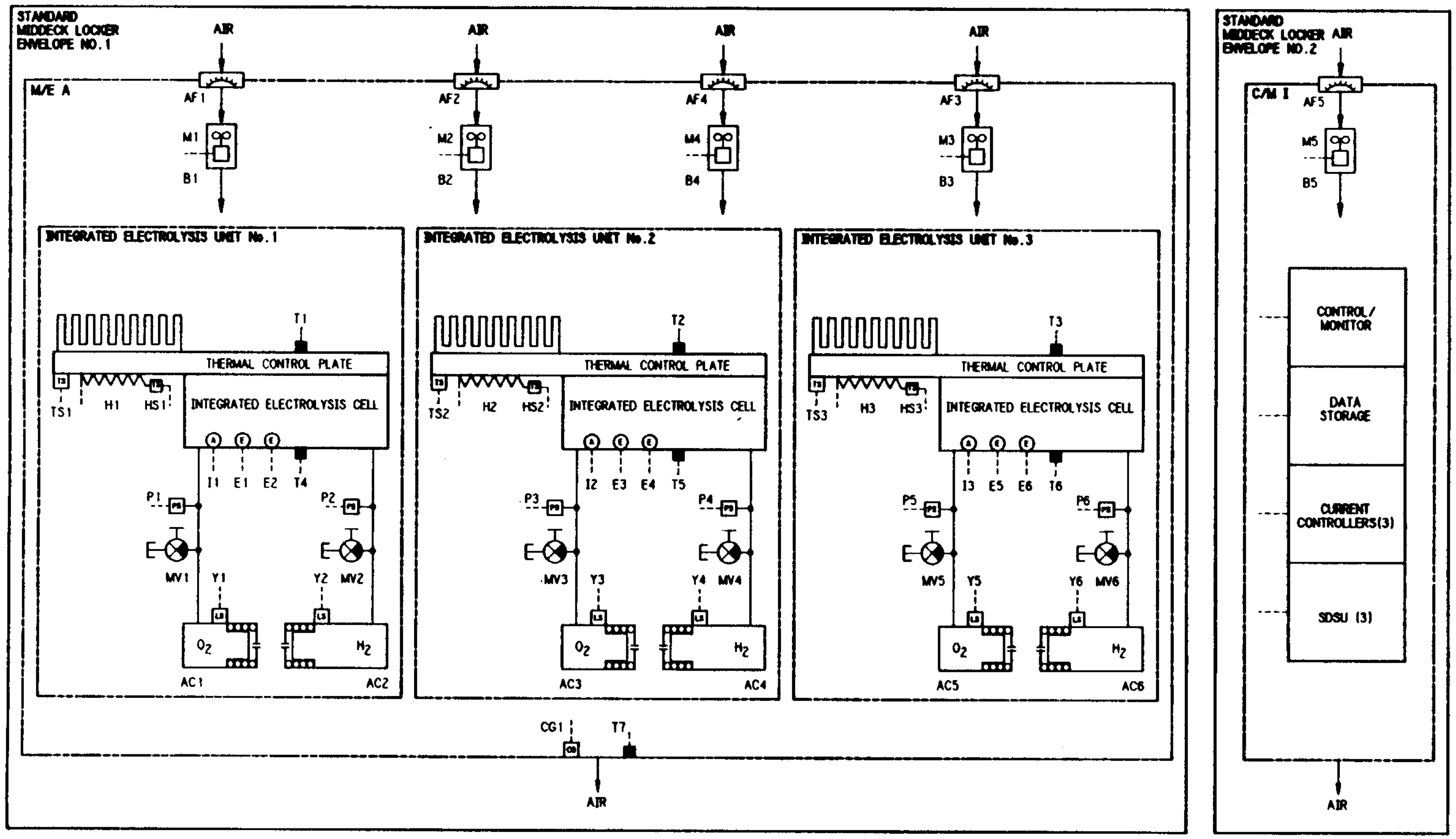
Each of these components is described below.

Integrated Electrolysis Cell. The integrated electrolysis cell consists of an electrolyzer cell core and a recombiner cell core configured together within polysulfone cell housing frames. Both of the cell cores incorporate unitized construction where the electrode-matrix-electrode sandwich is bonded together on the perimeter with a thermoplastic. This provides a surface for sealing and also simplifies assembly. The cell cores are separated by support screens and a hydrophobic separator. The hydrophobic separator simulates the SFE water vapor feed mechanism and prevents the forming of a liquid bridge between the electrolyzer and recombiner electrodes. All fluidic connections between the gas compartments are achieved via internal manifolding within the cell frame. The active area of the electrodes in the integrated electrolysis cell is 1.44 x 5.44 in or 7.82 in^2.

The cell frame includes double redundant seals on the internal seals and triple redundant seals on the external seals. The cell frame also provides sealed external tabs for current connection to the electrochemical cells. Two Resistance Thermal Detector (RTD) temperature sensors are positioned near the external surface of the electrolyzer side of the integrated electrolysis cell. One is used in the thermal control loop and the other the Sensor Dedicated Shutdown Unit (SDSU). The SDSUs are incorporated into the EPICS C/M I to provide backup shutdown protection, i.e., provide for two-failure tolerance protection.

In the experiment, the only difference between each of the IEUs is the microstructural configuration of the electrolyzer cell cores. One IEU will have a baseline SFE configuration while the other two will have minor variations to electrode porosity and matrix thickness.

Thermal Control Plate. The Thermal Control Plate (TCP) is used to maintain the integrated electrolysis cell at the desired operating temperature. The TCP is fabricated out of Inconel 718. Each TCP is equipped with a heater, six heat pipes, two thermostats and cooling fins. The heater is an adhesive-backed thin-film heater. One of the TCP thermostats is mounted



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

FIGURE 8 EPICS M/EA AND C/M I

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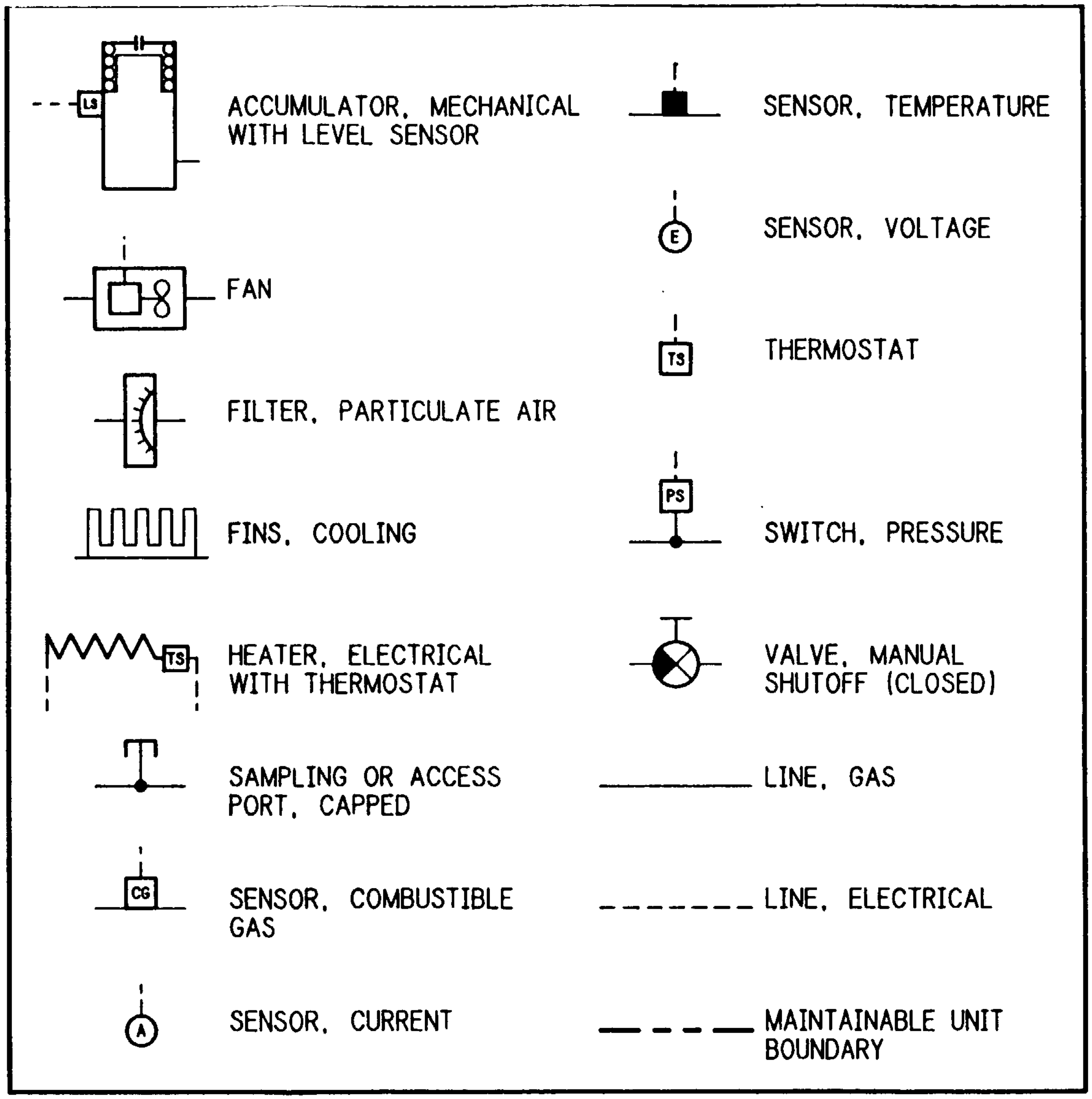

Figure 8 - continued

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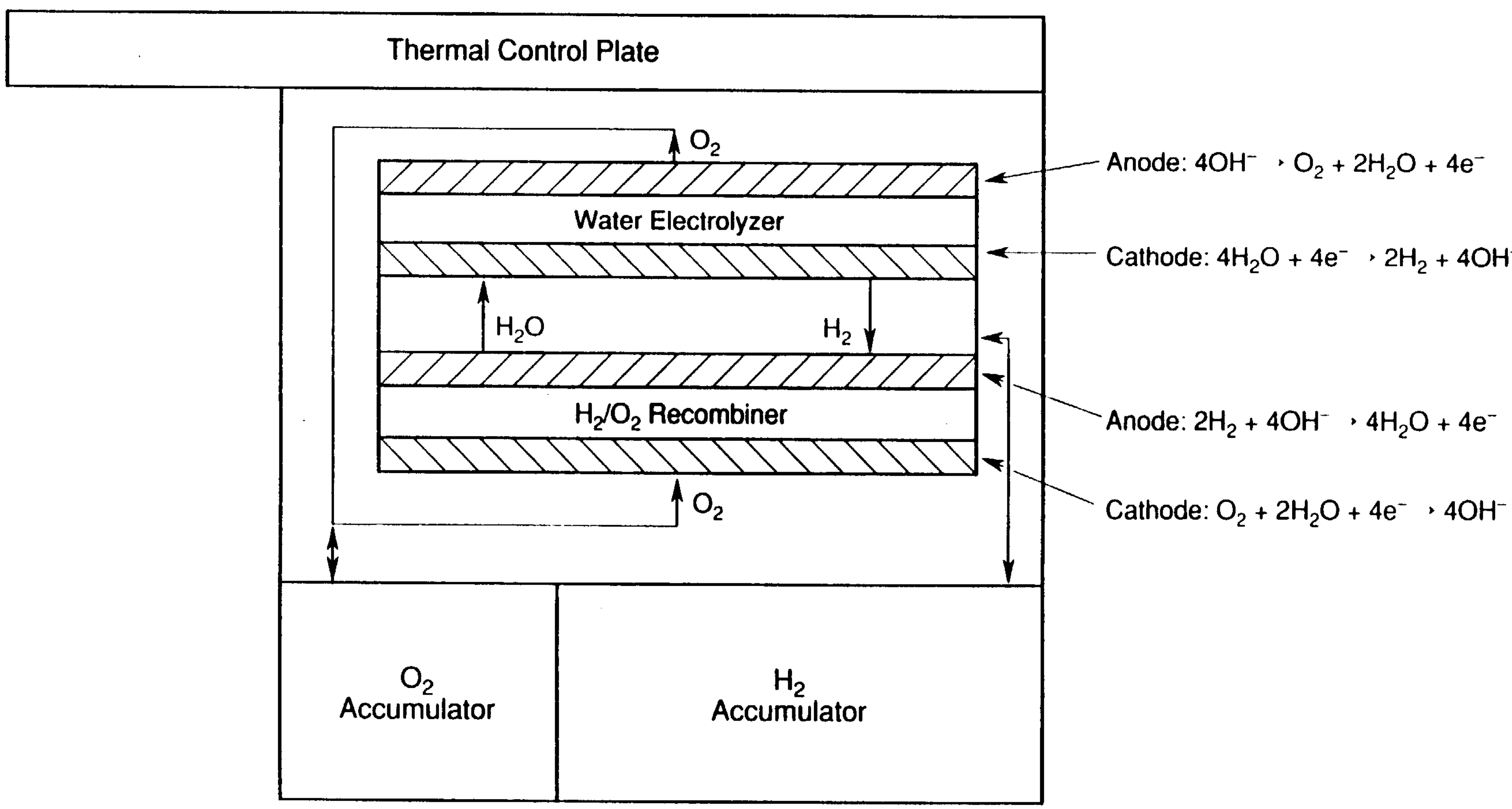

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FIGURE 9 FUNCTIONAL SCHEMATIC OF INTEGRATED ELECTROLYSIS UNIT (IEU) AND ELECTRODE REACTIONS

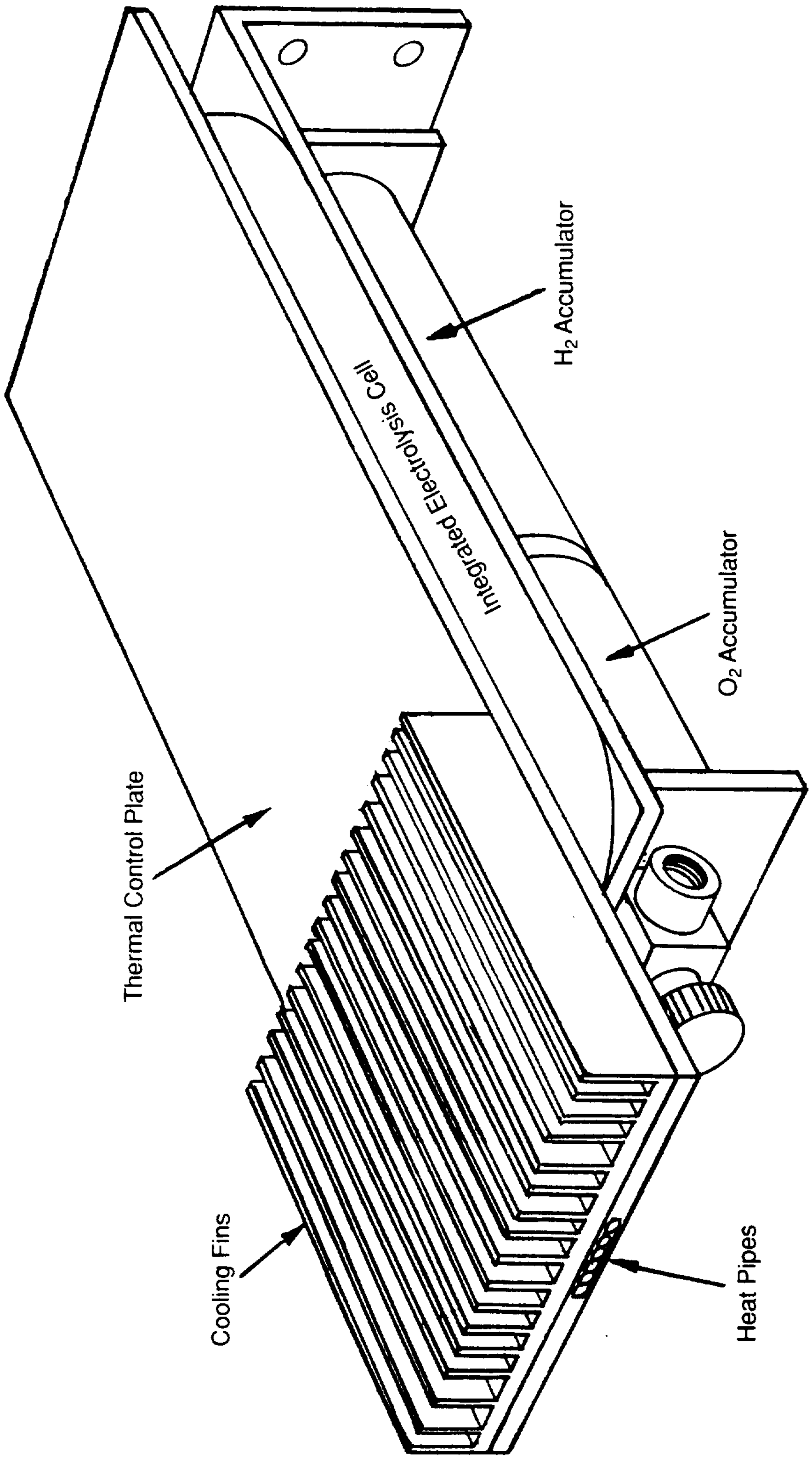

FIGURE 10 INTEGRATED ELECTROLYSIS UNIT

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directly on top of the heater. This thermostat is used for overtemperature protection and will interrupt current to the heater if the setpoint is exceeded. The heater has an active area of approximately 2.74 x 2.94 in or 8.06 in^2. The maximum heater output is 28 W. The heater thermostat setpoint is 160 F.

The other thermostat is located on the TCP near the heater. This thermostat is connected to an SDSU and is used to provide an additional level of protection for IEU overtemperature. The setpoint of this thermostat is 150 F.

The six mini-flat type heat pipes are located in the center region of the TCP. The heat pipes are positioned to transfer heat both into and away from the active area of the integrated electrolysis cell. The heat pipes will be bonded into place with a thermally conductive epoxy adhesive. The heat pipes utilize water as the working fluid.

The cooling fins are located on the TCP on the side opposite the heater. The cooling fins are bonded by thermally conductive epoxy to the TCP. The surface area of the cooling fins of a TCP is approximately 0.68 ft^2.

O_2 and H_2 Accumulators. The O_2 and H_2 accumulators are mechanical metal bellows. The bellows provide a buffer volume for O_2 and H_2 to account for electrochemical inefficiencies within the system. The accumulators provide a positive pressure gradient from internal to external due to the spring constant associated with bellows displacement. Mechanical compression springs were installed externally on the O_2 accumulator bellows to provide higher pressure in the O_2 side than the H_2 side for optimum recombiner performance. The maximum volume displacements for the O_2 and H_2 accumulators are 6.1 in^3 (100 cm^3) and 12.2 in^3 (200 cm^3), respectively. The internal pressure associated with full displacement is approximately 3.2 and 6.1 psig for the H_2 and the O_2 accumulators, respectively.

The accumulators are housed below the integrated electrolysis cell within an external shell. The shell is connected to the TCP with mounting brackets. The external side of the bellows is open to ambient pressure. The internal side of the bellows is fluidically connected to the integrated electrolysis cell through manifolding within the mounting brackets. Both accumulator assemblies are enclosed in a hydrophobic sleeve bonded to the bases of the accumulator housings in order to contain any liquid electrolyte that could be released from the electrode core in case of potential failure.

A manual valve is attached to each mounting bracket and connected fluidically to each accumulator. This valve is used only used during ground operations for pressure testing or system purging. During flight this valve stays closed and the outlet is capped.

A pressure switch is also attached to each mounting bracket and connected fluidically to each accumulator. The pressure switch is used to provide overpressure protection. The pressure switch setpoint is 20.2 ± 0.5 psia. If the internal IEU pressure exceeds the setpoint, then the pressure switch will remove power to the IEU through the SDSU.

The accumulators have a position indicating sensor. This device outputs a signal to the C/M I proportional to the accumulator displacement. This signal will be monitored by the C/M I to ensure that each of the accumulators are in the normal operating range and during electrolysis-only operation, the rate of change of position of the bellows is within an acceptable range.

Ancillary Components

The M/E A ancillary 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. Each fan has an inlet air filter. The inlet air filter is a 70 mesh stainless steel screen that will keep middeck airborne debris out of the fan.

