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ENDURANCE TEST AND EVALUATION OF ALKALINE WATER ELECTROLYSIS CELLS

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SUMMARY

Space electrical power systems delivering high power levels at low cost will be needed in the future to support Shuttle-based habitation and the use of near-Earth space. The development of space utility power plant technology requires means to store energy. One storage technology is the Regenerative Fuel Cell System which consists of a fuel cell subsystem and a water electrolyzer. The Regenerative Fuel Cell System is a strong candidate for energy storage in space on the basis of projected launch weight, efficiency, system volume, adaptability to cyclic operation and the existence of a strong technology base on which to build.

The fuel cell portion of the Regenerative Fuel Cell System has been the primary electrical power source for all United States manned space programs except Mercury and has established itself as a proven reliable power source. As an initial step toward evaluating alkaline water electrolysis for the electrolyzer portion of the Regenerative Fuel Cell System, four single alkaline water electrolyzers were built and endurance tested for a total of 23,450 hours (5,862 hours/cell). Emphasis was placed on evaluating operational readiness of the concept and the maturity of the cell hardware by demonstrating the reliability and state-of-the-art power consumption levels of Life Systems' alkaline water electrolyzers.

Life Systems alkaline water electrolyzers use the static feed water electrolysis cell. The static feed of water to the alkaline electrolyzer was chosen as the best electrolyzer candidate for space power systems because it is very simple and has the greatest potential for low cost, weight, and volume as well as high reliability because it minimizes the electrolyzer components. The static feed concept is entirely passive, requiring no moving parts, and is self-regulating.

Each of the four single water electrolysis cells were designed to operate at 355 K (180 F) and 162 mA/cm^2 (150 ASF) with voltages of less than 1.5 V for cells with super anodes and voltages of less than 1.70 V for cells with "advanced" anodes. Four individual test stands used to test the cells were designed and fabricated to ensure accurate data and reliable fail-safe operation.

The endurance test program was completed and all four cells were successfully tested. All performance and testing goals were met or surpassed. A total of 23,450 cell-hours of endurance testing was logged for the four cells (an average of 5,862 hours/cell).

It is concluded from the results reported herein that the static feed water electrolysis concept is reliable and due to the inherent simplicity coupled with the use of alkaline electrolyte has greater potential for Regenerative Fuel Cell System applications than alternative electrolyzers. The cells performed as expected. One slight anomaly was observed. A rise in cell voltage occurred after 2,000-3,000 hours of endurance testing which continued until the end of endurance testing. This change in performance was attributed to deflection of the polysulfone end plates due to creepage of the thermoplastic. At the end of endurance testing, more end plate support was added, and the performance of the cells was restored to the initial average cell voltages of 1.49 V and 1.58 V at 162 mA/cm^2 (150 ASF) and 355 K (180 F) for cells using

super and advanced anodes, respectively. Continued evaluation and development of static feed water electrolysis technology is recommended in the areas of high pressure operation, cyclic testing and scaled-up cell operation to evaluate the cell operation and enhance its performance level.

LIST OF PROGRAM ACCOMPLISHMENTS

Under Contract NAS3-21274 the following major accomplishments were achieved in the technological development of alkaline water electrolysis cells for space power application.

- o Designed and fabricated four single water electrolysis cells, two using LSI's advanced anodes and two using LSI's super anodes.

- o Designed and fabricated four single cell endurance test stands for life testing of alkaline water electrolyte cells

- o Demonstrated the solid performance of the advanced electrode, LSI's baseline water electrolysis electrode since 1974. LSI's continuing advancements in electrode fabrication have been demonstrated by further improvements in this electrode's performance.

- o Demonstrated the breakthrough performance of the super electrode. (Voltages of 1.50 V or less at 162 mA/cm^2 (150 ASF) and 355 K (180 F)).

- o Endurance tested the four single cells for over 5,000 hours each (combined total of 23,450 cell-hours) without significant cell deterioration or cell failure.

INTRODUCTION

The work performed under the program is part of a National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC) effort being conducted to advance the technology to a state of readiness so that it could be utilized in the development of multi-kW low orbit power systems. A basic premise is that all the power generated by the system will be derived from solar energy utilizing the latest in solar array technology. This, then, identifies the need of an energy storage system to supply the load demand during the dark side of orbit. A "regenerative" fuel cell electrolyzer system which consists of water electrolysis, reactant storage, water storage and a fuel cell subsystem is a strong candidate for this application on the basis of projected launch weight, efficiency, system volume, adaptability to cyclic operation and the existence of a strong technology base on which to build.

Only two types of water electrolysis systems exist which are oriented to a spacecraft environment. One utilizes an alkaline electrolyte, the other an acid. The current program is directed at the alkaline cell because it offers inherently lower system cost, less complexity, higher efficiency and higher reliability.

At present, the alkaline electrolyzer data base for space power application must be expanded to support the requirements of high reliability and long endurance operation which is a primary need for a low earth orbit power system.

This program is aimed at generating this data base and thus provide information needed to assess the competitiveness of the alkaline electrolyzer technology and its adaptability to a multi-kW power plant.

Background

Prior development efforts of water electrolysis cells, modules, and subsystems have included those that use the static water feed concept.[1-4] Subsystems using this concept have demonstrated an inherent simplicity and long operating life potential.[3,5] Electrical energy storage, using Static Feed Water Electrolysis (SFWE), has the potential for the lowest power-consuming electrolysis subsystem due to the alkaline electrolyte used.[1,6] Various approaches to the static feed design and the results of extensive test programs identified necessary key subsystem improvements.[2] These improvements were made and incorporated into the design of the hardware being developed by Life Systems, Inc. (LSI).[7]

In 1977 a significant reduction in state-of-the-art cell voltage levels was achieved with a Life Systems-developed catalyst for the O_2-evolving electrode (anode). This Contractor-developed electrode was endurance tested and a total of 136 days of single cell operation were accumulated on this electrode. The cell voltage averaged 1.45 V at 162 mA/cm^2 (150 ASF) and 355 K (150 F).[4] This endurance testing has been continued under a Life Systems funded program demonstrating a cell voltage of 1.49 V after 18,000 hours of operation (at the above conditions). This version of the anode has been termed "super anode" or "super electrode" as opposed to Life Systems baseline anode which is referred to as the "advanced anode" or "advanced electrode."

Program Objectives

The overall objective of this program is to assess the current state of alkaline water electrolysis technology and its potential as part of a regenerative fuel cell system of a multi-kW orbiting power plant. The first phase of this effort addresses the evaluation of the endurance capabilities of alkaline electrolyte water electrolysis cells. The objective of the Single Water Electrolysis Cell (SWEC) part of the overall technology program is to demonstrate the operational readiness of the concept and cell hardware by performing endurance and parametric tests at the cell level. This was done by successfully meeting the following objectives:

a. Fabricate and assemble four of the contractor's alkaline SWECs for testing.

b. Design and fabricate four SWEC test stands to provide the testing capability.

c. Endurance test four alkaline SWECs with a milestone of 5,000 or more hours per cell as a goal.