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 an 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

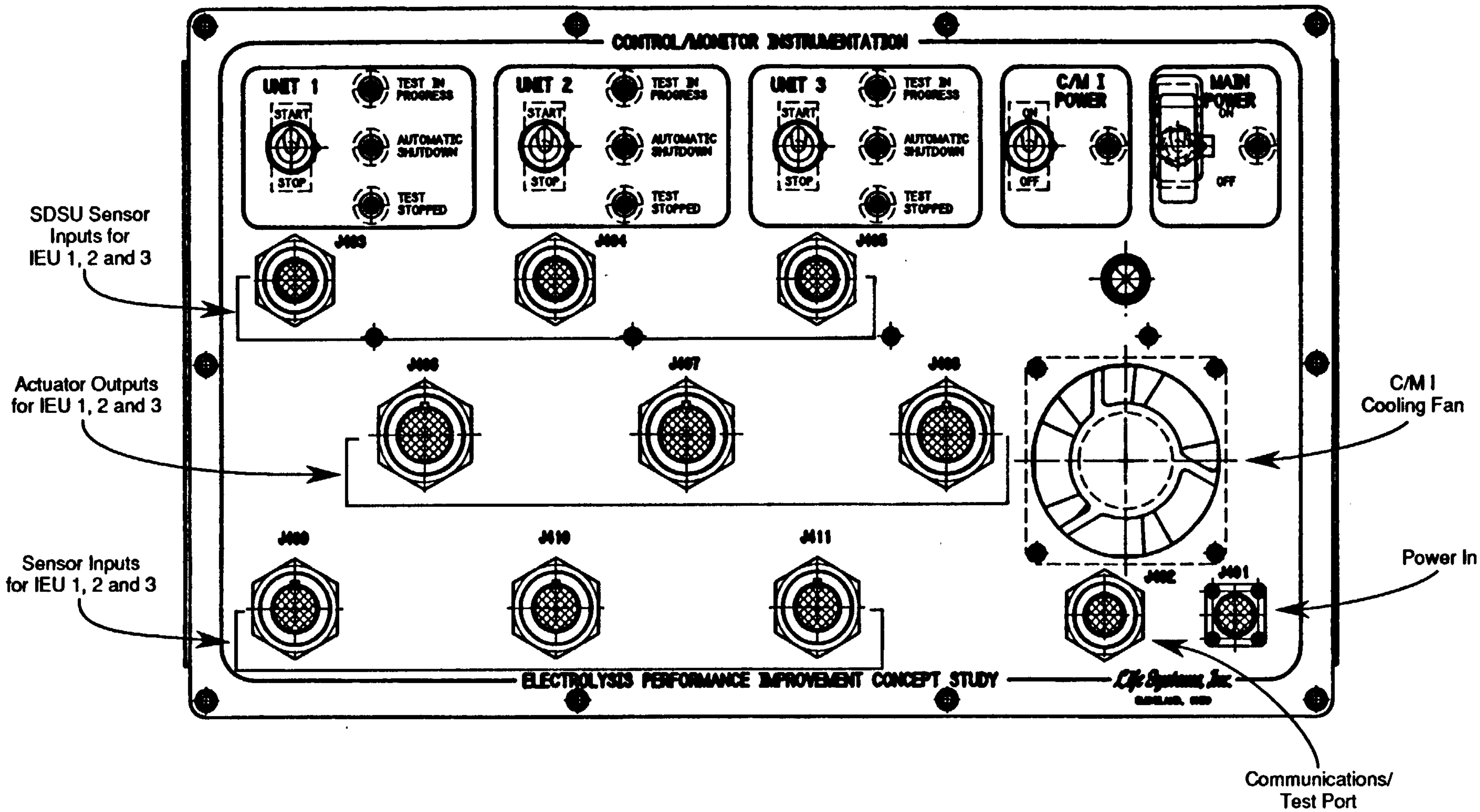

FIGURE 11 EPICS C/M I LAYOUT

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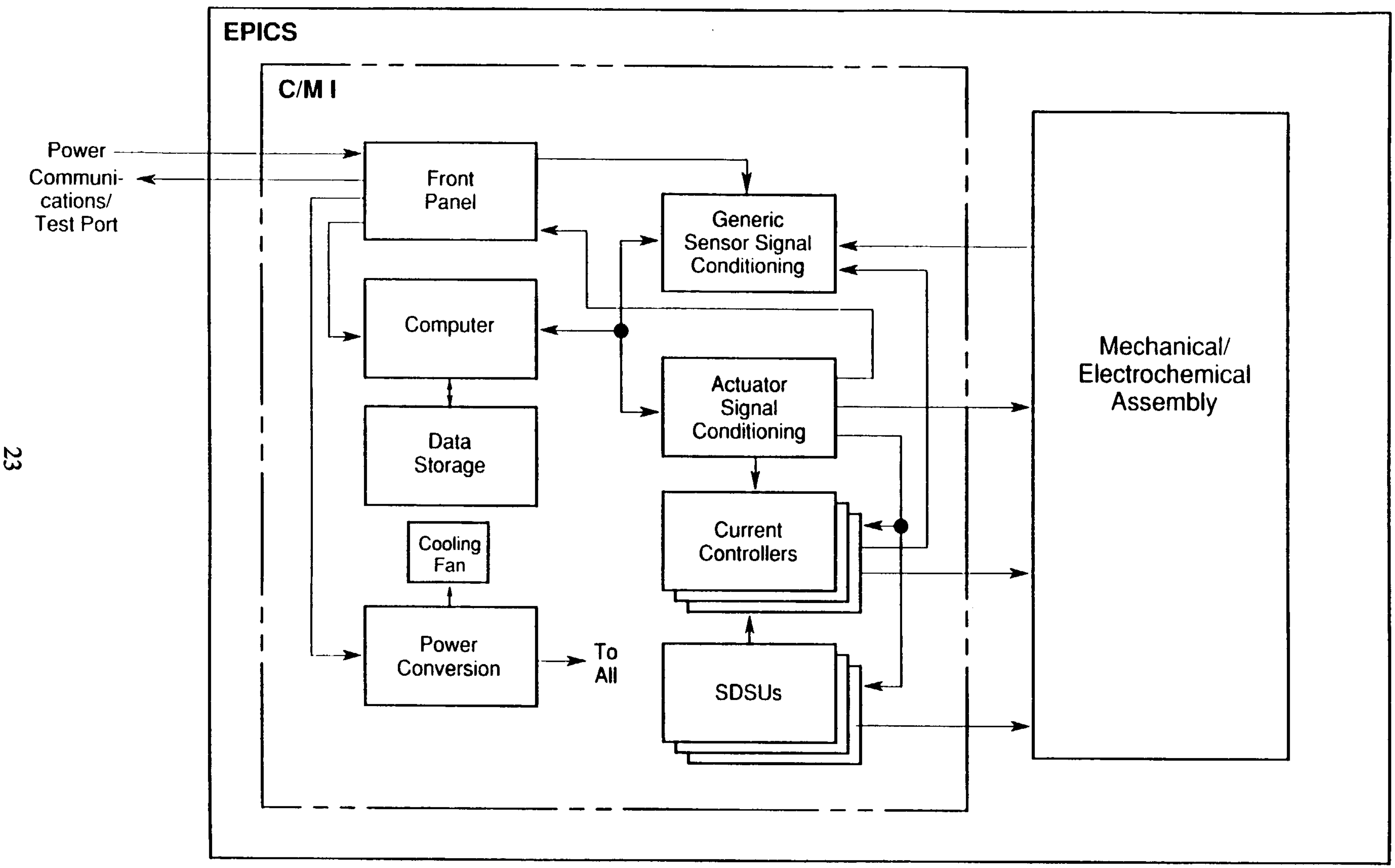

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FIGURE 12 EPICS ELECTRICAL BLOCK DIAGRAM

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- Current Controllers
- SDSUs
- Front Panel

Each of these functional blocks is described below.

Computer. The EPICS Computer characteristics are shown in Table 1 and a block diagram of the Computer is shown in Figure 13. The Computer is responsible for processing information and executing commands to ensure that the EPICS flight experiment operates as programmed.

TABLE 1 EPICS COMPUTER CHARACTERISTICS

Microprocessor	Intel 80C186
Processing Speed, MIPS	0.7
Processor Clock Rate, Mhz	10
Word Size, bits	16
RAM Memory, kbytes	64
ROM Memory, kbytes	128
Communications	RS-232
Watch Dog Timer	Yes

The Computer contains two devices capable of detecting failures of the Computer. The first device is an on-card computer watchdog timer. This device continuously monitors a toggling signal from the Computer. If the Computer should lockup, the computer watchdog timer will time out after 500 msec and initiate a reset of the Computer. The second device is the Computer Monitor Circuit (CMC). This device operates similarly to the computer watchdog with the exception that the timeout period is longer (1 sec) and the action taken is different. If the CMC times out, it will send a signal to the Power Conversion Subassembly to remove power to the C/M I. This will stop the experiment. The experiment can only be restarted after a manual reset is performed.

Power Conversion. The Power Conversion Subassembly is responsible for converting orbiter power into a useable format for the other electronic devices. A block diagram of the Power Conversion Subassembly is shown in Figure 14.

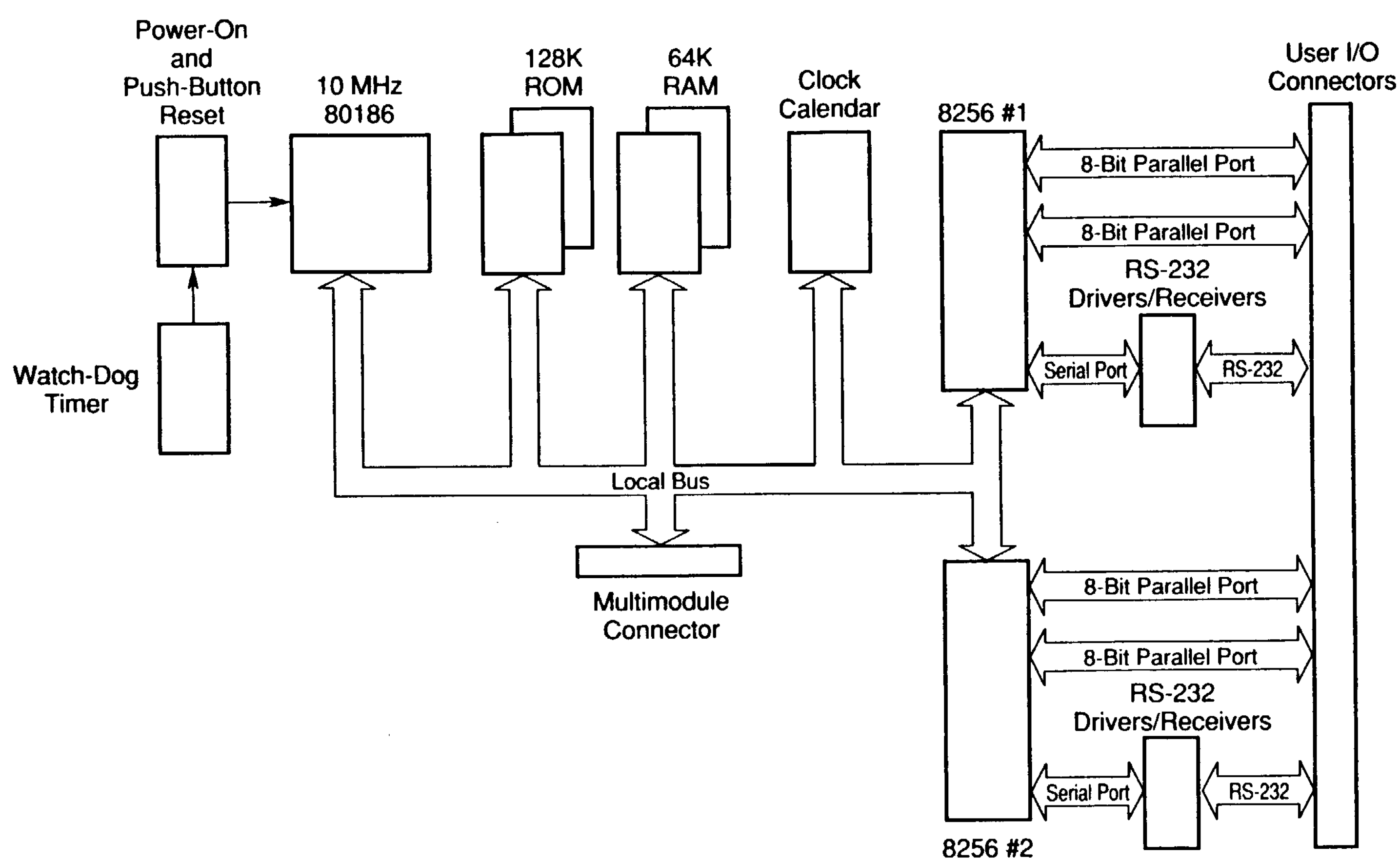

FIGURE 13 COMPUTER CARD

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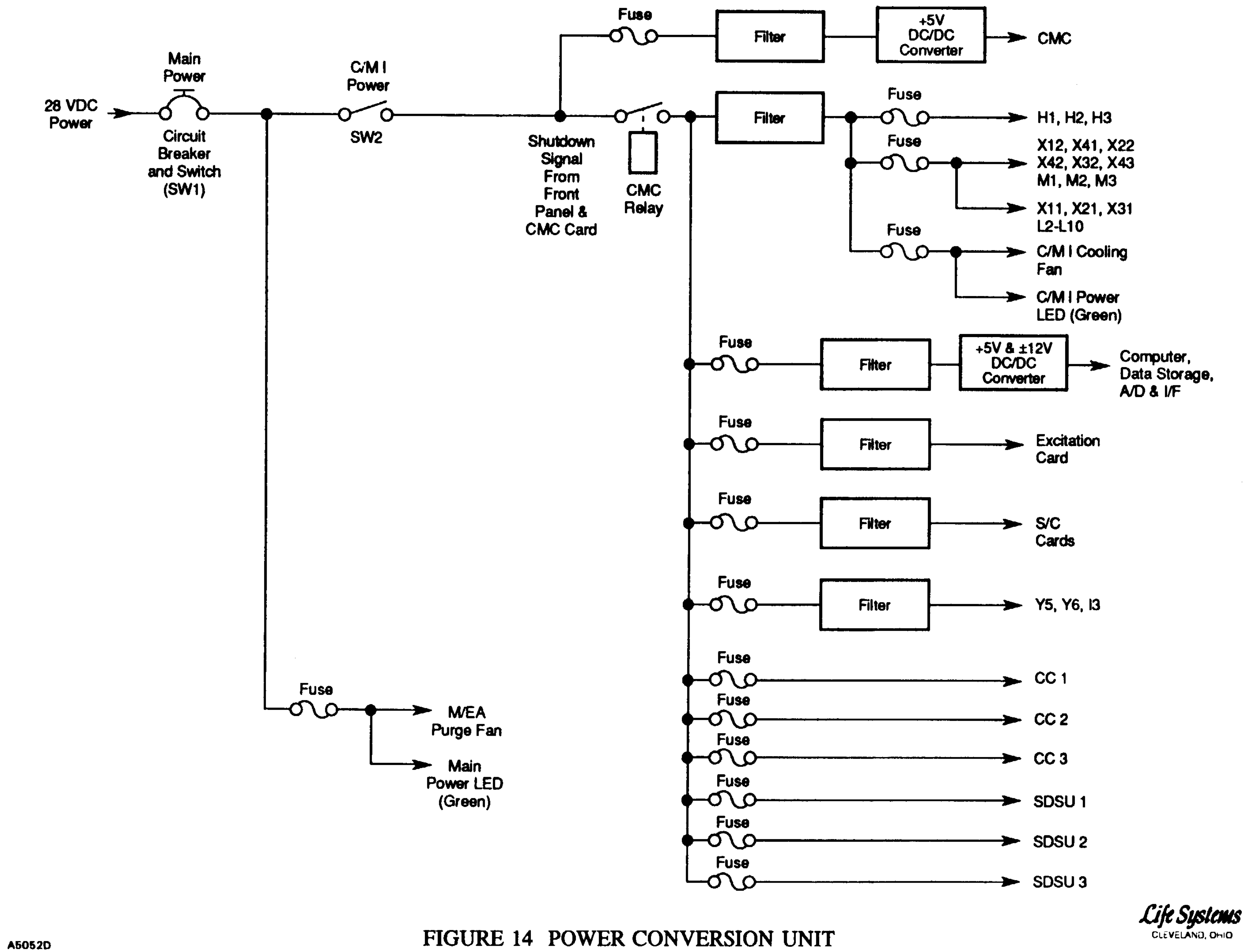


FIGURE 14 POWER CONVERSION UNIT

Data Storage. The C/M I Data Storage Subassembly is responsible for storing the EPICS experimental data. This device uses a nonvolatile flash memory cartridge with a capacity of 1 MB. Data is stored every 30 seconds during key experimental periods.

Generic Sensor Signal Conditioning. The C/M I Generic Sensor Signal Conditioning Subassembly is responsible for processing sensor signals from the M/E A. A schematic representation of the Generic Sensor Signal Conditioning Subassembly is shown in Figure 15. The sensor ranges and accuracies are shown in Table 2.

Actuator Signal Conditioning. The EPICS Actuator Signal Conditioning electronics processes the logic signals from the Computer to drive the actuators (i.e., heaters, fans and current controllers). The Actuator Signal Conditioning is shown in Figure 16. As indicated in this Figure, the Actuator Signal Conditioning includes an Actuator Watchdog Timer. This device continuously monitors a toggling signal from the Computer. If the Computer locks up, the Actuator Watchdog Timer will timeout after 500 msec and safe state (i.e., unpower) all actuators.

Current Controllers. The EPICS experiment contains three independent Current Controllers (i.e., one for each IEU). The Current Controllers are responsible for providing a controlled current to the integrated electrolysis cell in either a electrolysis-only or a dual electrolysis-recombination mode. A Current Controller is shown in Figure 17.

Sensor Dedicated Shutdown Unit. The C/M I includes three independent SDSUs (i.e., one SDSU for each IEU). These devices are independent circuit controls that will terminate power to the IEU heater and the Current Controller if a fault condition is detected on its dedicated sensors. A schematic representation of an SDSU is shown in Figure 18. As indicated in this figure, for each SDSU and IEU pair, the power to the IEU heater and Current Controller must travel through two relays connected in series. Three of the dedicated sensors are on/off devices (i.e., pressure switches and a thermostat). The fourth sensor is a temperature sensor. This sensor has its own signal conditioning and comparator circuit separate from the Generic Sensor Signal Conditioning circuitry.

Front Panel. The EPICS Front Panel is illustrated in Figure 19. This panel provides the ability to manually initiate the experiment and to stop all or part of the experiment if desired. Automatic shutdowns of the IEUs are indicated with a red Light Emitting Diode (LED).

A C/M I cooling fan is mounted on the Front Panel. This fan operates whenever the C/M I is powered. Similar to the other fans, it has an inlet air filter to keep middeck airborne debris out. The air filter is fabricated from a 70-mesh stainless steel screen.

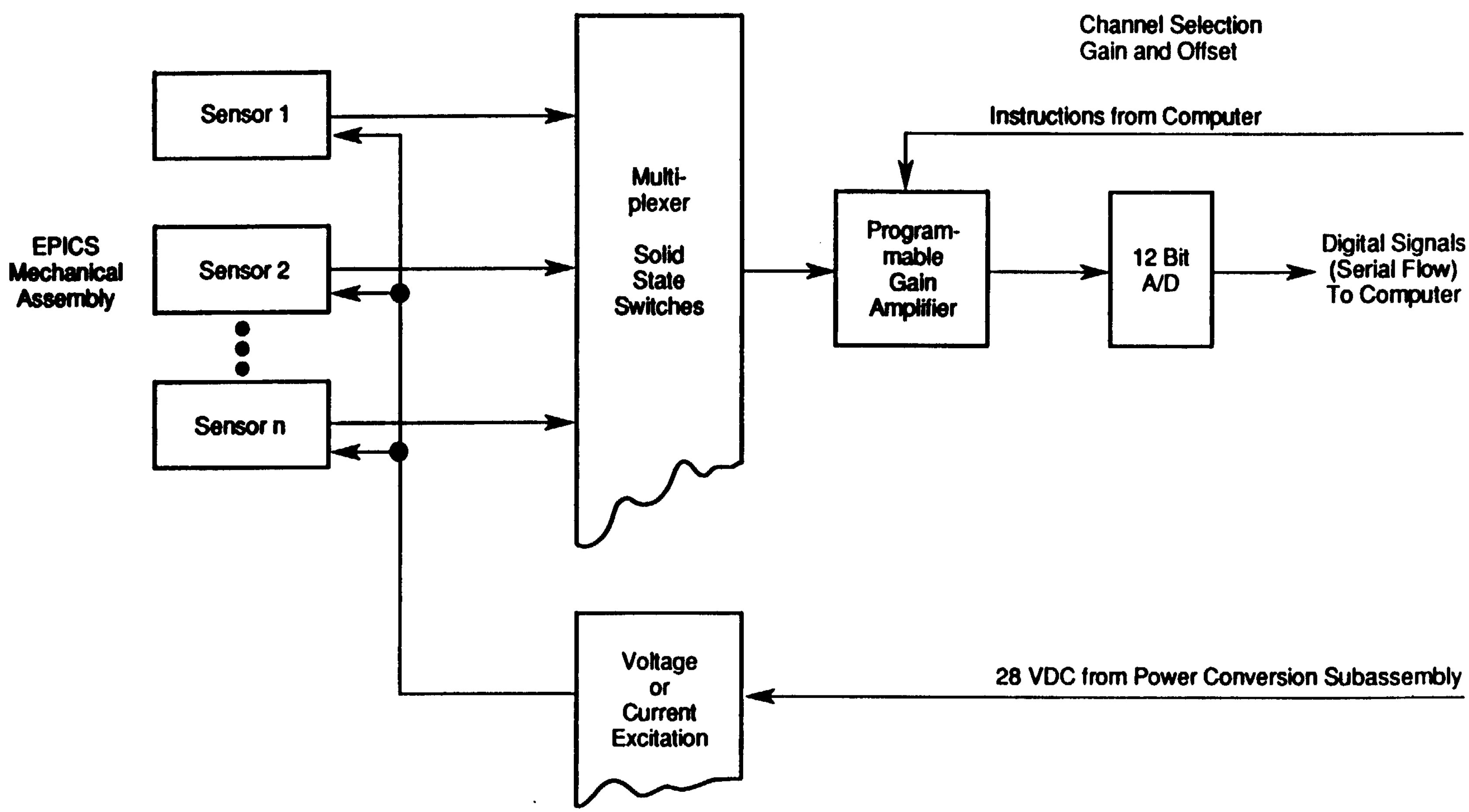
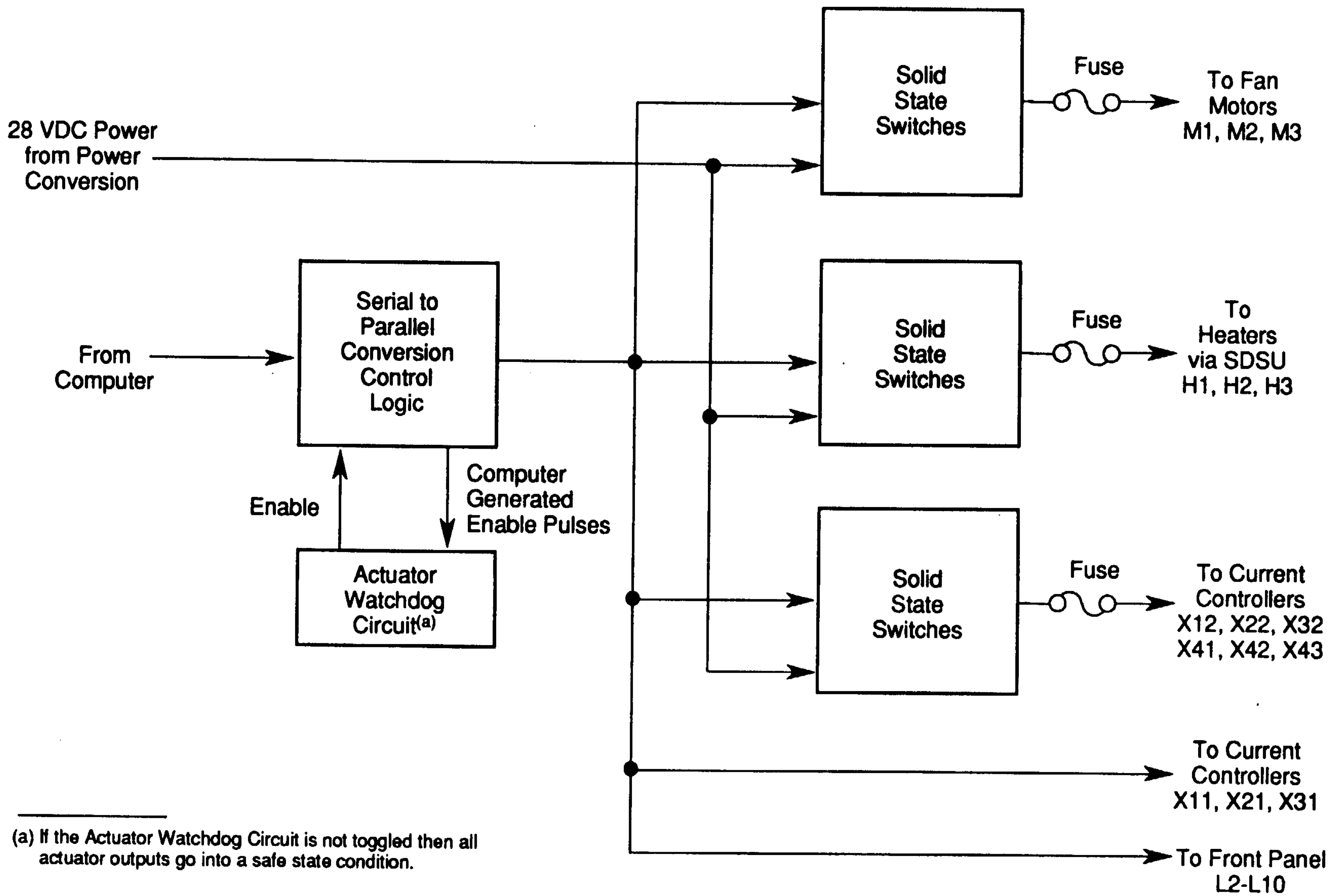


FIGURE 15 GENERIC SENSOR SIGNAL CONDITIONING

TABLE 2 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.



(a) If the Actuator Watchdog Circuit is not toggled then all actuator outputs go into a safe state condition.

FIGURE 16 ACTUATOR SIGNAL CONDITIONING

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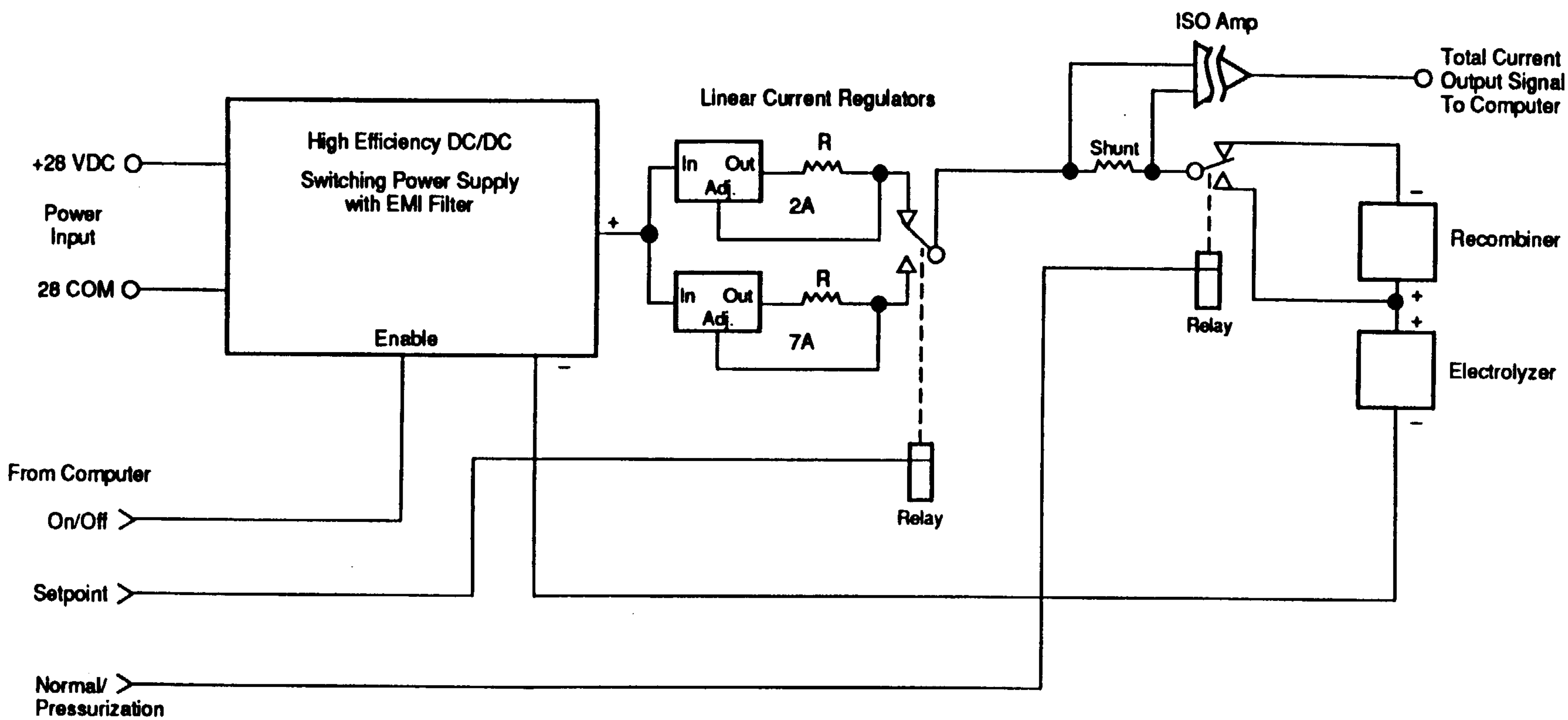

FIGURE 17 CURRENT CONTROLLER

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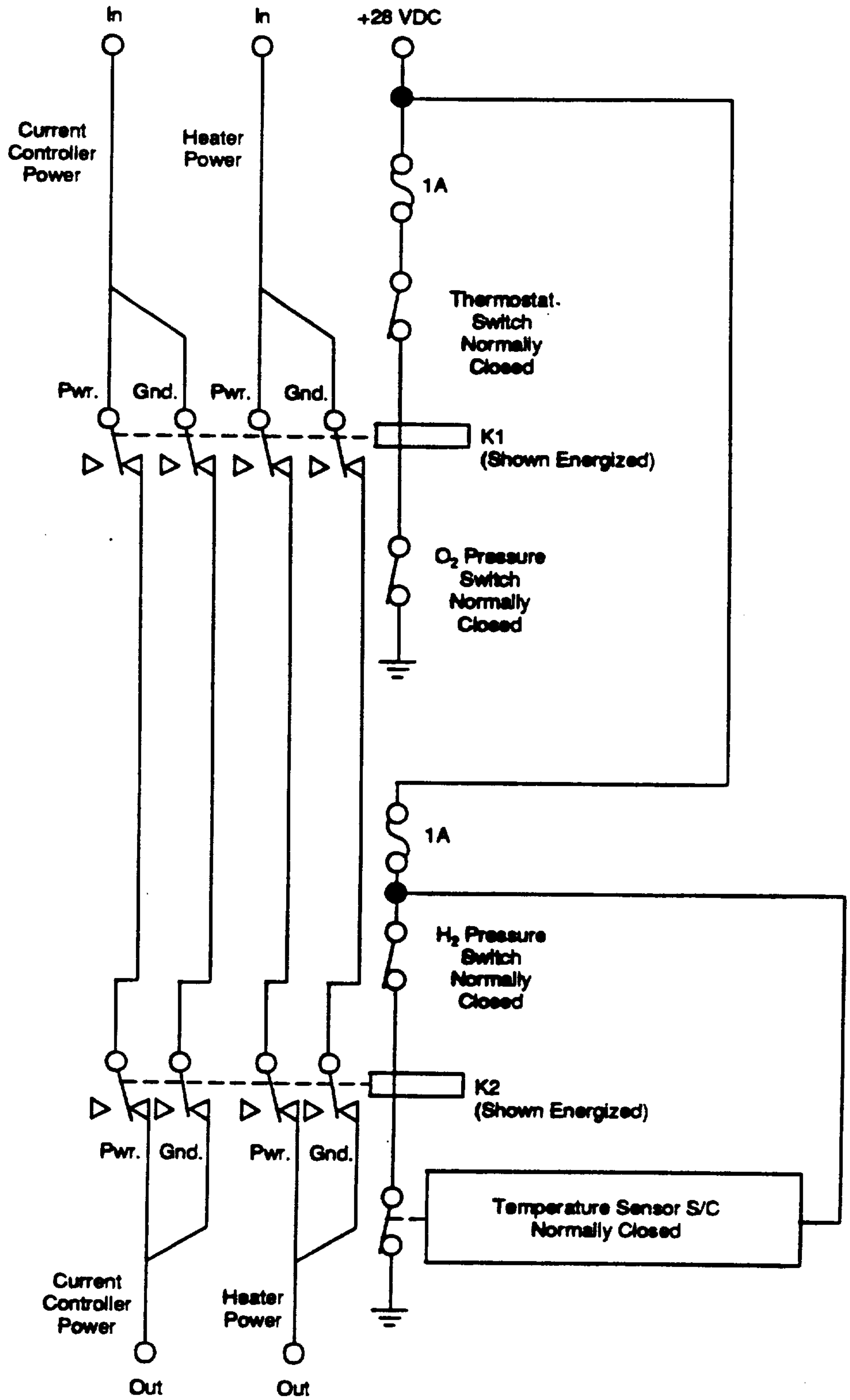

FIGURE 18 SENSOR DEDICATED SHUTDOWN UNIT

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S108E

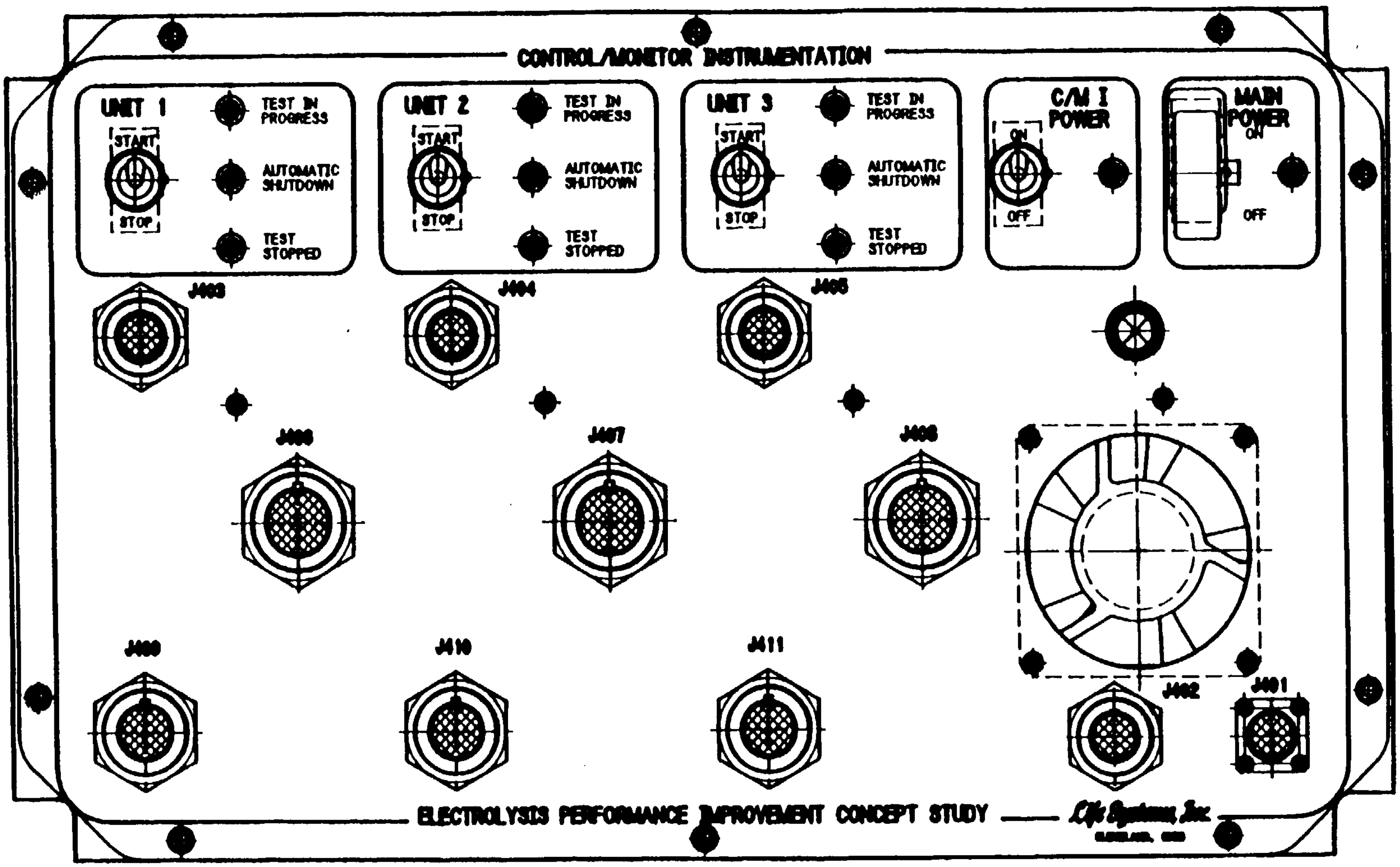

FIGURE 19 EPICS OPERATOR PANEL LAYOUT

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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 20 and described in Table 3.

During Normal mode, the software controls the test sequence, monitors sensors and manipulates actuators. The test sequence control loop block diagram is illustrated in Figure 21. The test sequence control consists of enabling current and temperature control loops with predetermined setpoints. The current control loop algorithm is illustrated in Figure 22. This loop maintains cell current at proper levels by sending setpoint information to the Current Controller and monitoring performance. The temperature control loop algorithm is illustrated in Figure 23. This 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.

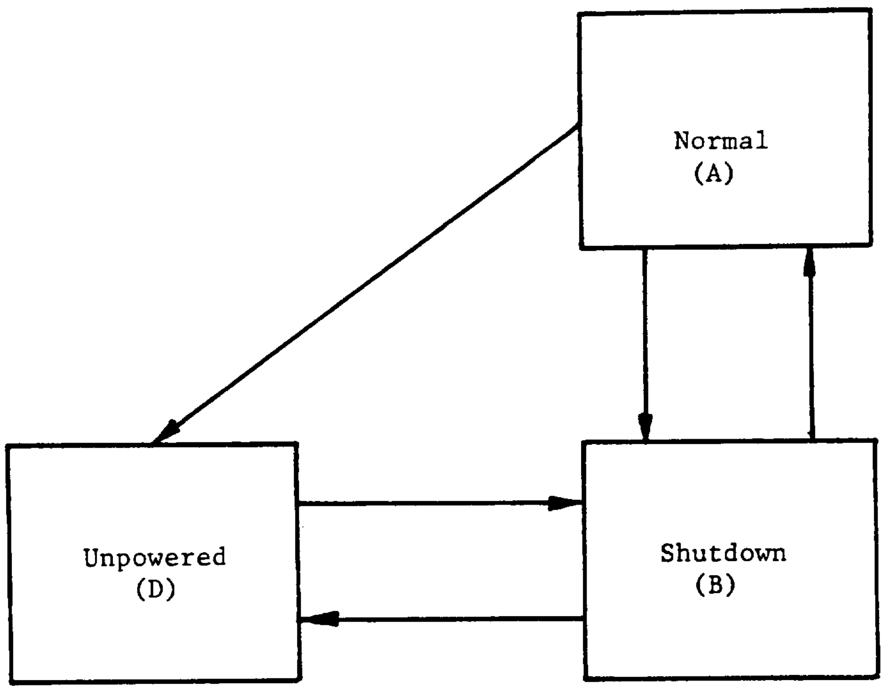
Simultaneously, while the test sequence is being controlled, the software is also monitoring the sensors for high or low limit alarms. The sensor limits that will initiate a shutdown are shown in Table 4.

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 24. The C/M I actions are described in Tables 5 and 6. The operating conditions are presented in Table 7.

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.

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.



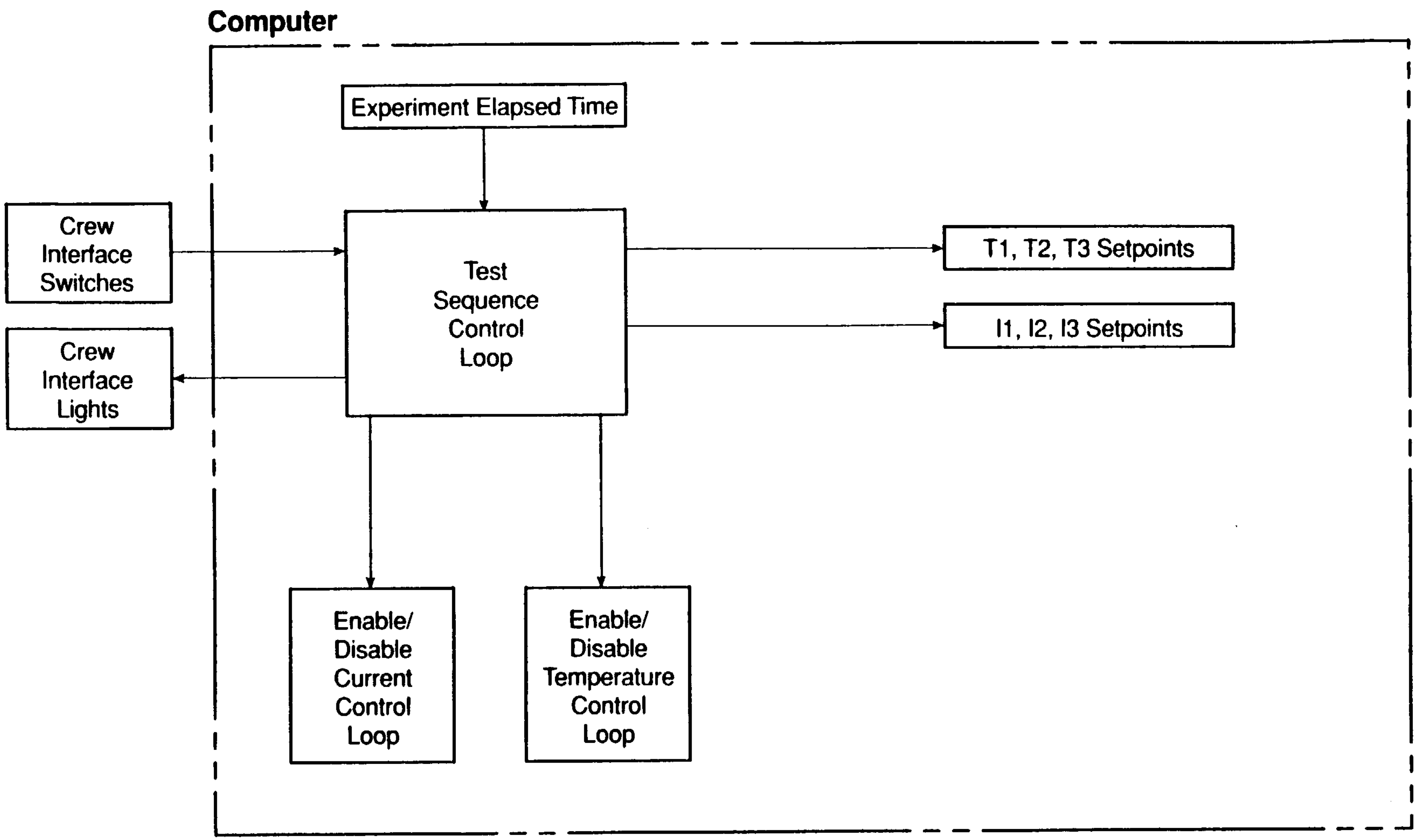
- 3 Modes
- 2 Operating Modes
- 5 Mode Transitions
- 3 Programmable, Allowable Mode Transitions

FIGURE 20 EPICS MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 3 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.