(1-4) References cited at end of report.

d. Periodically characterize the cell's performance with voltage versus current density data.

e. Demonstrate a very simple, low cost approach to electrolytic hydrogen (H_2) and oxygen (O_2) production with a static feed water electrolysis approach which

- o has a lower capital cost potential than other designs
- o has a high reliabilty, longer life potential than other designs at the same energy consumption levels
- o has both advanced and super electrodes characterized by cell voltages in the range of 1.7 and 1.5 V, respectively.

Program Organization

To meet the above objectives, the program was divided into the following six tasks. These six tasks were:

1.0 Design, fabricate and assemble four SWECs. Two cells with "advanced" electrodes and two cells with "super" electrodes for endurance testing, to demonstrate the operational readiness of the static feed concept and cell hardware for regenerative fuel cell systems.

2.0 Design, fabricate, assemble and checkout four Test Stands required to control and monitor the SWECs.

3.0 Provide a minimum level Product Assurance support with respect to receipt and inspection of all purchased parts, test stand instrumentation calibration and those safety aspects necessary for protection of personnel and equipment.

4.0 Perform testing of the SWECs to verify acceptable operation. The testing task will consist of checkout, shakedown, design verification tests and an endurance test of 5,000 hours minimum per cell, as a goal.

5.0 Incorporate the Contractor's data management functions to provide internal procedures for control of the collection, preparation, quality, assessment, distribution and maintenance of data.

6.0 Incorporate the management needed to successfully meet the program's Cost, Schedule and Technical Performance requirements and coordinate with the LeRC Technical Monitor and Contract Administrator through periodic telephone discussions.

PROCESS AND HARDWARE DESCRIPTION

Four SWECs were built and tested. The SWEC and SWEC Test Stand design requirements are listed in Table 1 while Table 2 lists the design specifications and ranges of the SWEC.

TABLE 1 SWEC DESIGN REQUIREMENTS

Independent Testing Operation of Each SWEC

Alkaline Electrolyte Held in a Porous Matrix

Static-Feed Water Addition

Fail-Safe and Automatic Operation

Ease of Maintenance Using Replaceable Components

Cell Design Life of >5 Years

Test Stand Design Life of 5 Years

Shelf Life Unlimited

TABLE 2 SWEC DESIGN SPECIFICATION

H_2 Generation Rate, sccm	56 to 224[a]	
O_2 Generation Rate, sccm	28 to 112	
Operating Pressure Range, kPa (psia)	101 to 115 (14.7 to 16.7)	
Operating Temperature Range, K (F)	294 to 366 (70 to 200)	
Pressure Differentials, kPa (psid)		
O_2 to H_2 (max.)	13.8 (2.0)	
H_2 to H_2O (max.)	13.8 (2.0)	
Performance (±0.005)[b], V	Super	Advanced
At 108 mA/cm^2 (100 ASF)	1.44	1.54
At 162 mA/cm^2 (150 ASF)	1.48	1.58
At 324 mA/cm^2 (300 ASF)	1.56	1.70
Water Supply		
Pressure	Ambient	
Temperature, K (F)	277 to 300 (40 to 80)	
Coolant		
Fluid	Water	
Pressure, kPa (psia)	$\leq$207 (30)	
Temperature, K (F)	$\leq$358 (185)	
Water Feed Mechanism	Static	
Active Cell Area, m^2 (ft^2)	0.0093 (0.1)	
Electrical Power, V		
DC	0 to 10	
AC	115 (60 Hz, 1 Phase)	
Packaging	Single Cell w/Test Stand	
Duty Cycle	Continuous	

(a) Off- and out-of-design specification will be included to allow initial characterization of next level technology.
(b) Initial performance at 358 K (185 F).

Static Feed Water Electrolysis Concept

The static water feed, alkaline electrolyzer is an attractive candidate for space power systems due to its inherent simplicity and potential for low cost and reliability. The static feed approach minimizes Water Electrolysis System (WES) components, is entirely passive, requires no moving parts and is self-regulating based upon the demands of the electrolyzer.

Figure 1 is a conceptual schematic of a cell designed for the Static Feed Water Electrolysis (SFWE) Module (SFWEM) concept. The overall static water feed concept operates as follows. Initially, the water feed cavity, the water feed matrix and the cell matrix contain an aqueous solution of potassium hydroxide (KOH) electrolyte at equal concentrations. Both the H_2 and O_2 cavities are void of liquid. An equilibrium condition exists prior to start of electrolysis. When power is applied to the electrodes, water from the cell electrolyte is electrolyzed. As a result, the concentration of the cell electrolyte increases and, therefore, its water vapor pressure decreases to a level below that of the feed compartment electrolyte. This water vapor pressure differential is a driving force causing water vapor to diffuse from the liquid gas interface within the water feed matrix, through the H_2 cavity and cathode electrode into the cell electrolyte. This process establishes a steady-state condition based on the water requirements for electrolysis (current density) and humidification of the product gases and continues as long as electrical power is applied to the cell electrodes.

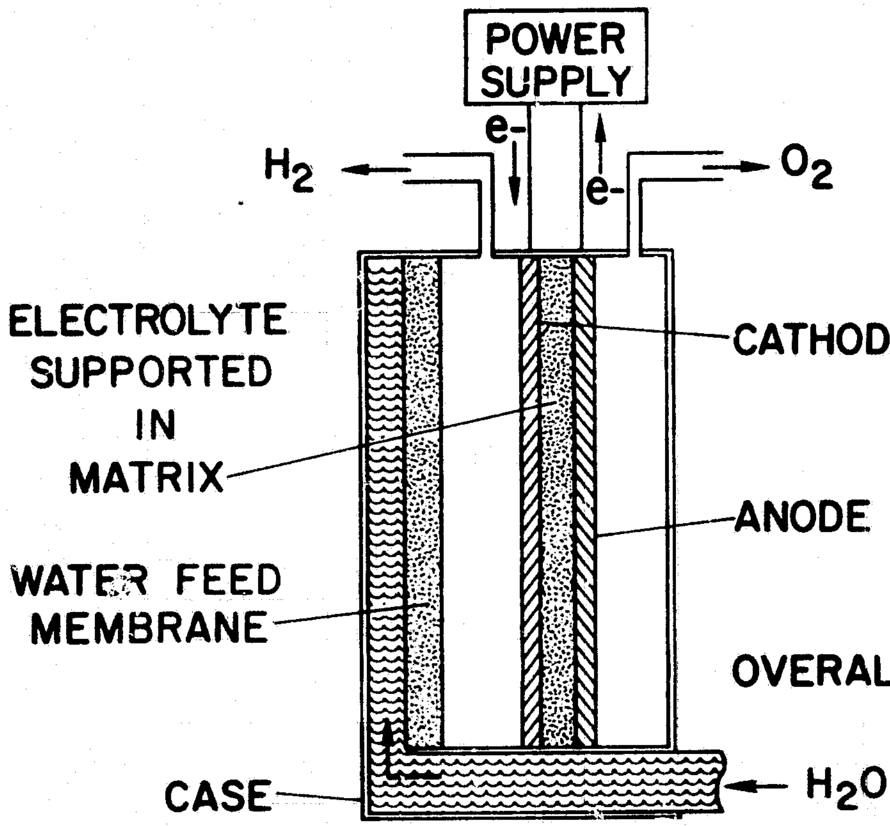
As water diffuses from the feed matrix and is removed from the water feed compartment, it is statically replenished from an external source to maintain a constant pressure, volume and electrolyte concentration within the feed compartment. Upon interruption of electrical power, water vapor will continue to diffuse across the H_2 compartment until the electrolyte concentration in the cell matrix is equal to that of the water feed matrix and compartment. At this point, the original equilibrium condition is regained with the electrolyte retained in the cell matrix and electrodes and equal to the initial charge volume and concentration.