If Enabled, This Control Sets Setpoints and Enables/Disables Control Loops as Required (Based on Preset Test Sequence)

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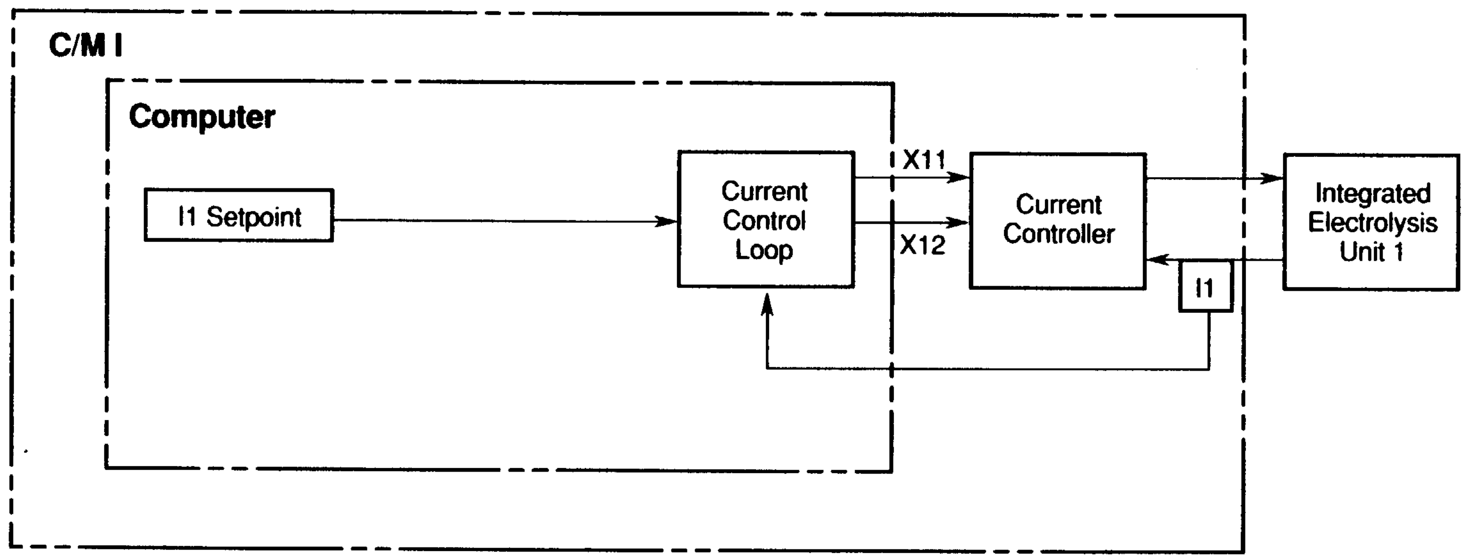
FIGURE 21 EPICS TEST SEQUENCE CONTROL



EPICS Current Control

If the Current Control is Enabled,

- The Current to IEU1 is Set to the I1 Setpoint
- X11 is Set to On
- I1 is Monitored for Performance

Otherwise,

- X11 is Set to Off and X12 is Set to 0 Amps

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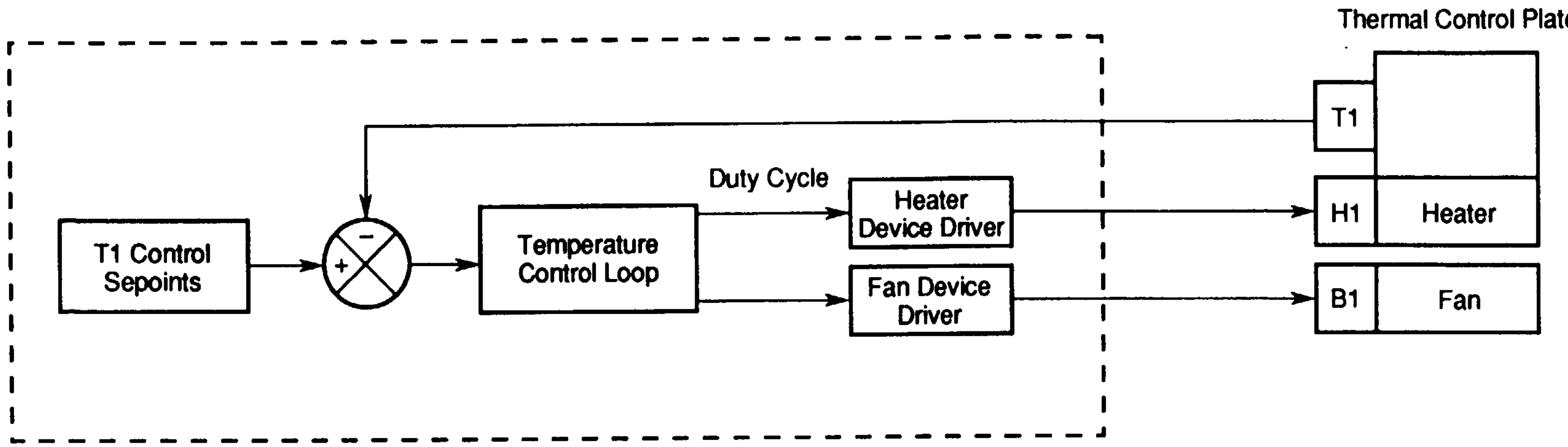
FIGURE 22 EPICS CURRENT CONTROL LOOP ALGORITHM



If Temperature Control Loop is enabled,
Heater is enabled when T1 is lower than the T1 low control setpoint and its duty cycle is controlled using a Proportional Control Algorithm

Fan is enabled at 100% duty cycle when T1 is higher than the T1 high control setpoint

Otherwise, both duty cycles are set to 0%

FIGURE 23 EPICS TEMPERATURE CONTROL LOOP ALGORITHM

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TABLE 4 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).

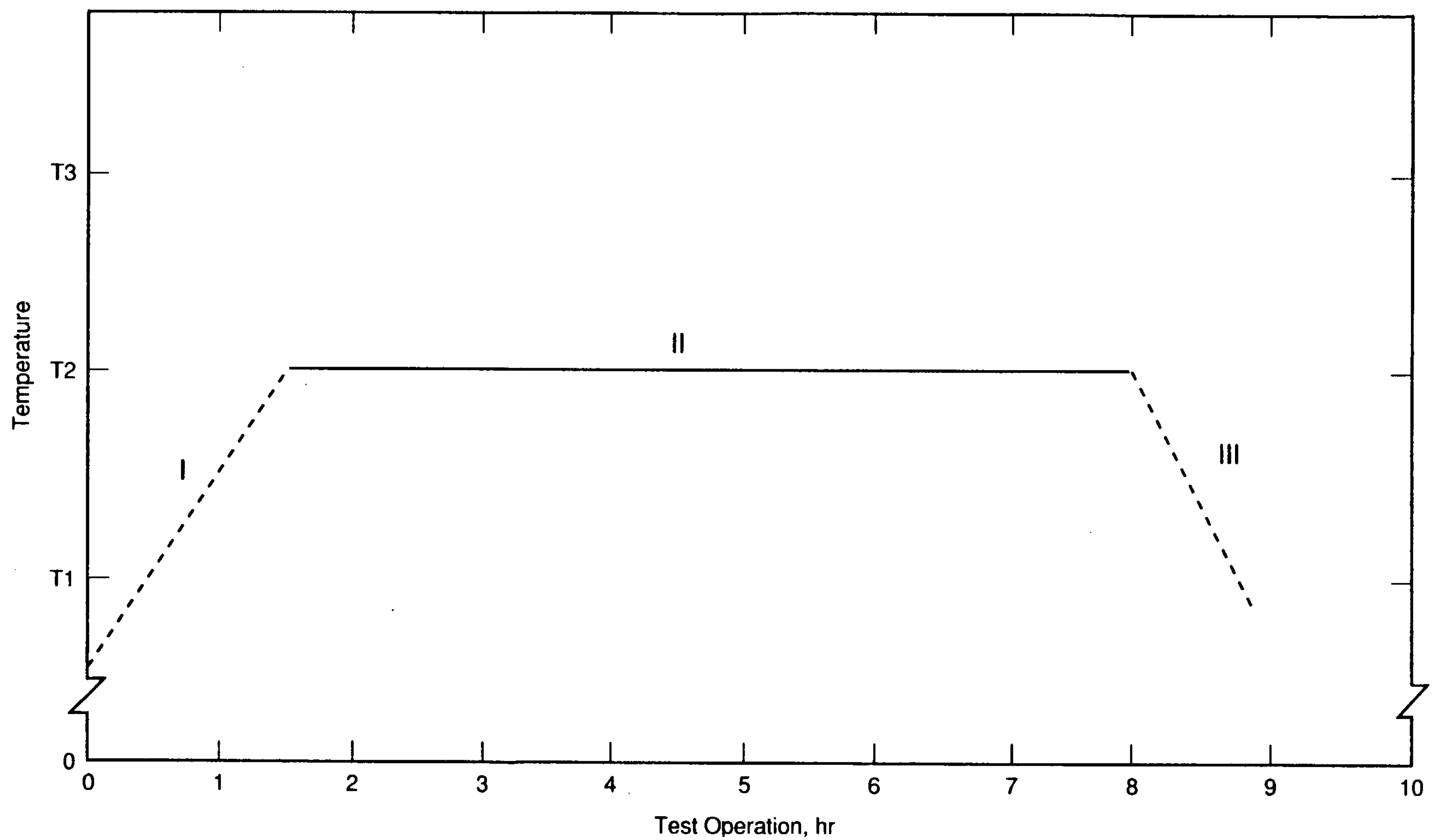

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FIGURE 24 EPICS EXPERIMENT TEST SEQUENCE

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TABLE 5 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 6 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 7 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

At the completion of the electrolysis/recombination operating period, the Current Controllers is 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 the 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, GSE is needed to prepare the EPICS flight hardware for the flight experiment. A summary of these GSE operations is shown in Table 8. The EPICS GSE to support these operations is summarized in Table 9. This GSE includes all of the equipment needed to test, handle, support and calibrate the EPICS flight unit. Functional descriptions of each major GSE item to be supplied by Life Systems including its purpose, characteristics and utilization scenario are presented in the following.

Test Support Accessories

The EPICS Test Support Accessories (TSA) is a custom fabricated apparatus used extensively during GSE operations at Life Systems. It was also used for functional performance testing before and after various environmental certification tests conducted at JSC. The primary purpose of the TSA is to provide the capability for purging and evacuating the Integrated Electrolysis Units (IEU's) and to provide simulated mechanical and electrical interfaces for testing. The mechanical schematic for the EPICS TSA is shown in Figure 25. A summary of the characteristics is presented in Table 10.

Before testing the IEU's, any residual air must be purged. This is accomplished by first connecting both test ports of an IEU to the TSA. A vacuum is applied to the IEU using the vacuum pump, PU1, and positioning three-way valve MV4 in the vacuum position. The amount of vacuum provided by the vacuum pump can be monitored using pressure gauge PG3 and controlled using the vacuum pump bypass valve RX1. After applying the desired vacuum of 20 in Hg Vac, the IEU is back-filled with humidified nitrogen (N_2) at 1 psig by moving valve MV4 to the purge position. The back-fill rate is monitored using pressure gauges PG2 and PG3 and controlled using valve MV3. The vacuum/back-fill cycle is repeated once. Finally, vacuum is applied to the IEU's before they are isolated using the manual valves on the IEU's.

The EPICS TSA also provides the electrical and mechanical interfaces for testing the EPICS hardware. The electrical interface is achieved using a commercial power supply that outputs 28 VDC to simulate Orbiter power. The TSA has built-in meters to monitor both the supply voltage and current for power calculation. The mechanical interface is achieved using a payload mounting panel simulator. The TSA has two built-in temperature sensors with a digital display unit to monitor the EPICS cooling air inlet and outlet temperature.

TABLE 8 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

TABLE 9 SUMMARY OF EPICS GSE

Item	Usage Category
Test Support Accessories	Service/Test[a]
Diagnostic Computer[b]	Test/Calibration Check
Calibration Equipment:	
- Calibrated Voltage Source[c]	Calibration Check
- Digital Multimeter[c]	Calibration Check
- Digital Thermometer[c]	Surface Temperature Measurement
- Power Supply, 28 VDC	Calibration Check

(a) The TSA which is equipped with a transportation plate with support structure for mounting the EPICS flight hardware was used in supporting the certification and associated functional performance testing at JSC. The transportation/mounting structure was also used in setting up the flight hardware for instrumentation calibration check at KSC.
(b) Includes all interface cabling.
(c) Includes all probes and cables.

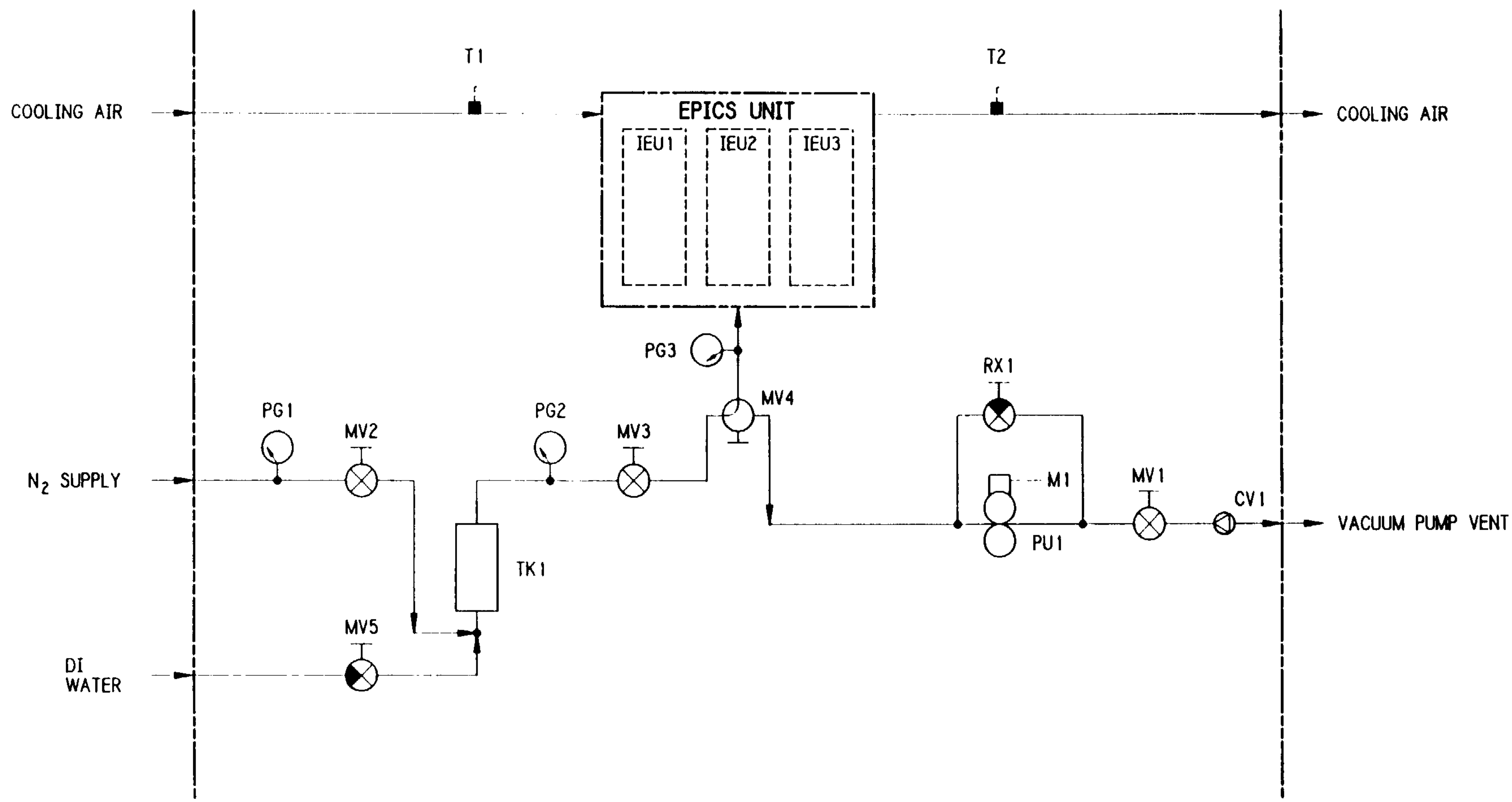

FIGURE 25 EPICS EXPERIMENT TEST STAND MECHANICAL SCHEMATIC WITH SENSORS

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TABLE 10 CHARACTERISTICS OF EPICS TEST SUPPORT ACCESSORIES

Item Name:	EPICS Test Support Accessories
Model Number:	--
Top Assembly Number:	D-8715
Estimated Weight, lb:	100
Estimate Size (LxWxH), in:	30 x 48 x 75
Work Area Required, ft^2	48
Interfaces:	Deionized Water High Purity N_2 Facility Power at 208 VAC, 3-Phase
Estimated Power Requirements, W:	500
Wire Harness/Test Cable Requirements:	Power Interface Cable with Standard Orbiter Power Connector
Fluid Requirements[a]:	Deionized Water 200 cc (Batch Charged) High Purity N_2 40 L (Supplied at 5 psig)

(a) Fluid requirements are maximum values based on one complete purge cycle for all three IEUs.

Diagnostic Computer

The EPICS diagnostic computer is a standard IBM-compatible computer. This computer was utilized extensively during testing at Life Systems and at the JSC and the Kennedy Space Center (KSC). The primary purposes of the diagnostic computer are to provide a means of displaying internal C/M I data and to provide a mechanism for issuing control commands to the C/M I. The diagnostic computer operates independently of the C/M I and utilizes Life Systems Diagnostic Test Software (DTS). The diagnostic computer uses the RS-232 serial interface to communicate to the C/M I. The major characteristics for the diagnostic computer are shown in Table 11.

When the diagnostic computer is connected to the EPICS C/M I serial interface and the DTS program is executed, the operator has the capability to view setpoints, raw sensor values, processed sensor values and other C/M I parameters. For calibration purposes, a known voltage can be supplied to the external voltage channel and a comparison can be made to the processed values. In addition to the display capability, the DTS program also provides the capability to override controls or manually activate the actuators. This feature is utilized when a hazard control or actuator needs to be tested. It should be noted that these changes are temporary and do not affect the software stored in the Erasable Programmable Read Only Memory (EPROM). In order to obtain the original EPICS software (i.e., free of alteration) the C/M I needs only to be powered down then powered up.

Calibration Equipment

The EPICS GSE calibration equipment consists of calibrated voltage source and a digital multimeter. These devices were utilized at Life Systems and KSC to check the calibration of the EPICS C/M I. The characteristics of these devices are shown in Tables 12 and 13.

The calibration equipment was utilized prior to acceptance testing and both prior to and following the mission. This equipment was used in conjunction with the diagnostic computer. The calibration check consisted of connecting a calibrated and verified voltage source to the EPICS external voltage connector and comparing the internal C/M I values with the source values. An interface block diagram for this operation is shown in Figure 26.

Mission Scenario

The mission for the actual flight experiment extends to two consecutive 24-hour days of testing for approximately eight hours of testing each day. The test plan is shown in Figure 27 and basically consists of two current variations, 2 and 7 A, over the two-day period. Since the EPICS flight experiment is fully automated, the only requirement for the crew is the initial actuation of the experiment. The C/M I is designed to handle the complete sequencing of the experiment and 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 11 CHARACTERISTICS OF DIAGNOSTIC COMPUTER

Item Name:	Diagnostic Computer
Model Number[(a)]:	IBM PS/2 Model 70 386
Top Assembly Number:	Not Applicable
Estimated Weight, lb:	50
Estimate Size (LxWxH), in:	30 x 24 x 20
Work Area Required, ft^2	9
Interfaces:	Facility Power at 115 VAC RS-232 Serial Communications
Estimated Power Requirements, W:	500
Wire Harness/Test Cable Requirements:	Custom Serial Interface Cable from EPICS C/M I to Serial Port on the Computer
Fluid Requirements:	Not Applicable

(a) The model number shown here is only one of many. Any computer compatible with this model is acceptable.