Figure 2 illustrates a conceptual schematic of an alkaline electrolyzer based on the SFWE concept. The subsystem consists of only three main parts: an electrochemical module, a water feed tank and a pressure controller.

SWEC Mechanical Design

A functional schematic of the SWEC cell showing the four compartment cell is illustrated in Figure 3. The four compartments are (1) the O_2 cavity, (2) the H_2 cavity, (3) the water feed cavity, and (4) the liquid coolant cavity. Intercavity sealing is achieved by O-rings and by squeezing the cell and water feed matrices between the polysulfone frame components, forming the O_2, H_2 and water feed cavities. The coolant cavity is formed by the cell frame and the cell end plate. Figure 4 illustrates the SWEC in cross-section. Electrical current passes from the anode current collector, through the cell, into the cathode current collector and into the current studs by means of current collector connection screws.

WATER ELECTROLYSIS CELL SCHEMATIC AND REACTIONS



REACTIONS

CATHODE (-) $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$

ANODE (+) $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

OVERALL $2H_2O + \text{POWER} \rightarrow 2H_2 + O_2$

FIGURE 1 WATER ELECTROLYSIS CELL SCHEMATIC AND REACTIONS

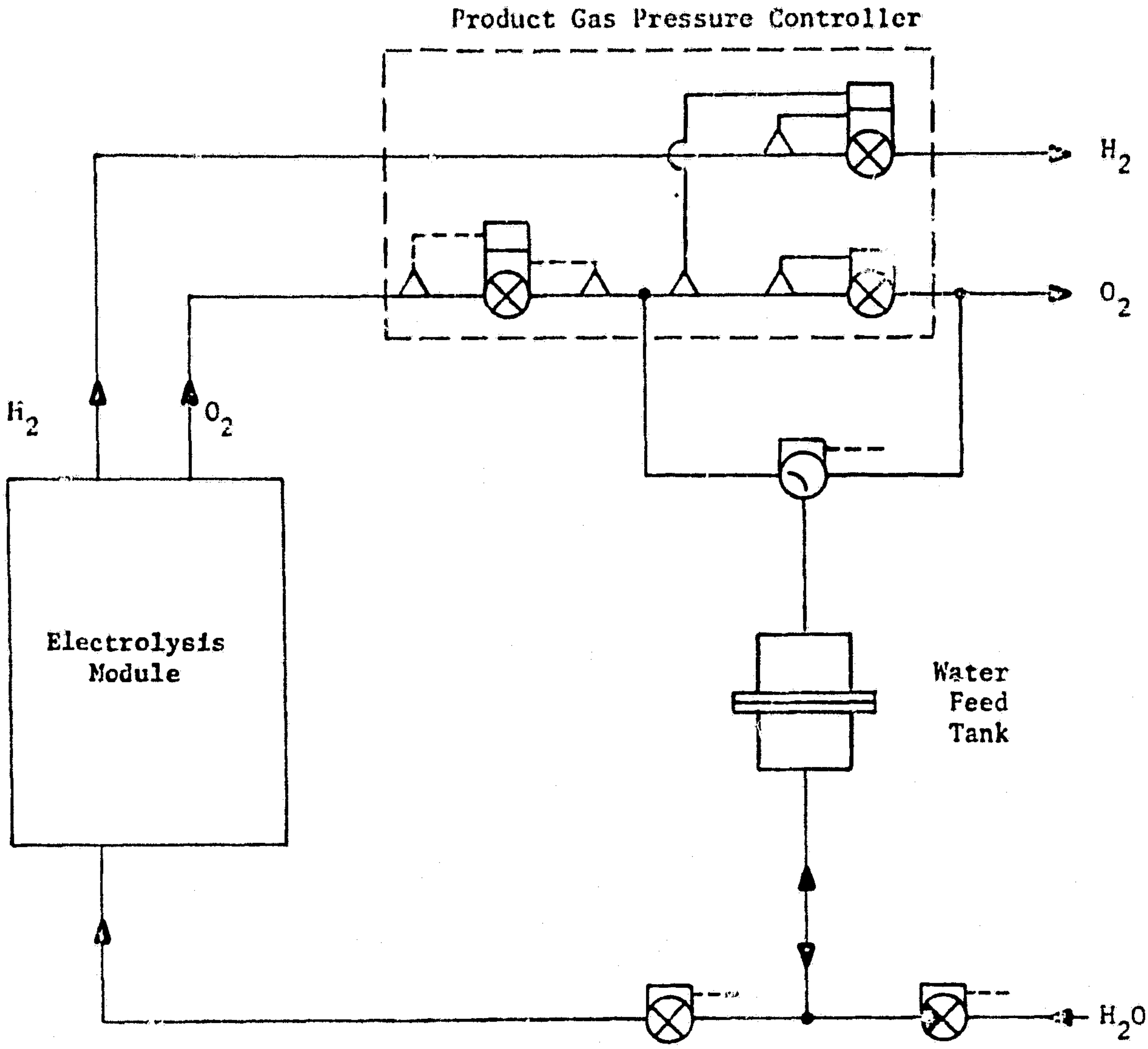


FIGURE 2 STATIC FEED WATER ELECTROLYSIS CONCEPT

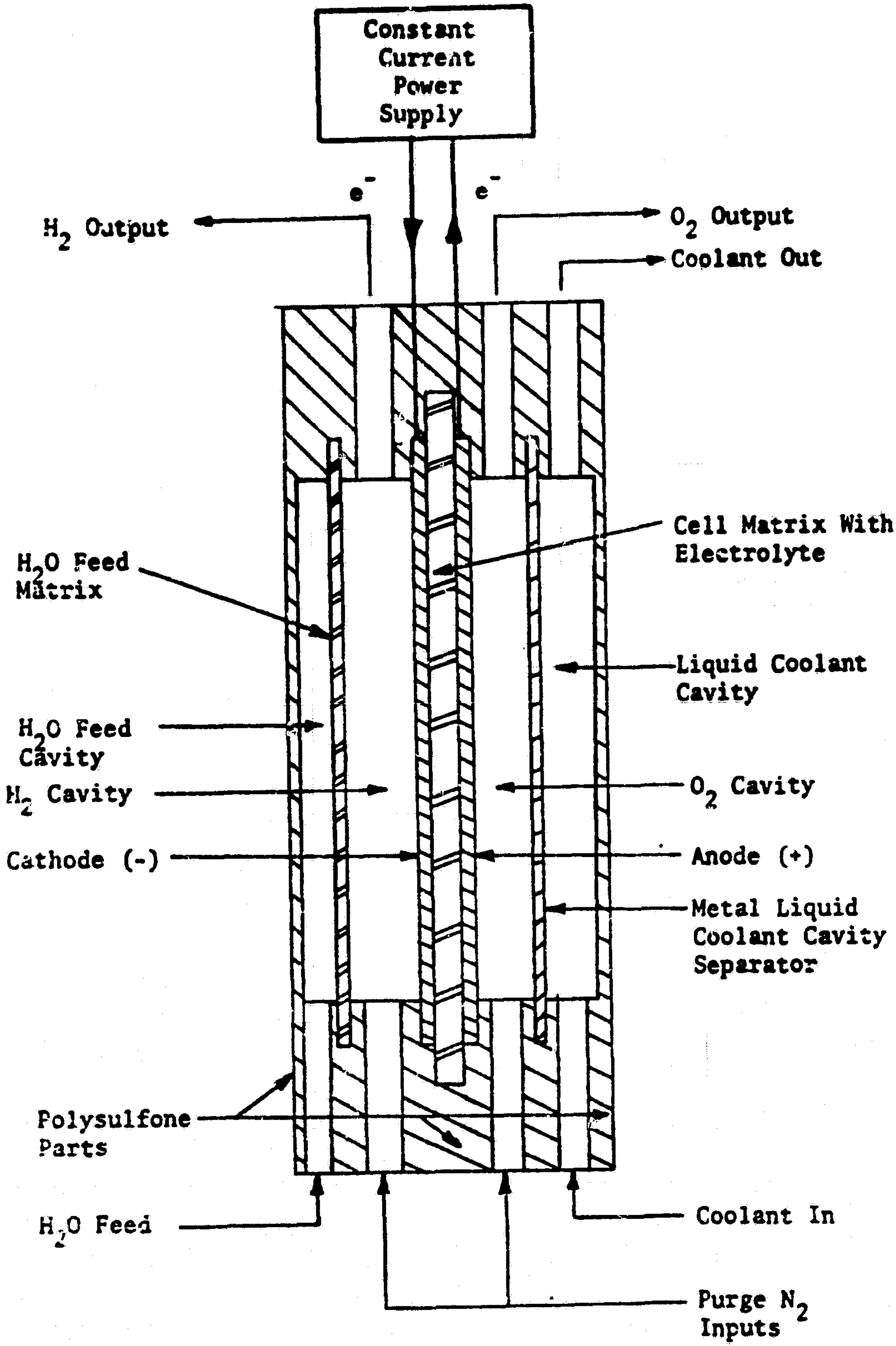


FIGURE 3 FUNCTIONAL SCHEMATIC SFWEM CELL

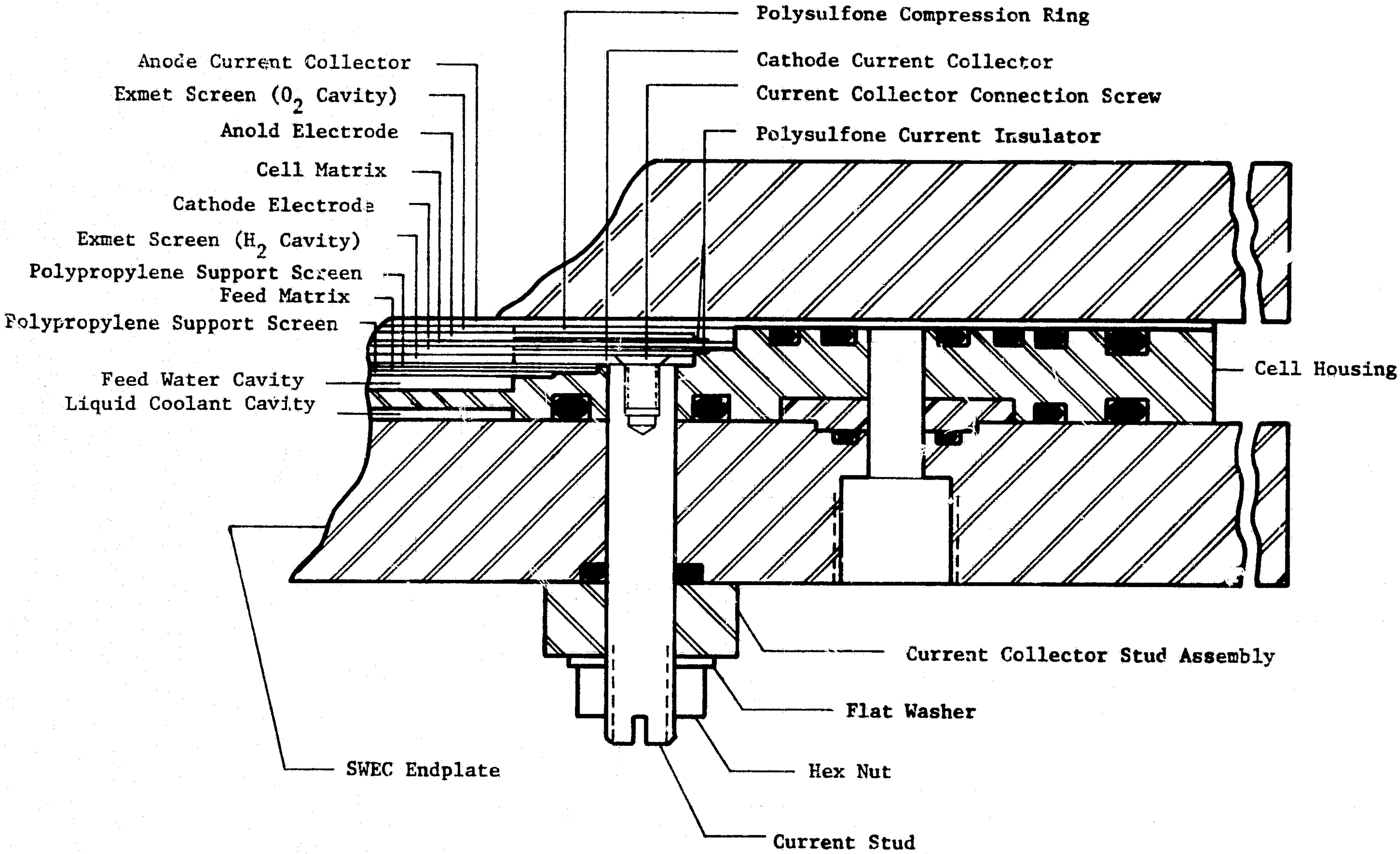


FIGURE 4 SWEC CROSS SECTION

Figure 5 displays the components of a single cell and the fully assembled SWEC. These components plus the SWEC end plates and compression bolts comprise the SWEC. Table 3 lists the cell components and their materials of construction. The materials were selected based upon their compatibility with long-term alkaline electrolyzer operation and low cost, both requirements of alkaline electrolyzer-based, regenerative fuel cell power systems. Figure 6 displays the four fully assembled SWECs prior to installation on the test stands.

SWEC Test Stand Design

Figures 7, 8, 9 and 10 show the mechanical schematic, front panel of the SWEC Test Stand, a single test stand assembly and all four test stands, respectively. A test stand assembly drawing is given in Appendix 1. Basically, the test stand has two liquid circulation loops; one loop for the liquid coolant that maintains the cell operating temperature, and a second loop for delivering feed water from the water feed tank to the cell. The latter is only used for single cell testing and is not required at the system level.

A significant amount of water vapor is removed with the product gases when operating at both ambient pressure and high temperature. To remove water that has condensed in the product gas lines, the product gases of the cell are fed through condensate traps (TR1 and TR2) and then through water backpressure regulators (PR1 and PR2) (see Figure 7 for component identification/location).

The liquid coolant used on the SWEC test stand is water. The coolant is circulated by M2 through the SWEC. Manual valves and a flowmeter are included to control the coolant flow. A water tank is used to allow for coolant expansion and coolant temperature control.

Due to the low pressure operation of the cell, feed water is not added to the SWEC directly, but rather statically fed to an external feed water circulation loop. This allows for separation of dissolved gases which are carried into the cell by the feed water and which come out of solution at the higher temperature and KOH salt. At end item application pressures these gases do not come out of solution. The M1 circulates the feed water through the SWEC. A manual valve and flowmeter are included to control the feed water flow. Feed water is statically fed to the water accumulator WA1, from the water feed tank WT1, as feed water is consumed in the electrolysis process. The negative pressure this creates in the feed water loop maintains the gas/liquid separation within the SWEC.

Table 4 lists the baseline operating conditions of the test stand during the endurance testing.

Electrical Design

The SWEC test stands were designed for simple, fail-safe operation. Figure 11 illustrates the operating modes and allowable mode transitions. Table 5 defines each of these operating modes and the conditions under which each mode is called. Appendices 2 and 3 further define the steady-state actuator conditions and the intermode transition sequences for the test stand.

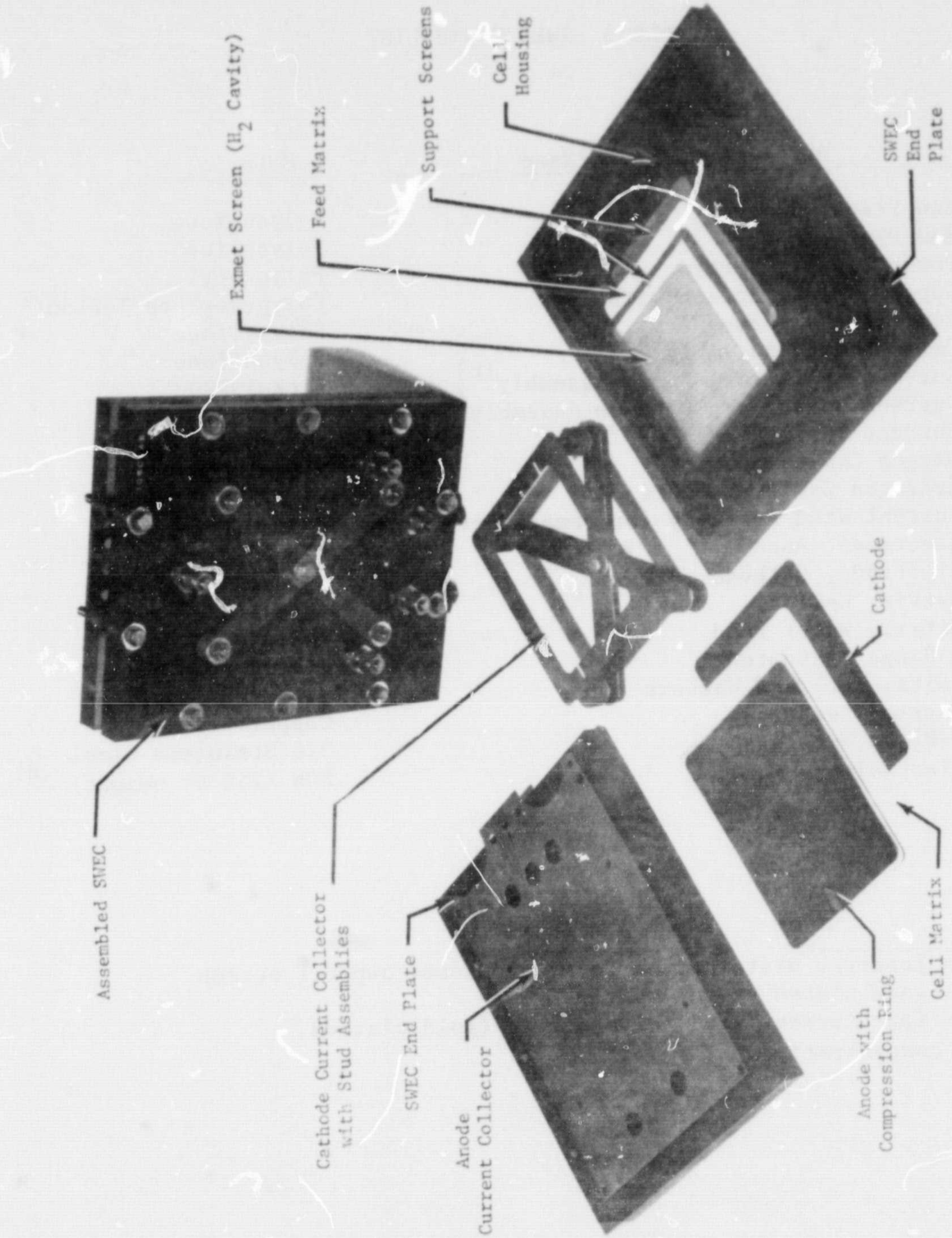


FIGURE 2-1 CELL COMPONENTS AND ASSEMBLED SWEC

TABLE 3 SWEC PARTS LIST

Description/Title/Name	Material
End Plate, Upper	Polysulfone
End Plate, Lower	Polysulfone
Lower Support Screen	Polypropylene
Upper Support Screen with Tape	Polypropylene/Teflon
Compression Frame	Polysulfone
Cell Housing Assembly[(a)]	Polysulfone
Current Collector, Anode Assembly[(b)]	Nickel 200
Current Collector, Cathode Assembly[(c)]	Nickel 200
Current Insulator	Polysulfone
Oxygen Cavity Spacers	Nickel 200
Hydrogen Cavity Sapcers	Nickel 200
Current Stud Assembly (or remain. pcs.)	Polysulfone
Electrode, Anode	Porous Media
Electrode, Cathode	Porous Media
Matrix, Cell	Asbestos
Matrix, Water Feed	Asbestos
O-Rings, Assorted	Ethylene Prop.
Bolts, Nuts and Washers	316 Stainless Steel
Current Leads	Copper
O-Rings Fittings	316 Stainless Steel
Electrolyte	KOH (25% by weight)[(d)]