TABLE 12 CHARACTERISTICS OF CALIBRATED VOLTAGE SOURCE

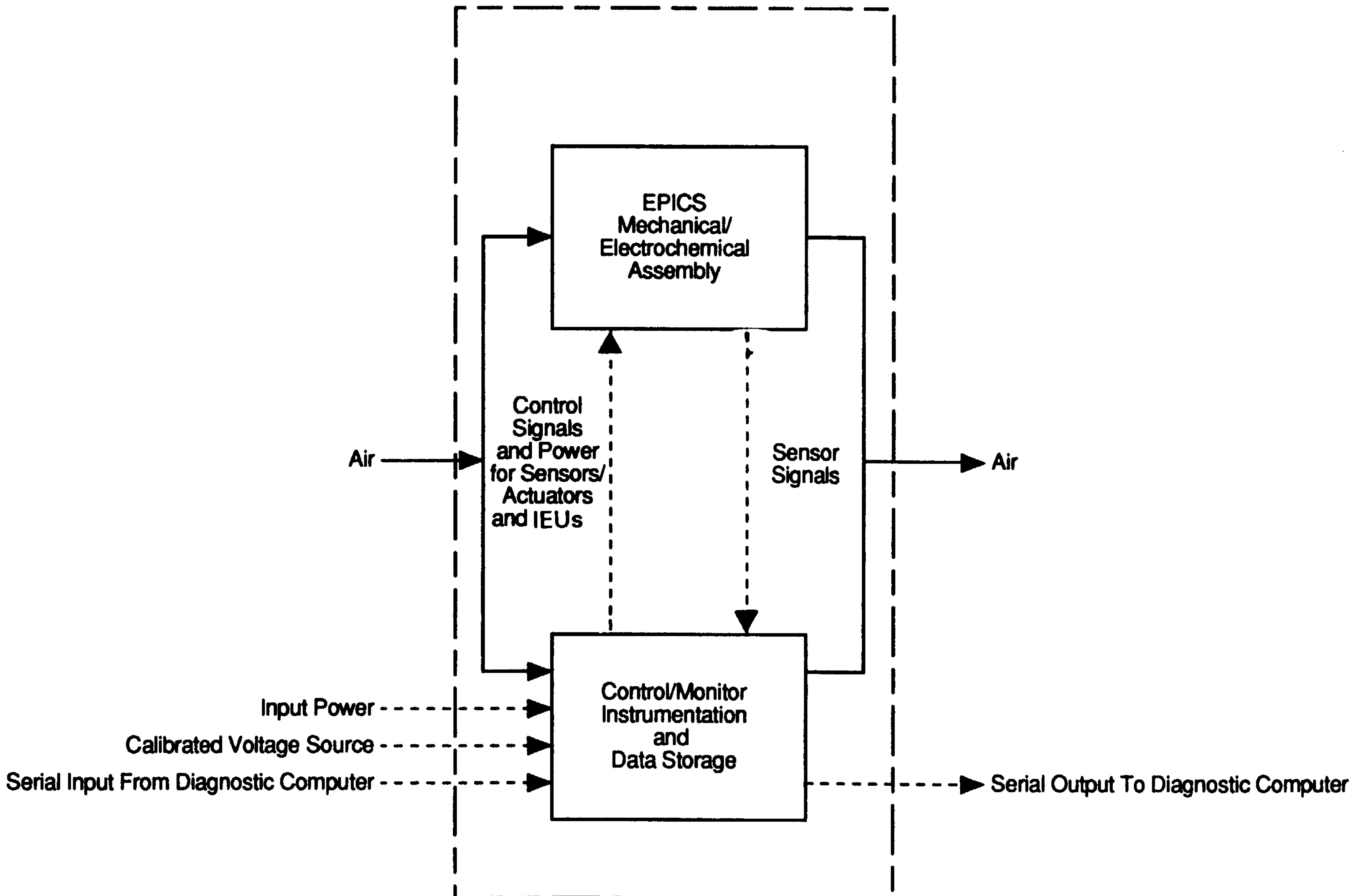
Item Name:	Calibrated Voltage Source
Model Number[(a)]:	Datel DVC 8500
Top Assembly Number:	Not Applicable
Estimated Weight, lb:	3
Estimate Size (LxWxH), in:	6 x 6 x 3
Work Area Required, ft^2	4
Interfaces:	Facility Power at 115 VAC C/M I External Voltage Channel
Estimated Power Requirements, W:	10
Wire Harness/Test Cable Requirements:	Standard Test Leads Interface Cable to C/M I
Fluid Requirements:	Not Applicable
Transportation/Handling Requirements:	Normal Requirements for Portable Instrumentation

(a) Any equivalent model number to the one shown here is applicable.

TABLE 13 CHARACTERISTICS OF DIGITAL MULTIMETER

Item Name:	Digital Multimeter
Model Number[a]:	FLUKE 8060A
Top Assembly Number:	Not Applicable
Estimated Weight, lb:	1
Estimate Size (LxWxH), in:	8 x 4 x 2
Work Area Required, ft^2	4
Interfaces:	Test Connection
Estimated Power Requirements, W:	Battery Powered (9 VDC)
Wire Harness/Test Cable Requirements:	Standard Test Leads
Fluid Requirements:	Not Applicable
Transportation/Handling Requirements:	Normal Requirements for Portable Instrumentation

(a) Any equivalent model number to the one shown here is applicable.



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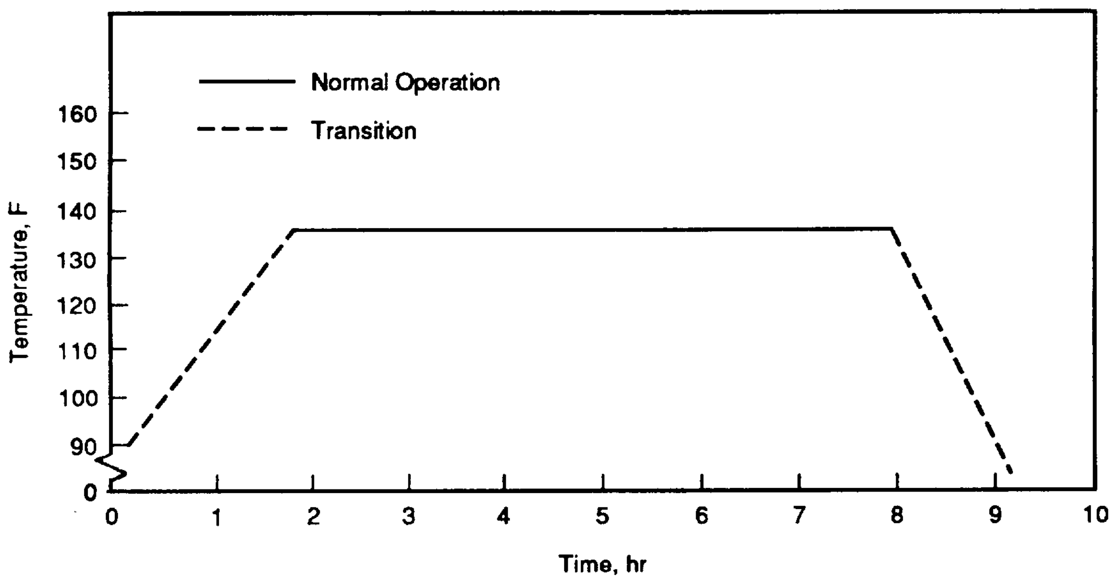
Life Systems CLEVELAND, OHIO

FIGURE 26 EPICS INTERFACE BLOCK DIAGRAM FOR PRE-TEST CHECKOUT

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 27 FLIGHT TEST PLAN FOR EPICS EXPERIMENT

TESTING AND DATA ANALYSIS

Acceptance Testing

A two-day operational test was performed as a part of the Acceptance Test. The cell voltage, current, temperature and accumulator positions of the IEU's are presented in Figures 28 through 39. Figure 40 represents the air outlet temperature date during the two-day test.

Flight Experiment

The flight experiment of the EPICS on STS-69 Endeavor was activated at the Mission Elapsed Time (MET) of 4:09 on September 7, 1995. Discussed below are the results and analysis of the flight experiment operation data of the three IEUs:

IEU1

Approximately 22 min into the initial warmup period on the first day, IEU1 went into a safe automatic shutdown. Post-flight analysis of flight data, verification tests and investigation of anomaly at components level determined that the automatic shutdown was caused by a defective temperature sensor, T4.

This temperature measurement falsely indicated that the cell had exceeded the high cell temperature limit of 150 degrees F, when it was actually 116 degrees 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.

IEU2

Testing of IEU2 continued successfully through the first day of operation at 2A (37 ASF), into the 16-hr quiescent period and into the warmup period for the second day of operation at 7A. The performances of both the electrolyzer cell and recombiner cell were nominal, at 1.53 volts nd 0.8 volts, respectively. Approximately 24 min into the second day warmup period, IEU2 went into a safe automatic shutdown. Post-flight data analysis and tests determined that the shutdown was caused by an erroneously enabled fault detection during the warmup period sensing the electrolyzer cell voltage lower than 1.3V, a voltage which is normal for an open circuit mode.

The low electrolyzer cell voltage fault detection should not have been enabled during the warmup period. 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 V was not reached during pre-flight ground testing, and the missing line of software code was not detected. The shutdown was recreated during post-flight testing by simulating a low cell voltage input during the second warmup phase.