(a) Includes inserts, distribution cover and lower support screen.
(b) Includes gold plated oxygen spacer.
(c) Includes four current studs with screws (gold plated).
(d) Initial concentration.

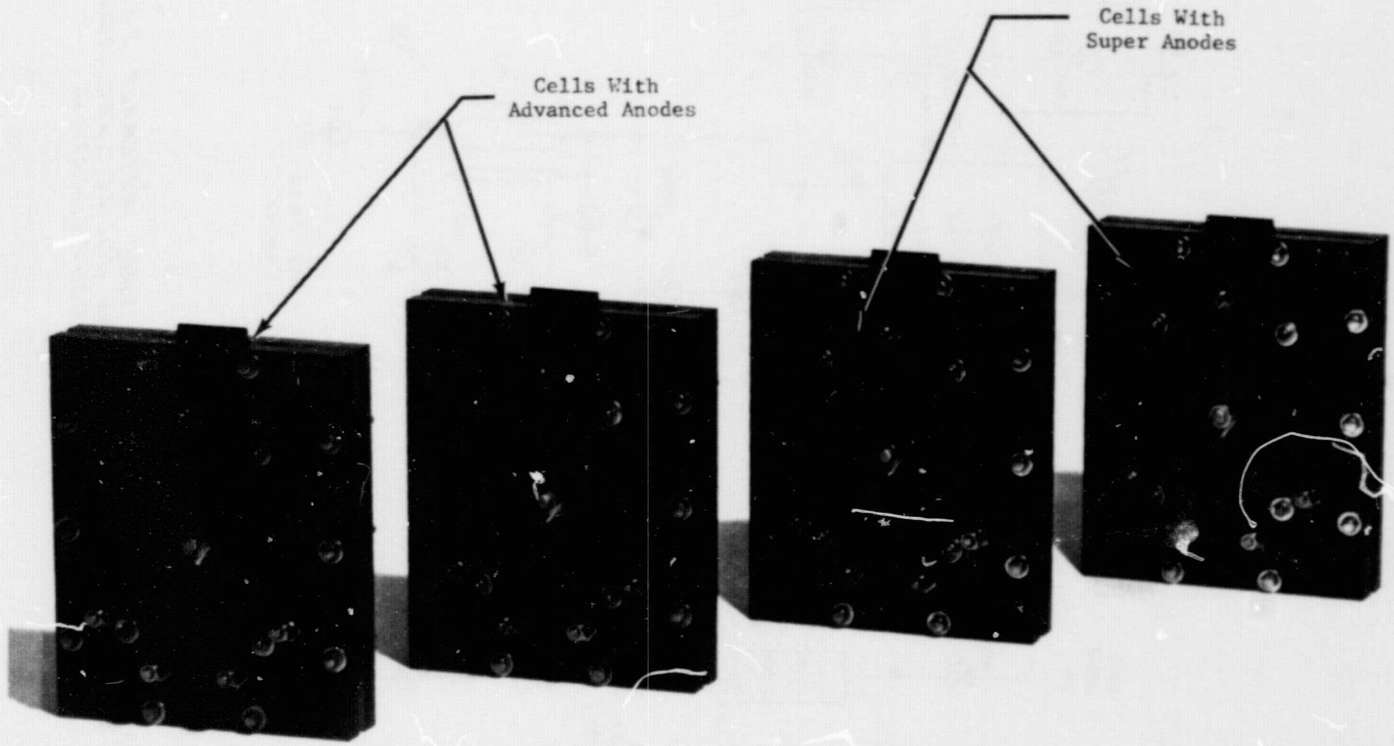
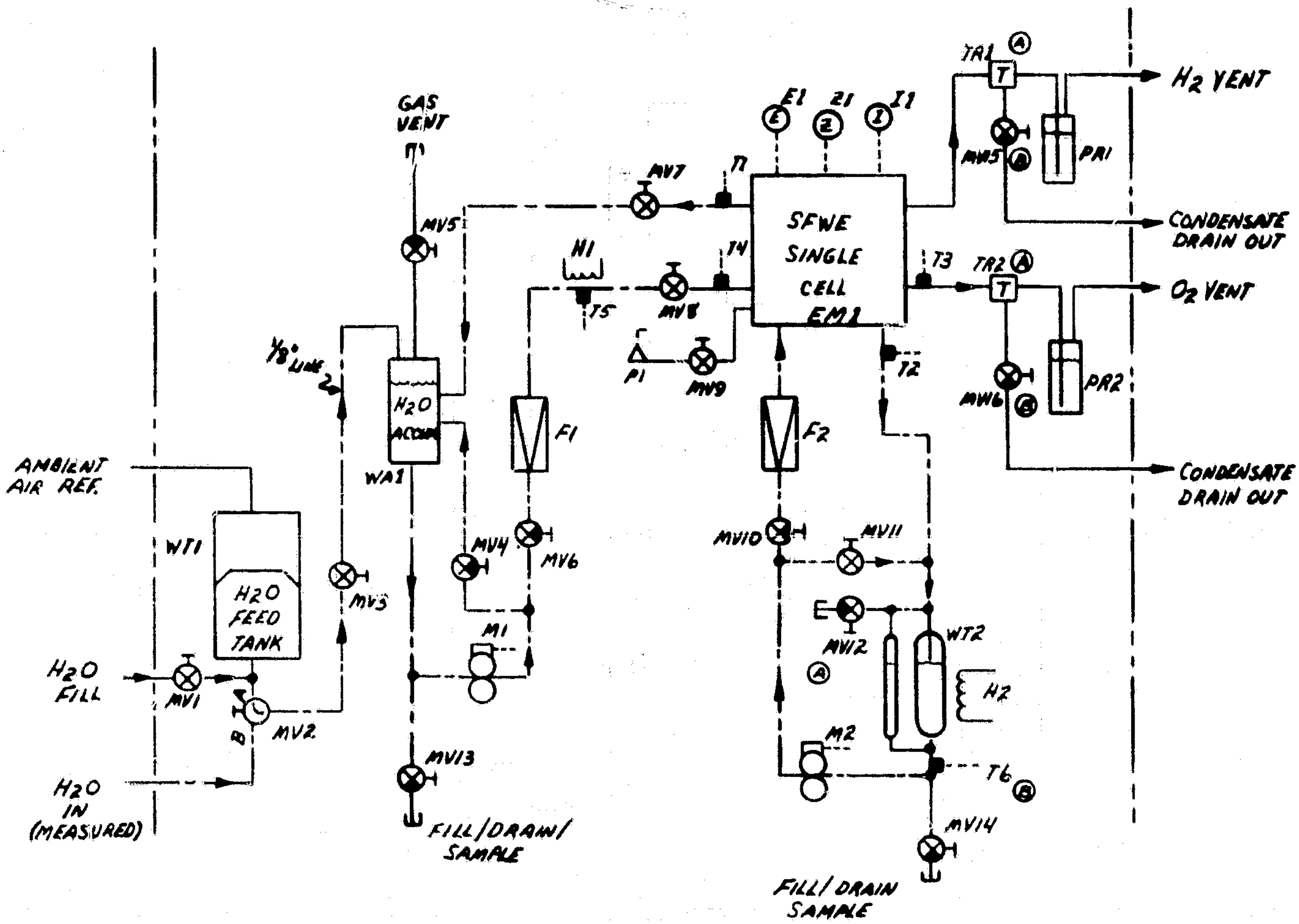