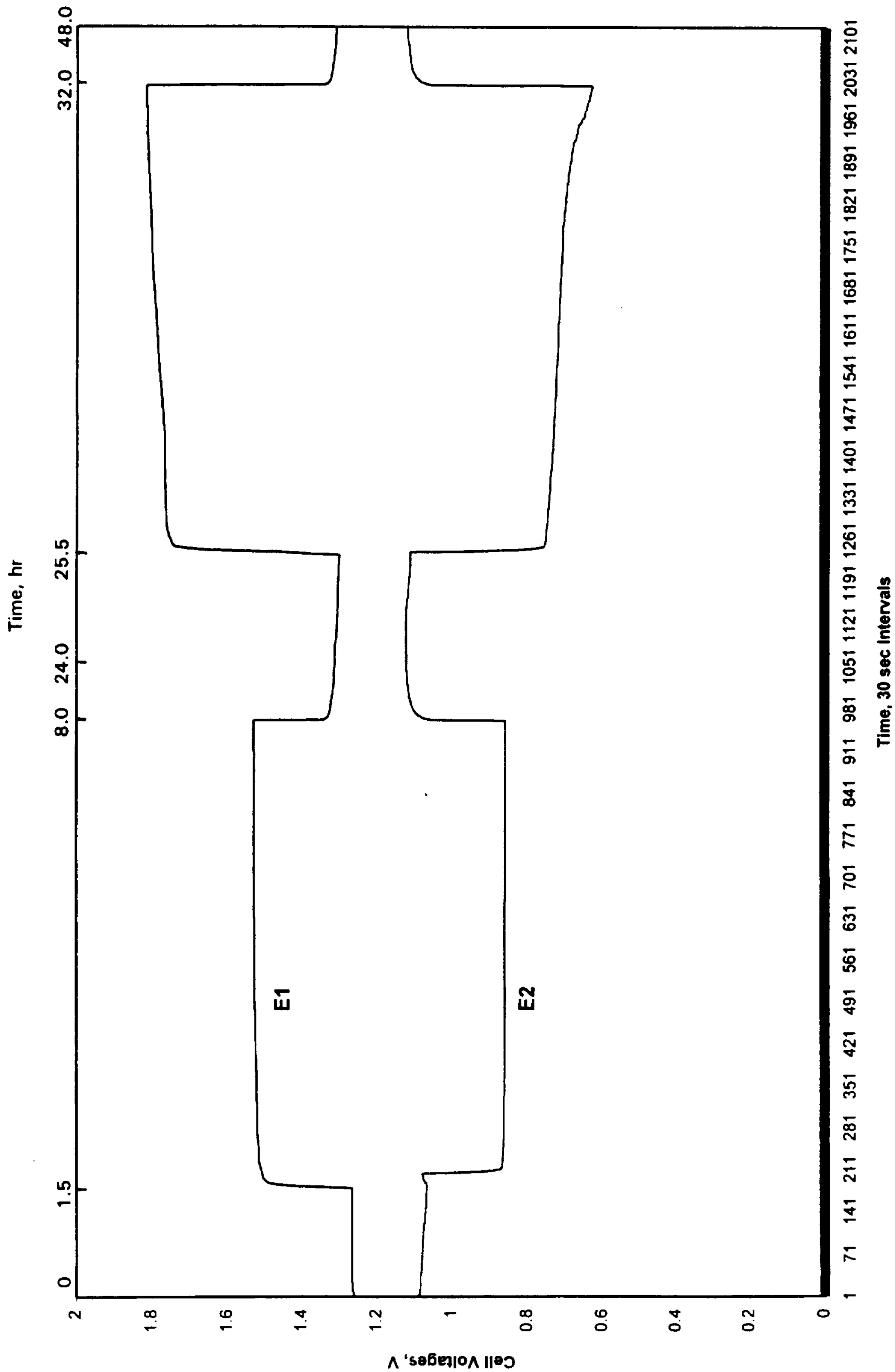


FIGURE 28 IEU NO. 1 CELL VOLTAGES, E1 & E2, VERSUS TIME

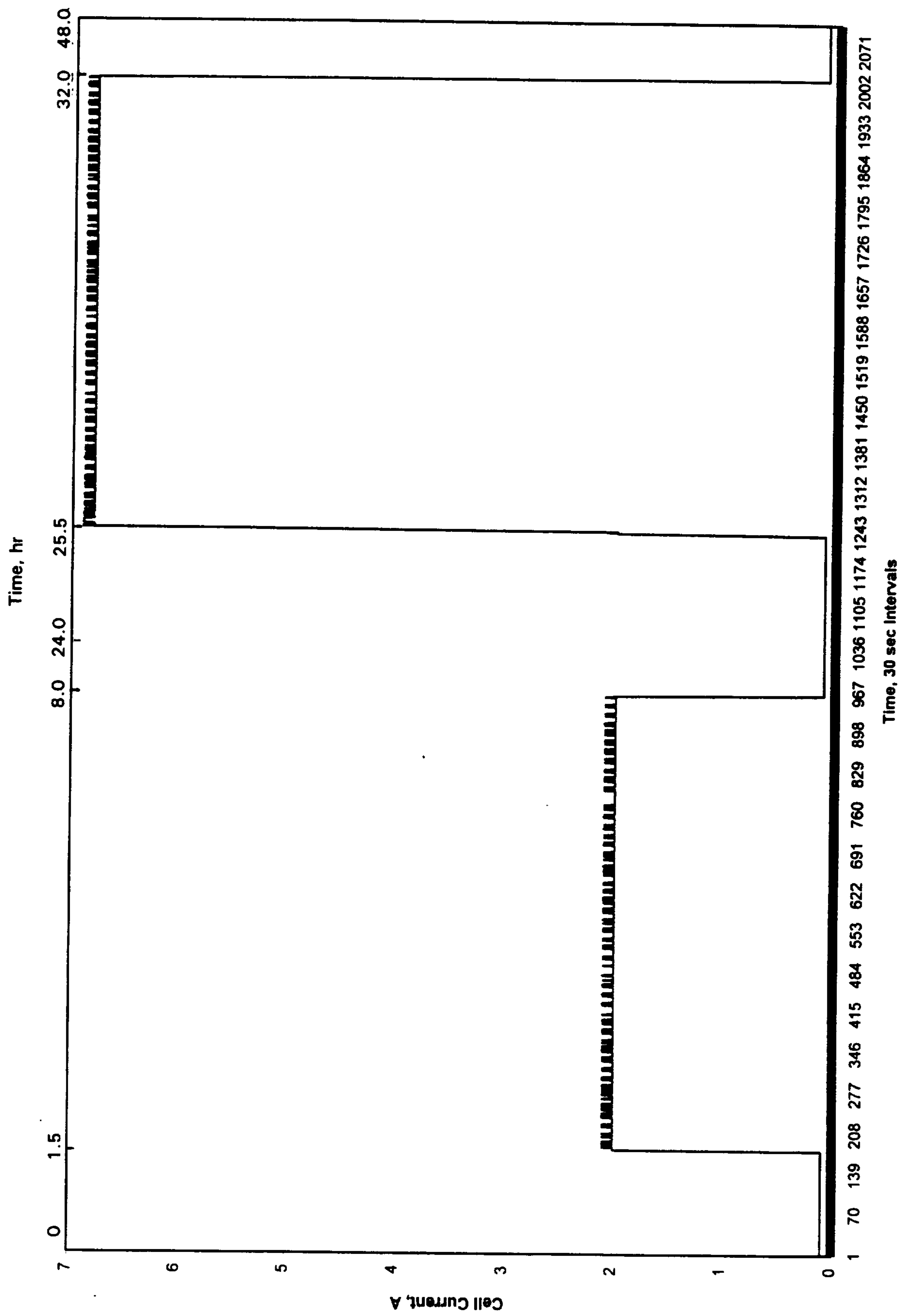


FIGURE 29 IEU NO. 1 CELL CURRENT VERSUS TIME

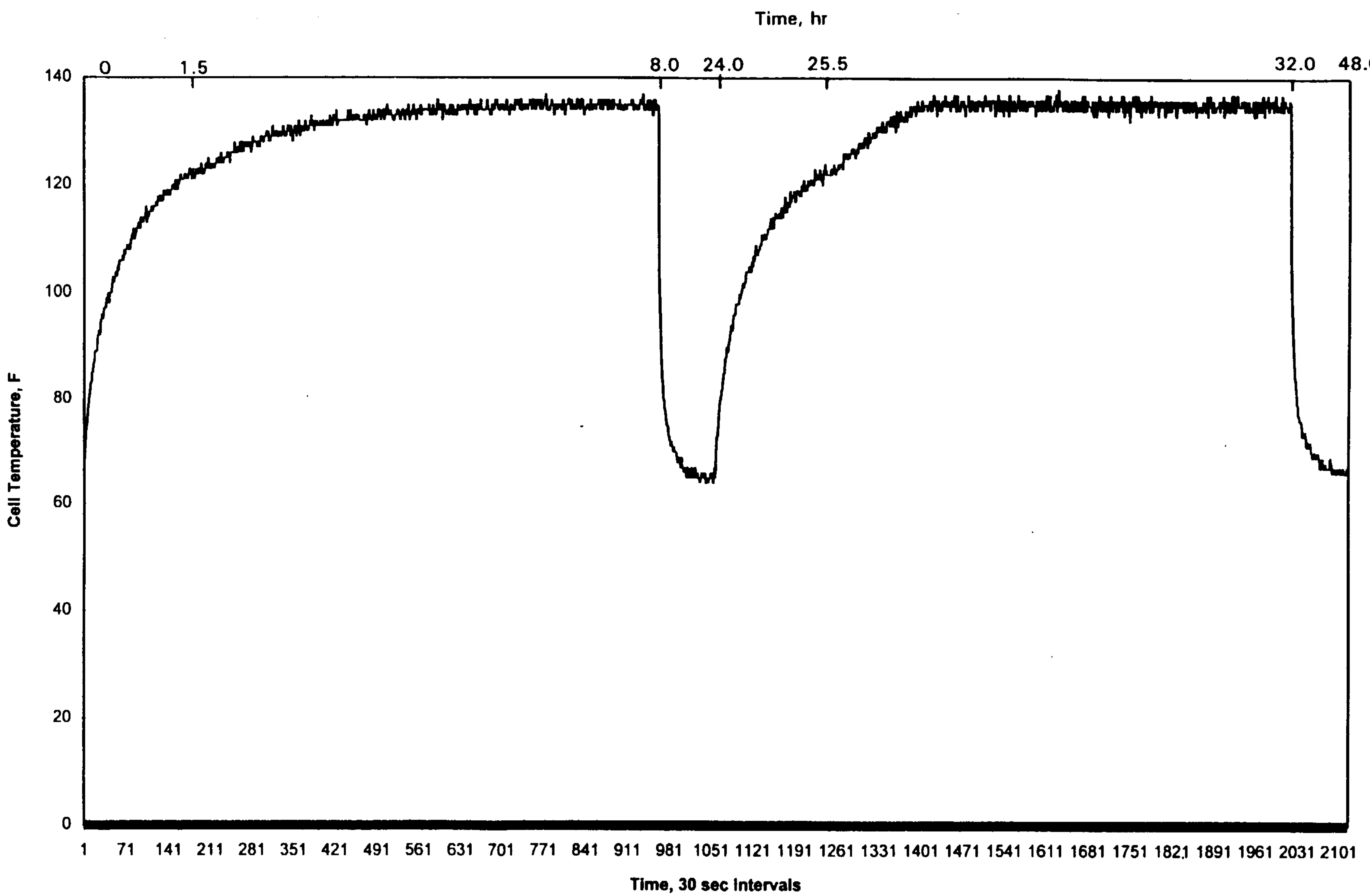


FIGURE 30 IEU NO. 1 CELL TEMPERATURE VERSUS TIME

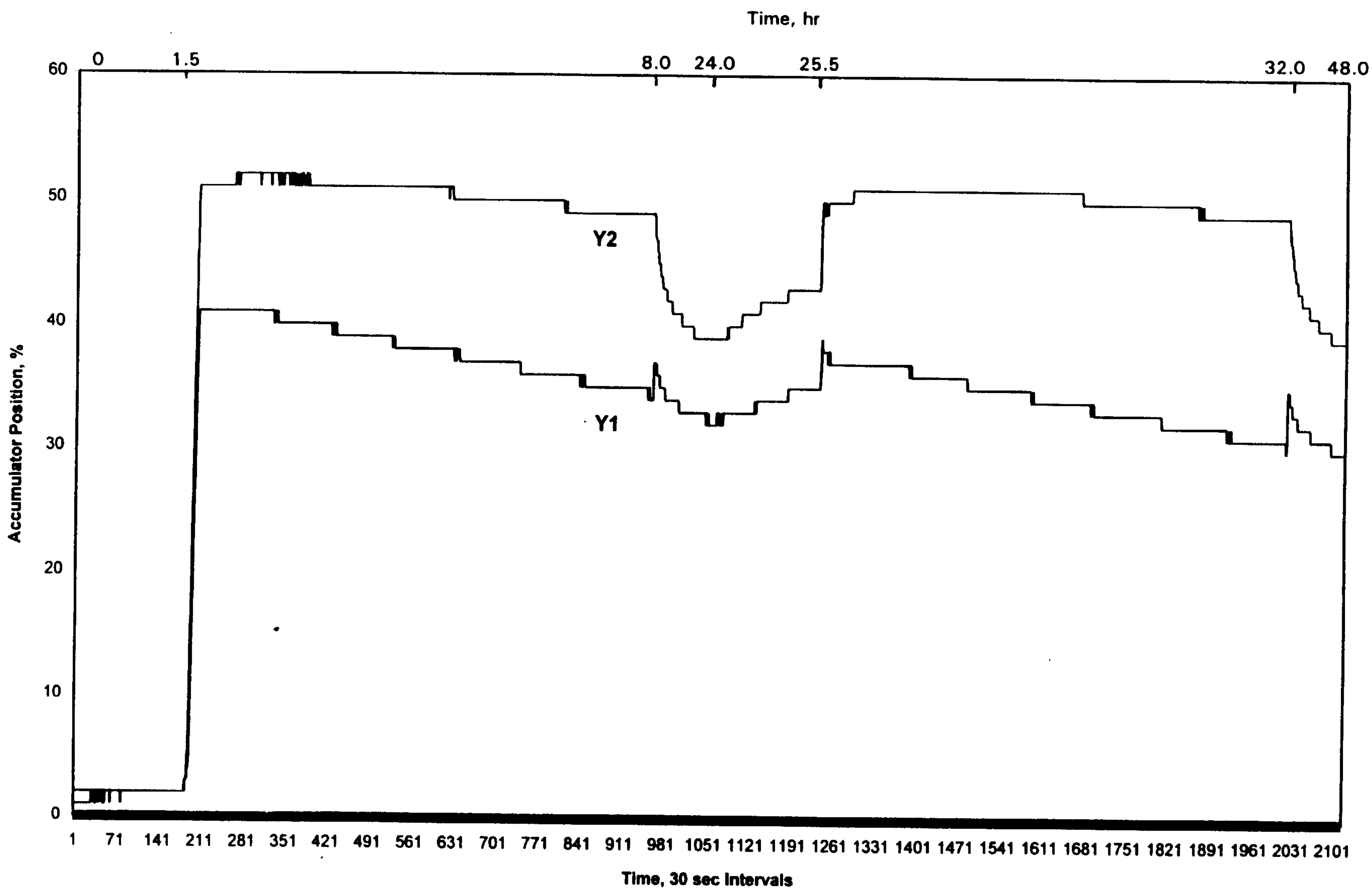


FIGURE 31 IEU NO. 1 ACCUMULATOR POSITIONS, Y1 & Y2, VERSUS TIME

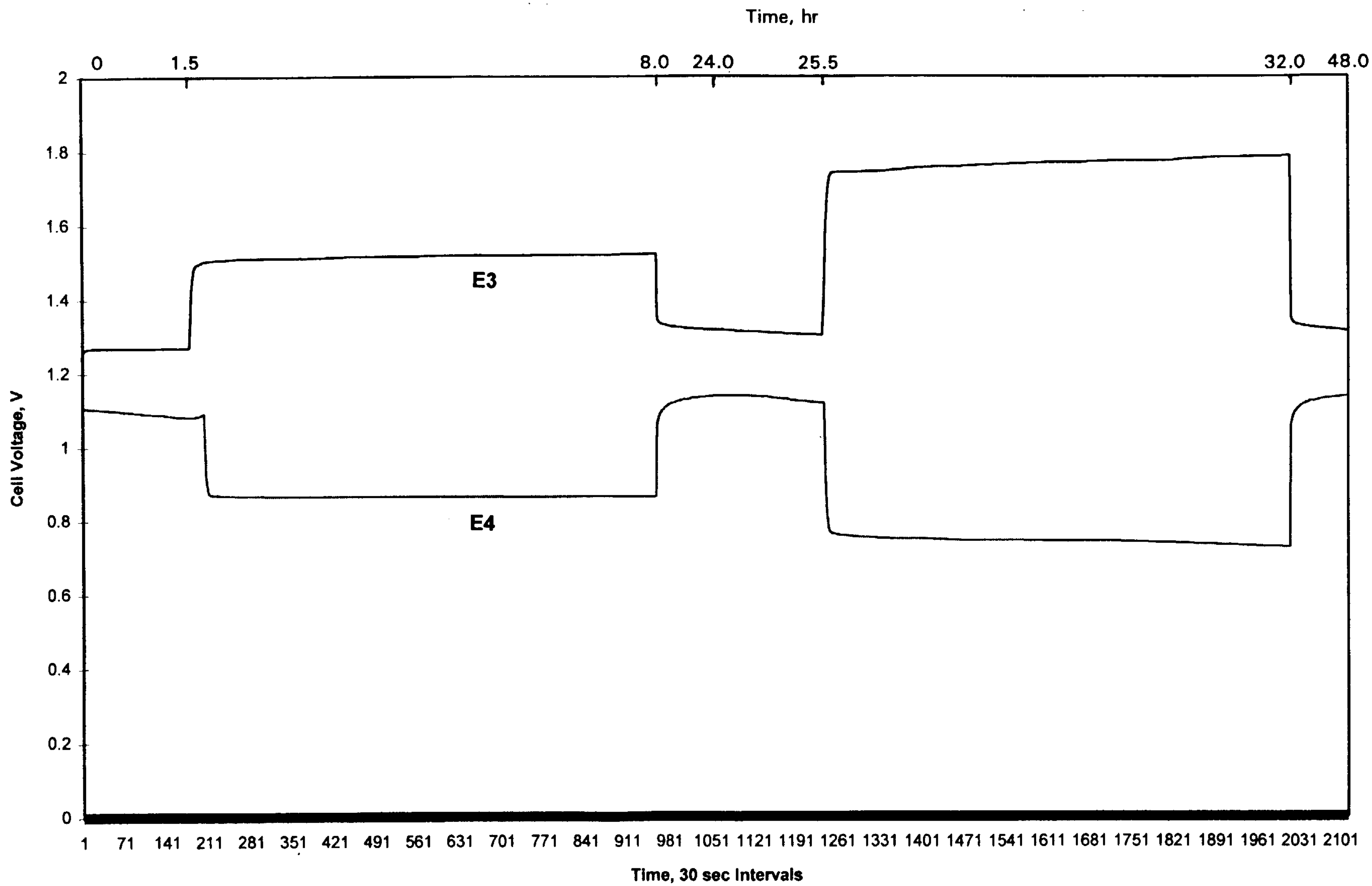


FIGURE 32 IEU NO. 2 CELL VOLTAGES, E3 & E4, VERSUS TIME

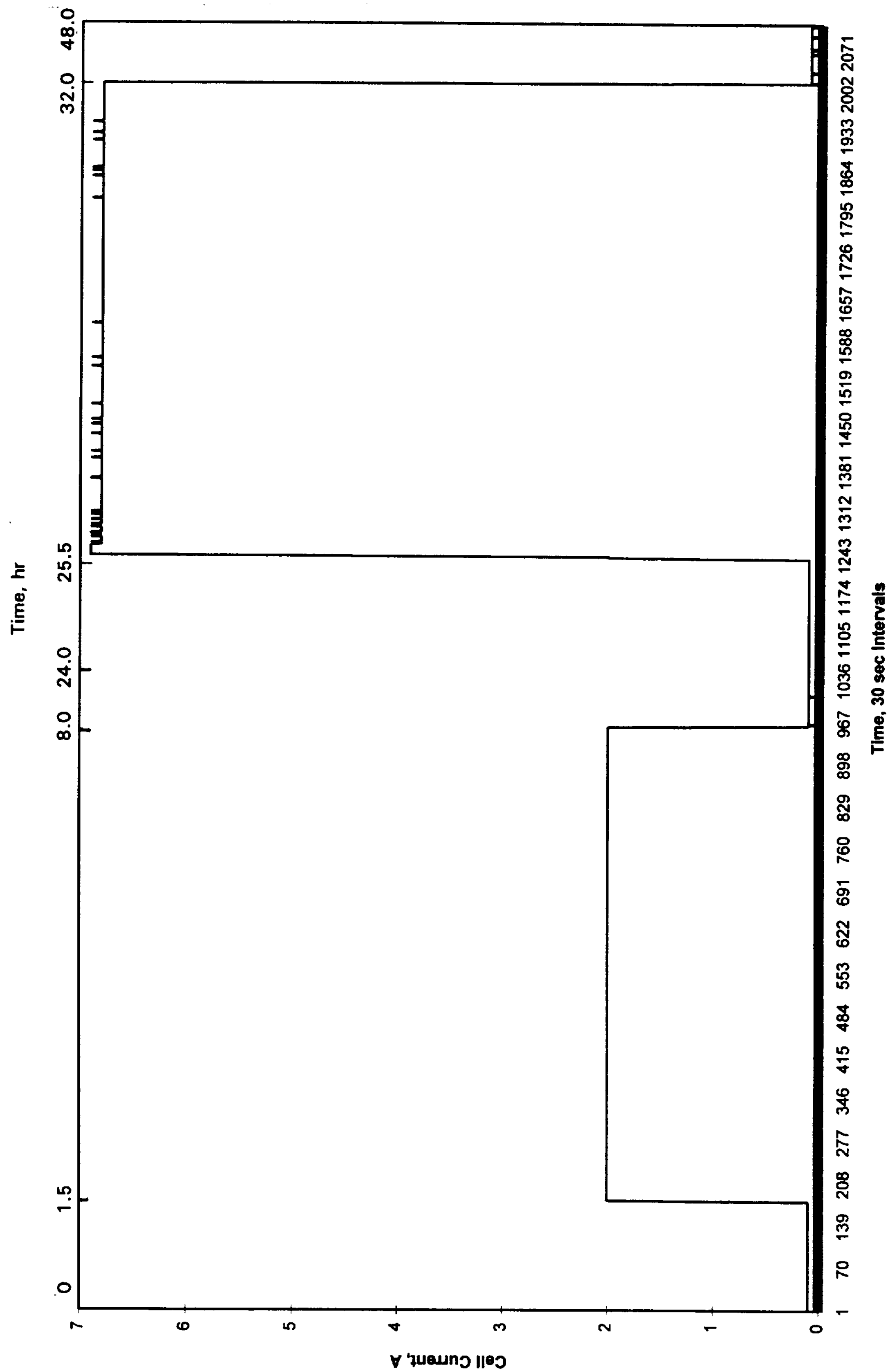


FIGURE 33 IEU NO. 2 CELL CURRENT VERSUS TIME

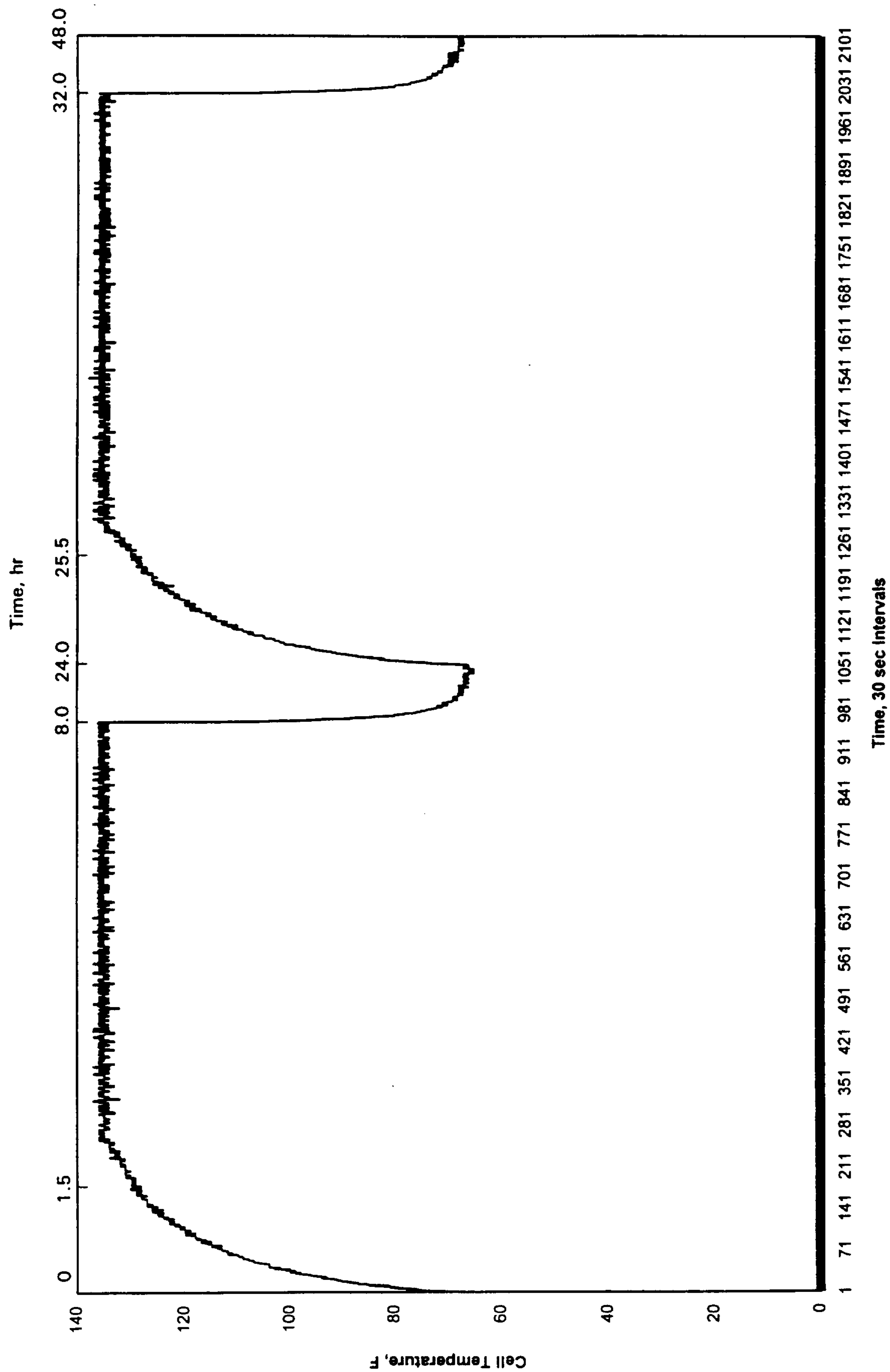


FIGURE 34 IEU NO. 2 CELL TEMPERATURE VERSUS TIME

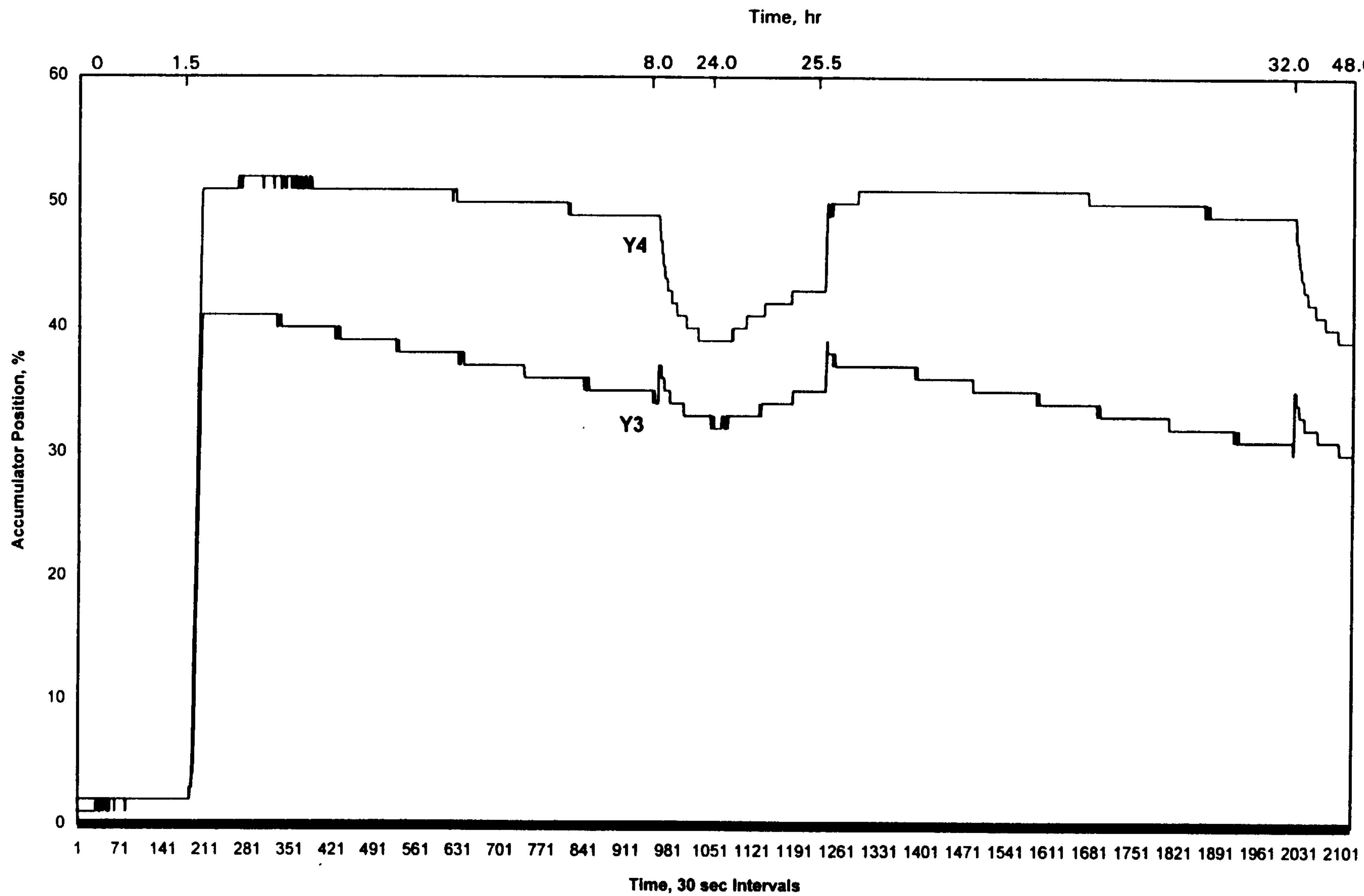


FIGURE 35 IEU NO. 2 ACCUMULATOR POSITIONS, Y3 & Y4 VERSUS TIME

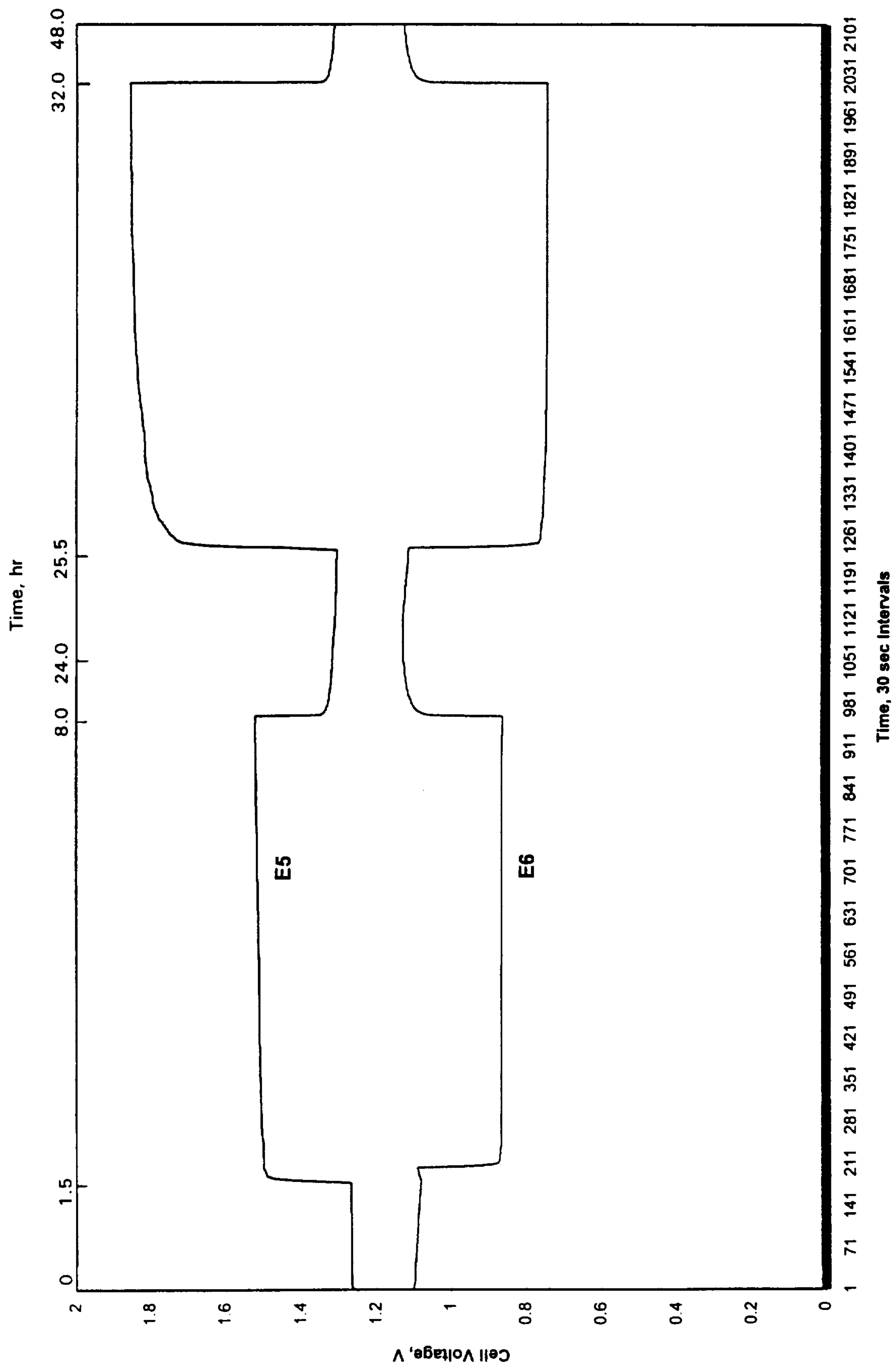


FIGURE 36 IEU NO. 3 CELL VOLTAGES, E5 & E6, VERSUS TIME

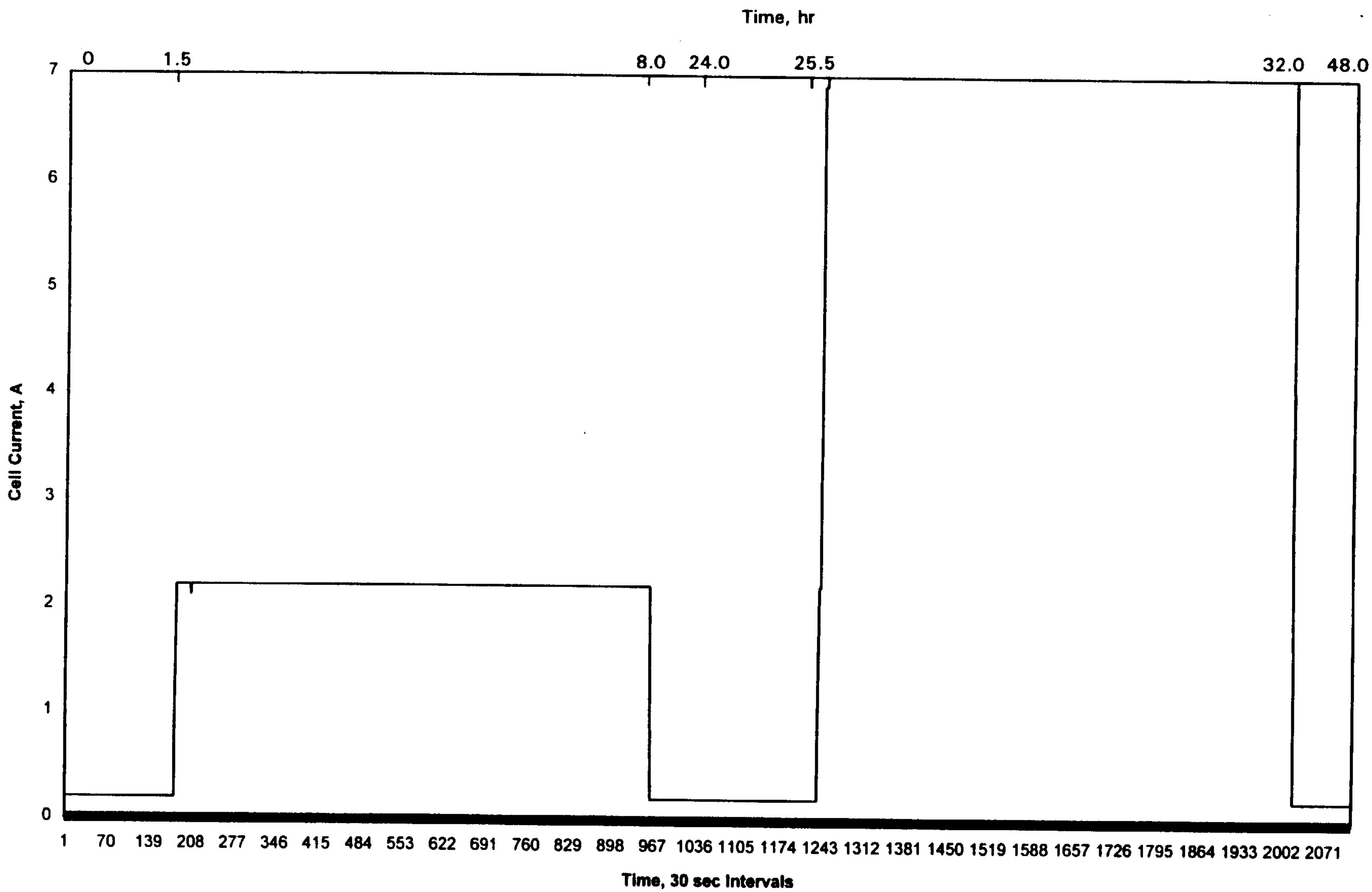


FIGURE 37 IEU NO. 3 CELL CURRENT VERSUS TIME

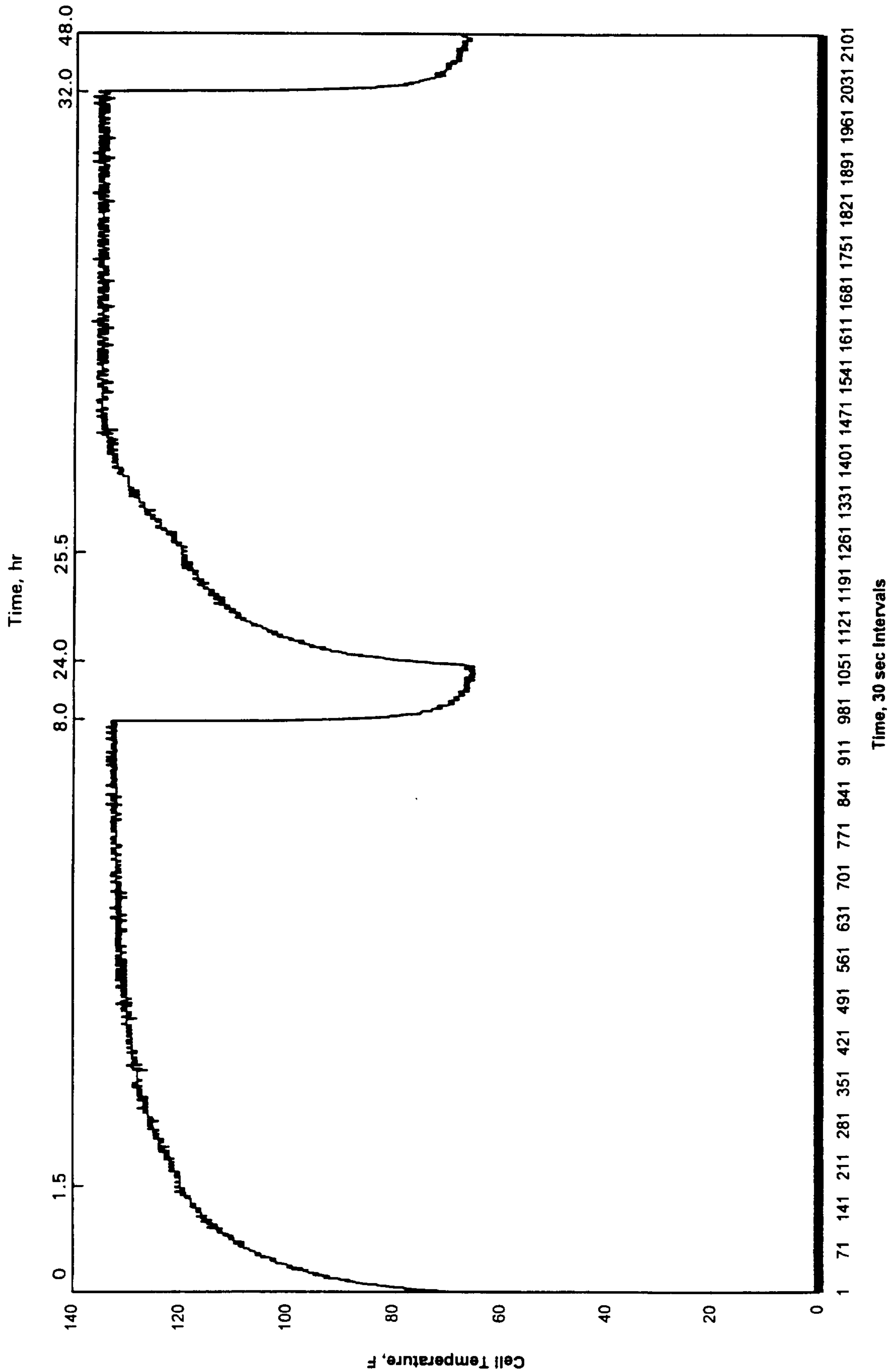


FIGURE 38 IEU NO. 3 CELL TEMPERATURE VERSUS TIME

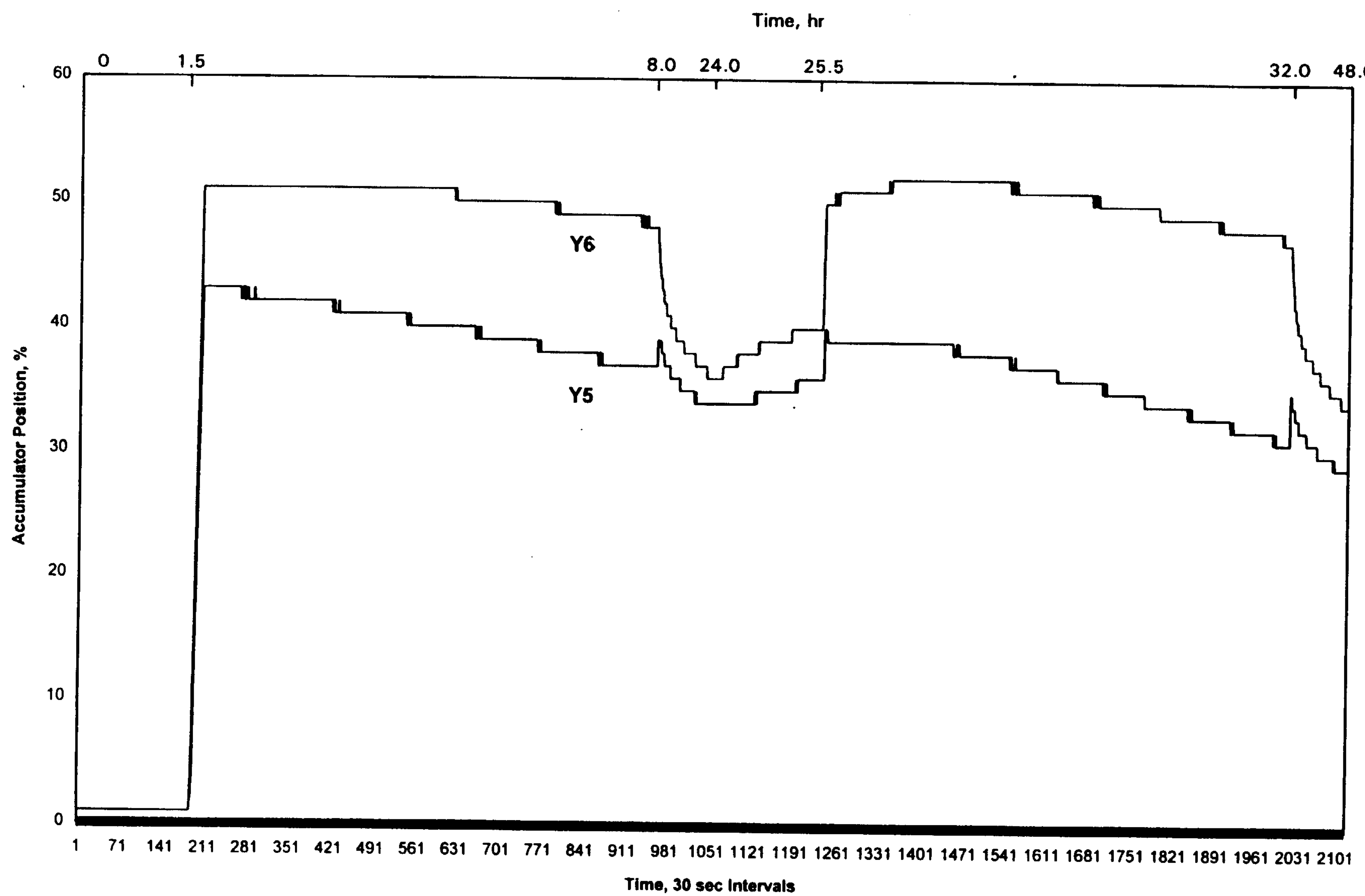


FIGURE 39 IEU NO. 3 ACCUMULATOR POSITIONS, Y5 & Y6 VERSUS TIME

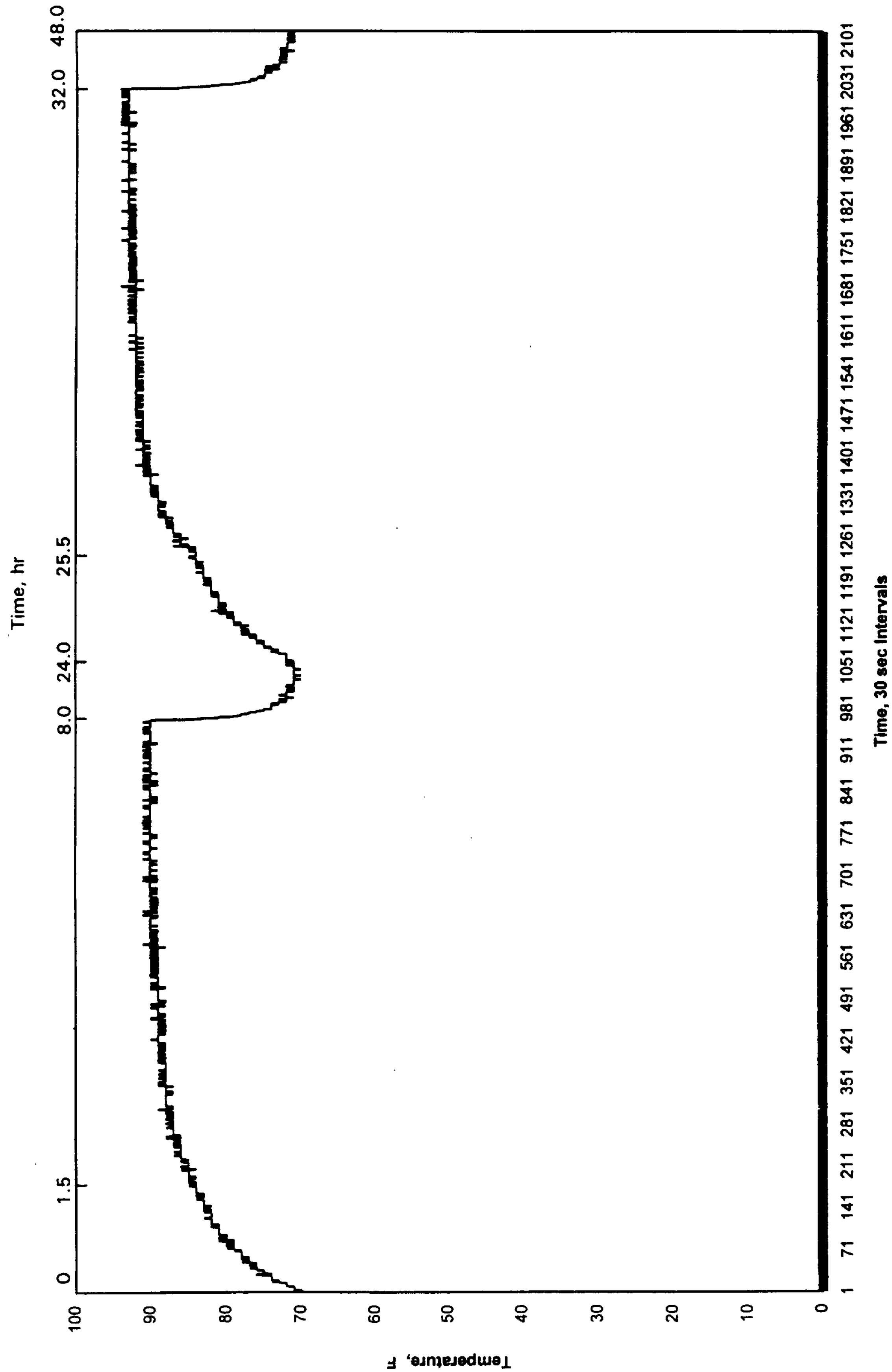


FIGURE 40 T7 VERSUS TIME

IEU3

Testing of IEU3 continued successfully through the first day of operation at 2A (37 ASF), into the 16-hr quiescent period and into the warmup period for the second day of operation at 7A. Approximately 25 min into the warmup period, IEU3 went into a safe automatic shutdown. Post-flight data analysis and tests determined that the shutdown was caused by the same reason as that for IEU2.

Flight Experiment

The results of the flight experiment during the first day of operation at 2A (37 ASF) are shown in Figures 41 through 46.

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. Performance improvements, both in power consumption and heat load generation were observed which are considered attributable to beneficial effects of the microgravity environment. A 3 to 6% reduction in power and 30 to 60% reduction in heat load were observed at the operating current density of 37 amps/ft^2.

3. The two failure tolerant design concepts incorporated in to the EPICS resulted in safe on-orbit operation and shutdown protection.

4. A first ever demonstration of the unitized regenerative fuel cell concept for potential energy storage application was successfully demonstrated by consuming water generated by the electrochemical reactions of a fuel cell and producing power by consuming reactants generated by the electrochemical reaction of the electrolysis cell.

5. Inhibits and shutdown protection implemented via software must be verified on an individual basis for all phases of experiment operation to avoid inadvertent unwanted shutdowns.

RECOMMENDATIONS

1. Refly the EPICS experiment at the earliest opportunity.

2. Replace failed temperature sensor on IEU1 with verified device.

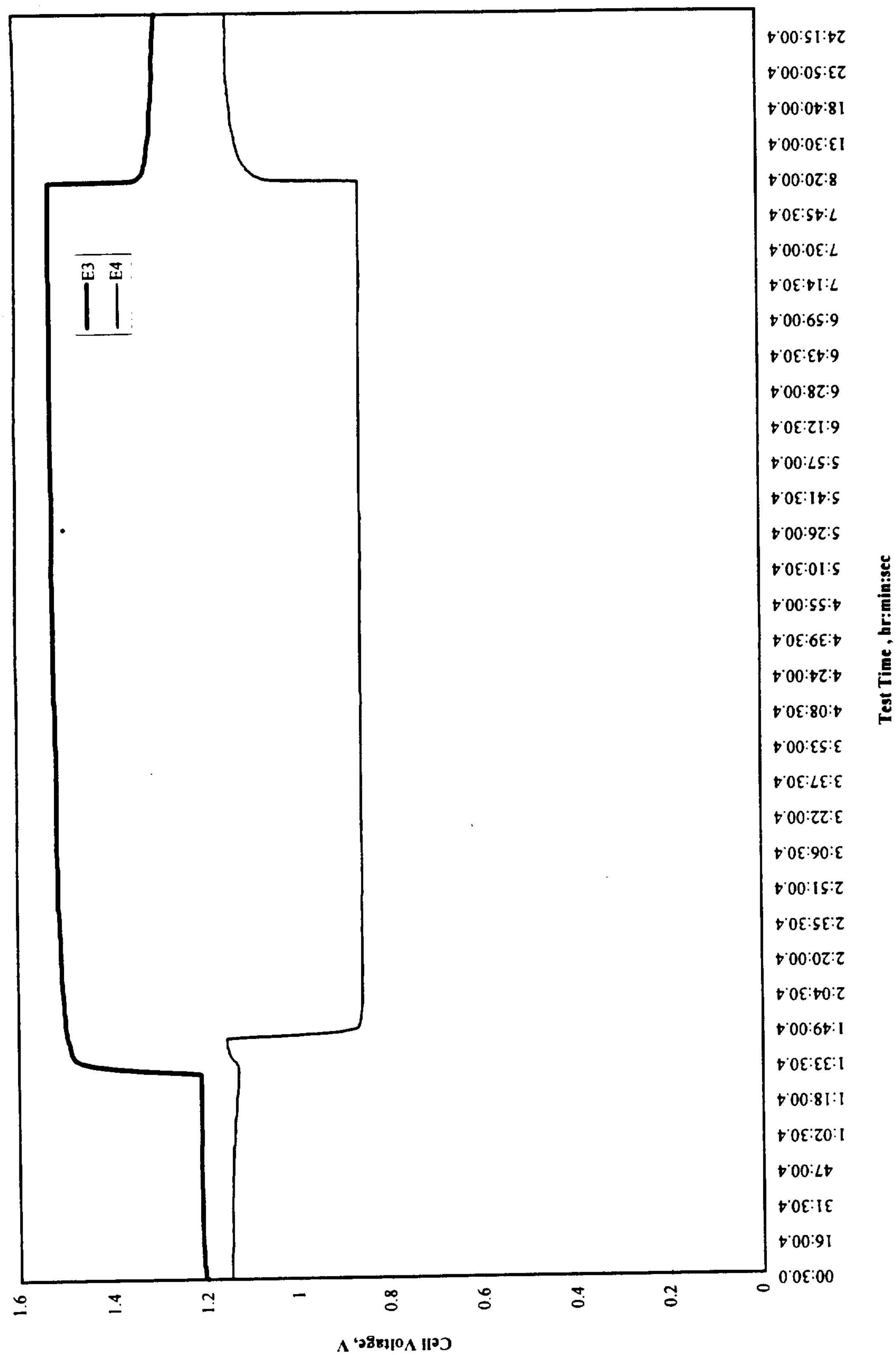


FIGURE 41 IEU2 CELL VOLTAGES VERSUS TIME

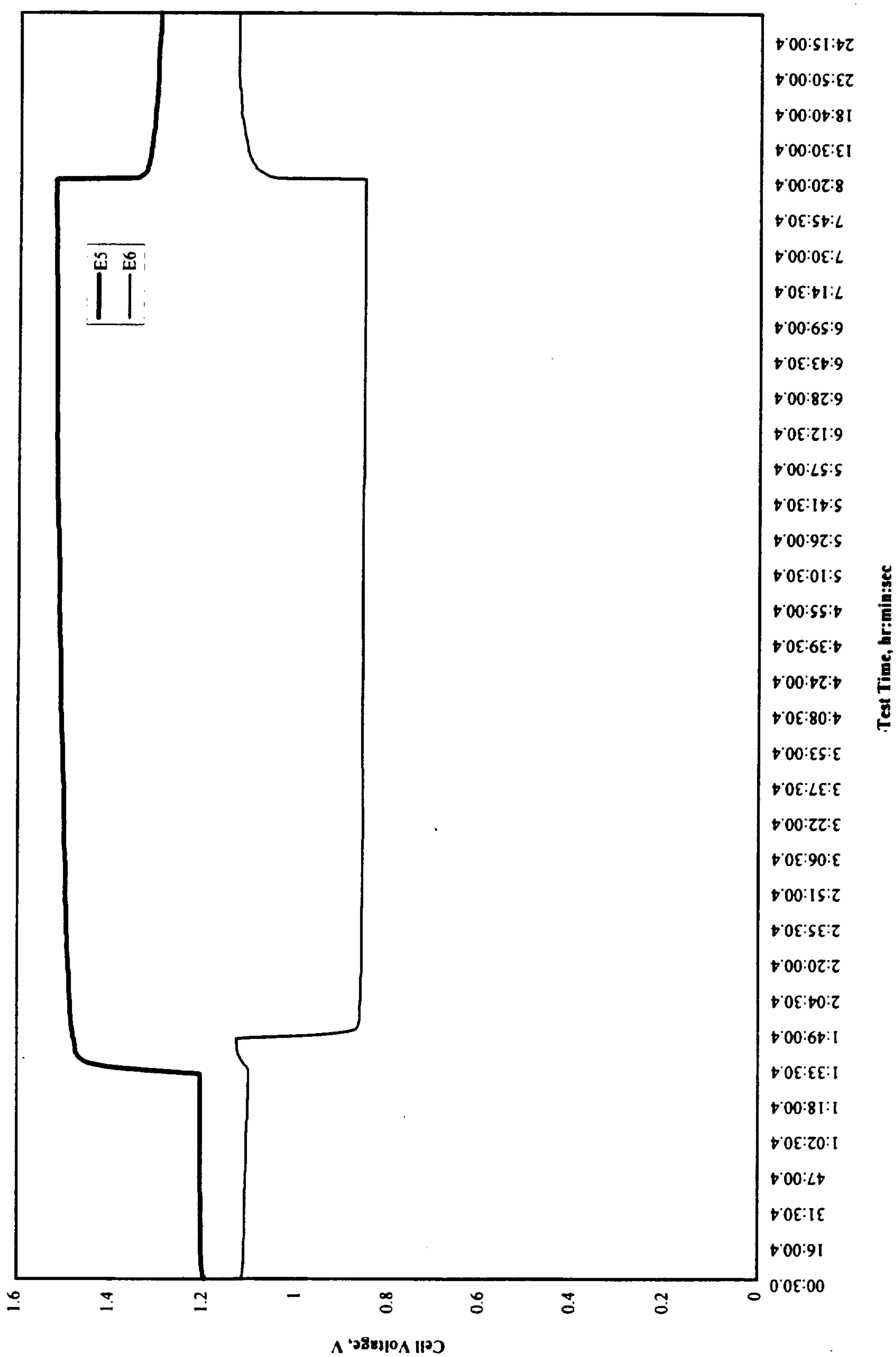


FIGURE 42 IEU3 CELL VOLTAGES VERSUS TIME

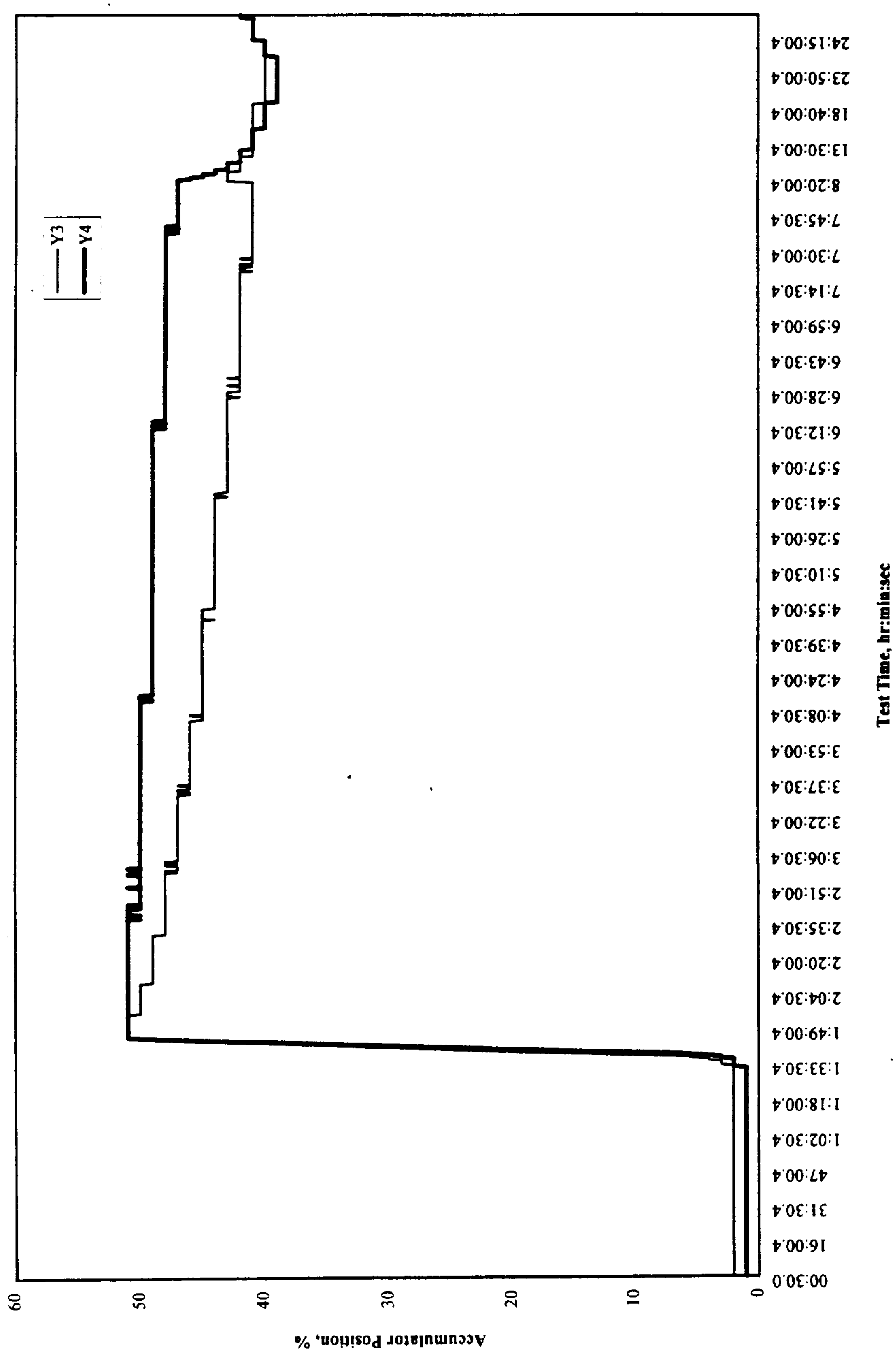


FIGURE 43 IEU2 ACCUMULATOR POSITIONS VERSUS TIME

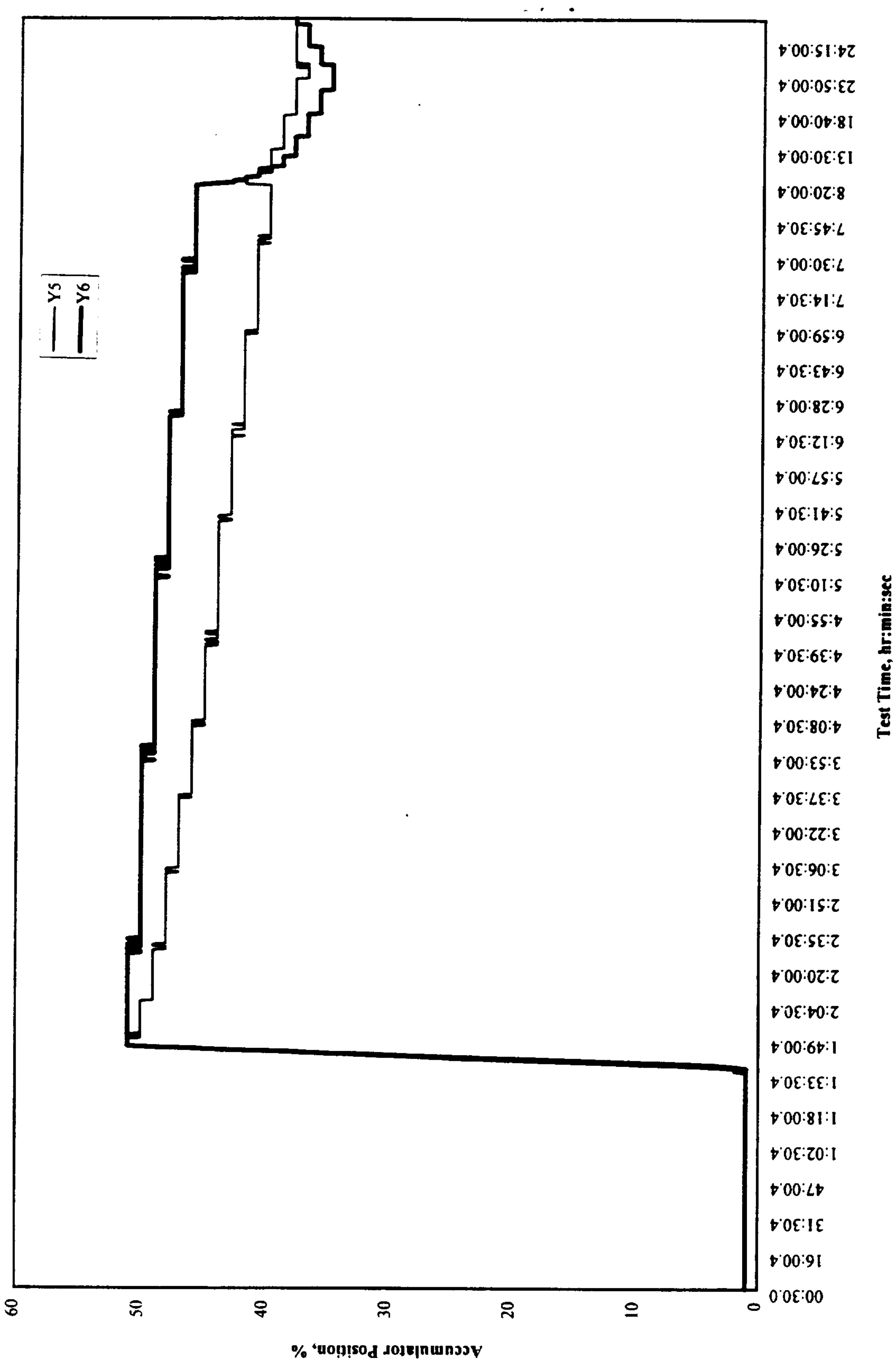


FIGURE 44 IEU3 ACCUMULATOR POSITIONS VERSUS TIME

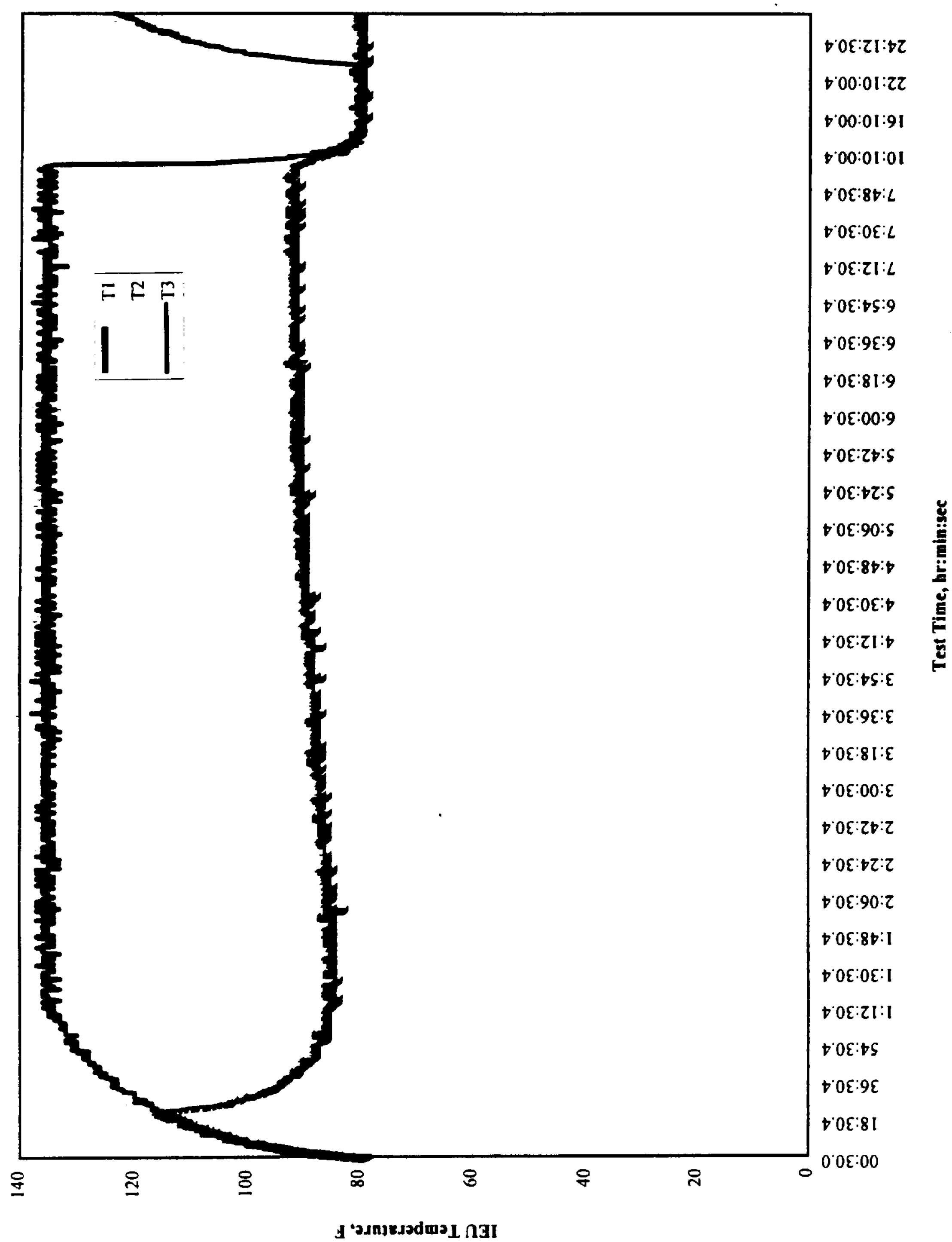


FIGURE 45 IEU TEMPERATURES VERSUS TIME

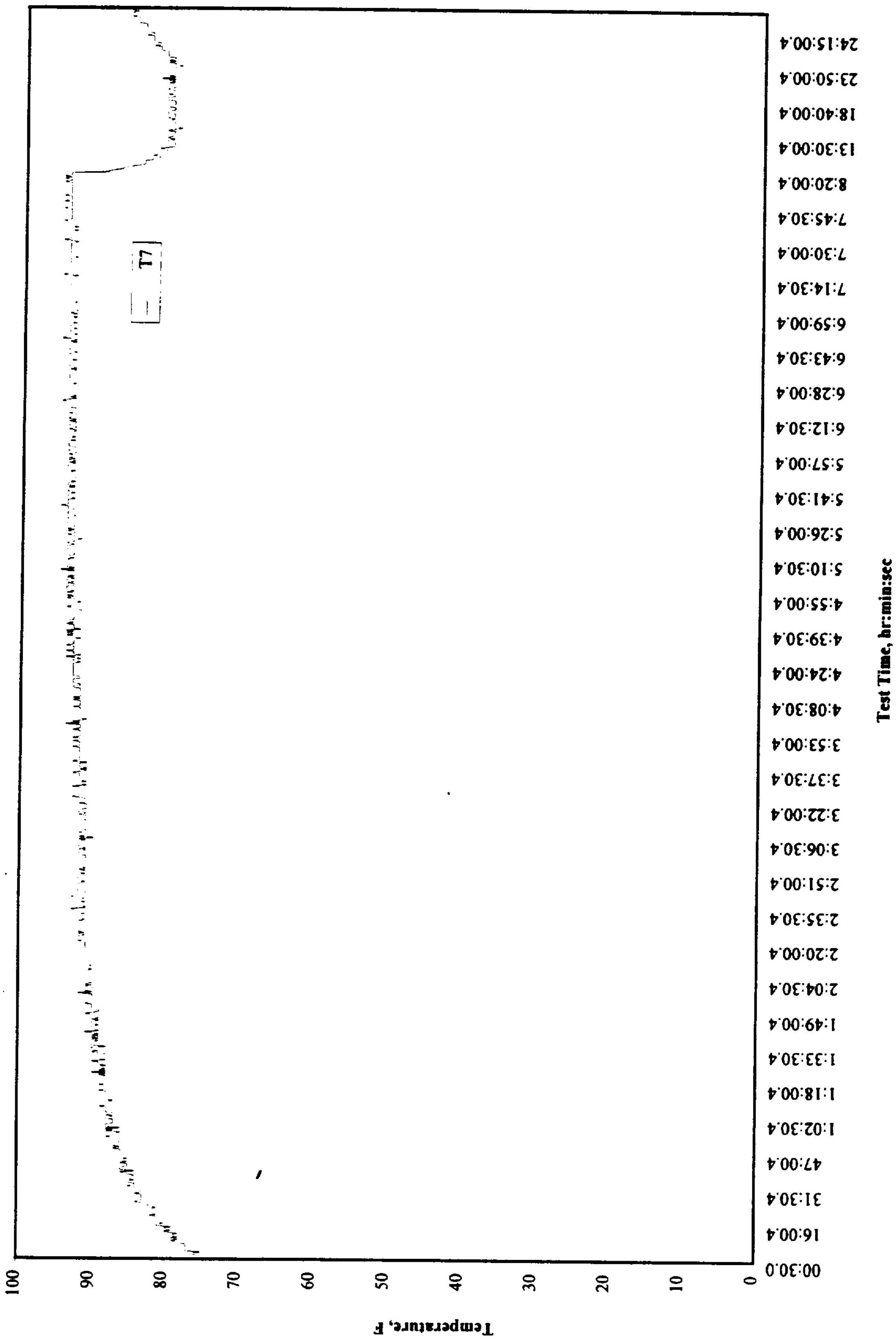


FIGURE 46 AIR OUTLET TEMPERATURE

3. Reevaluate 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 EPICS firmware.

5. Re-run acceptance test procedure and compare with all previous data.

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

7. Reevaluate the rationale and impacts of adding operational enhancements which allow for on-orbit diagnostics, data down-loading, and restart by the crew.

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

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

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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. 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.