FIGURE 6 FOUR ASSEMBLED SWECs



NOTE:
1) ALL LINES 1/4" O.D. STAINLESS (316) UNLESS NOTED.

2) TEST STAND 105 UTILIZES SWEC ASSEMBLY J-2559; TEST STANDS 106 & 108 CAN UTILIZE SWEC ASSEMBLY J-2229 OR OTHER SWEC CONFIGURATION.

FIGURE 7 MECHANICAL SCHEMATIC OF SWEC TEST STAND

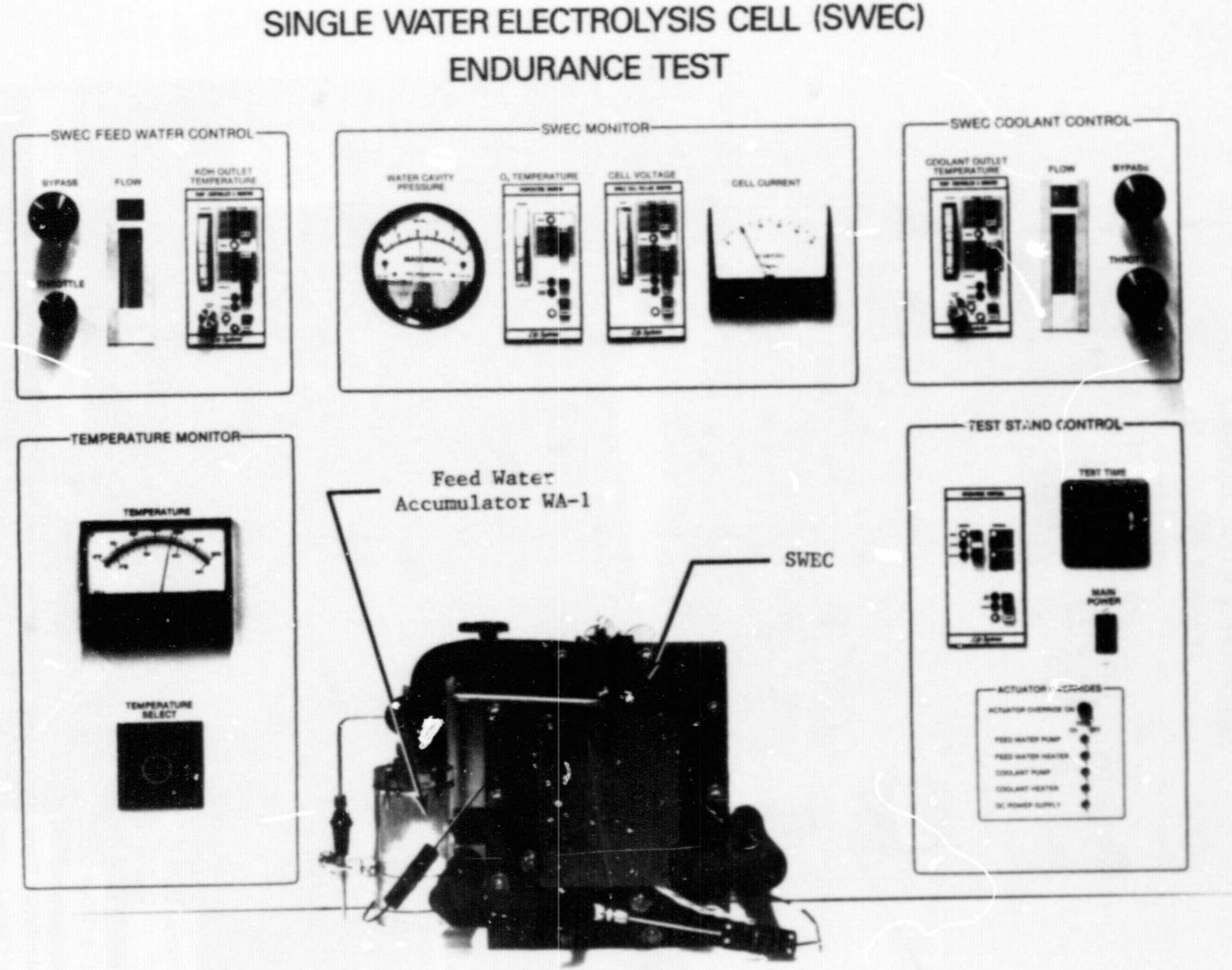


FIGURE 8 SWEC TEST STAND FRONT PANEL

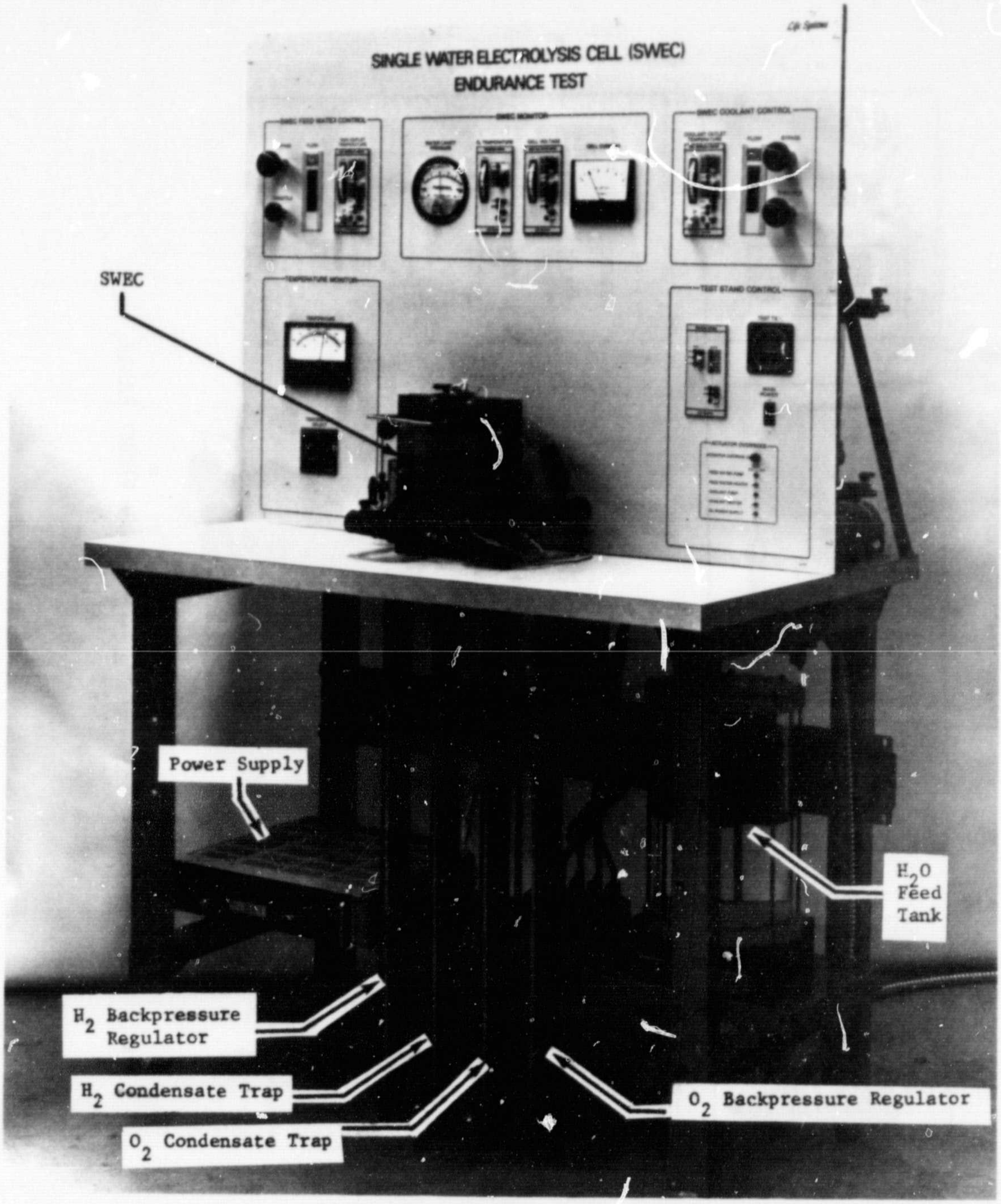


FIGURE 9 SWEC TEST STAND

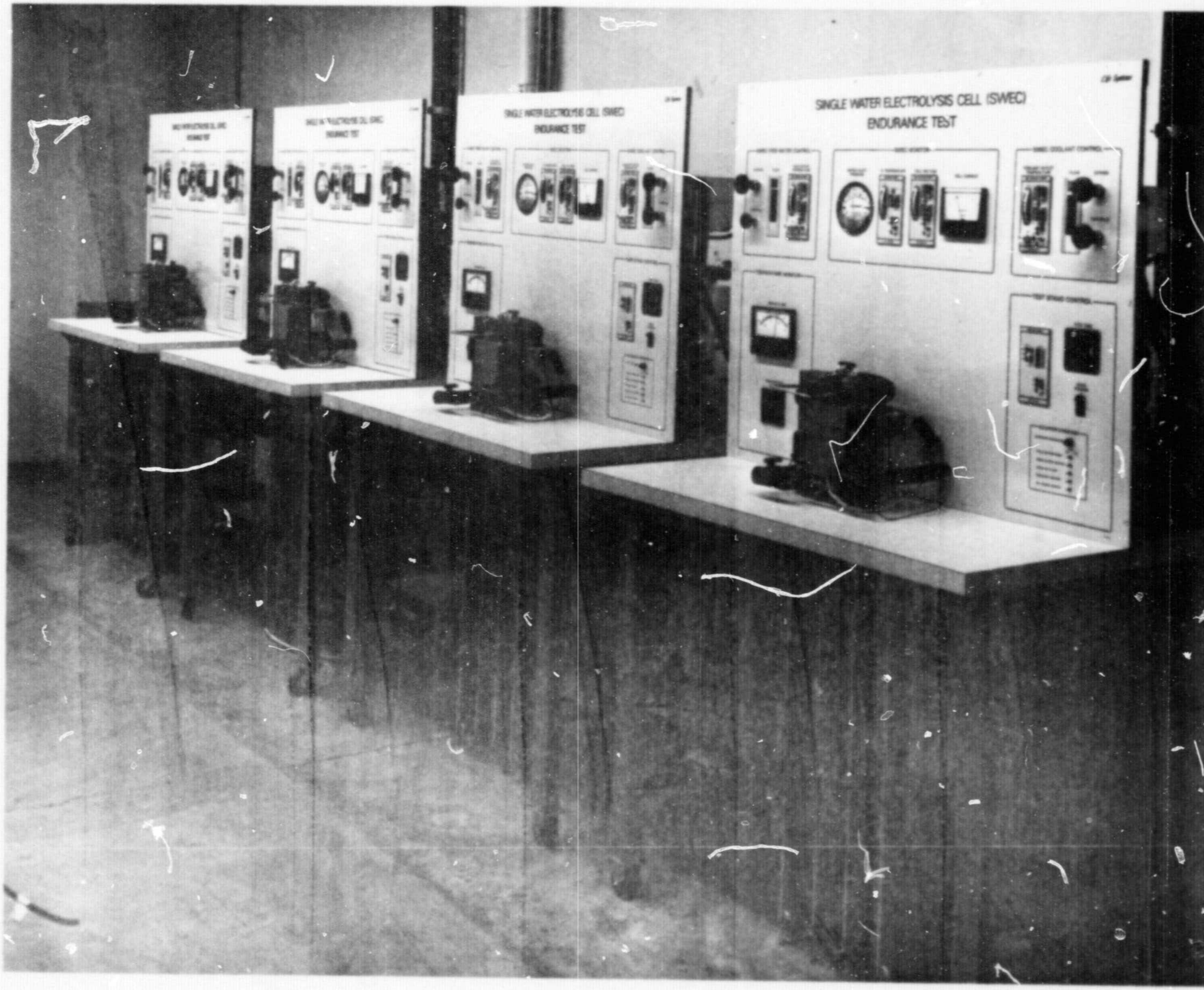
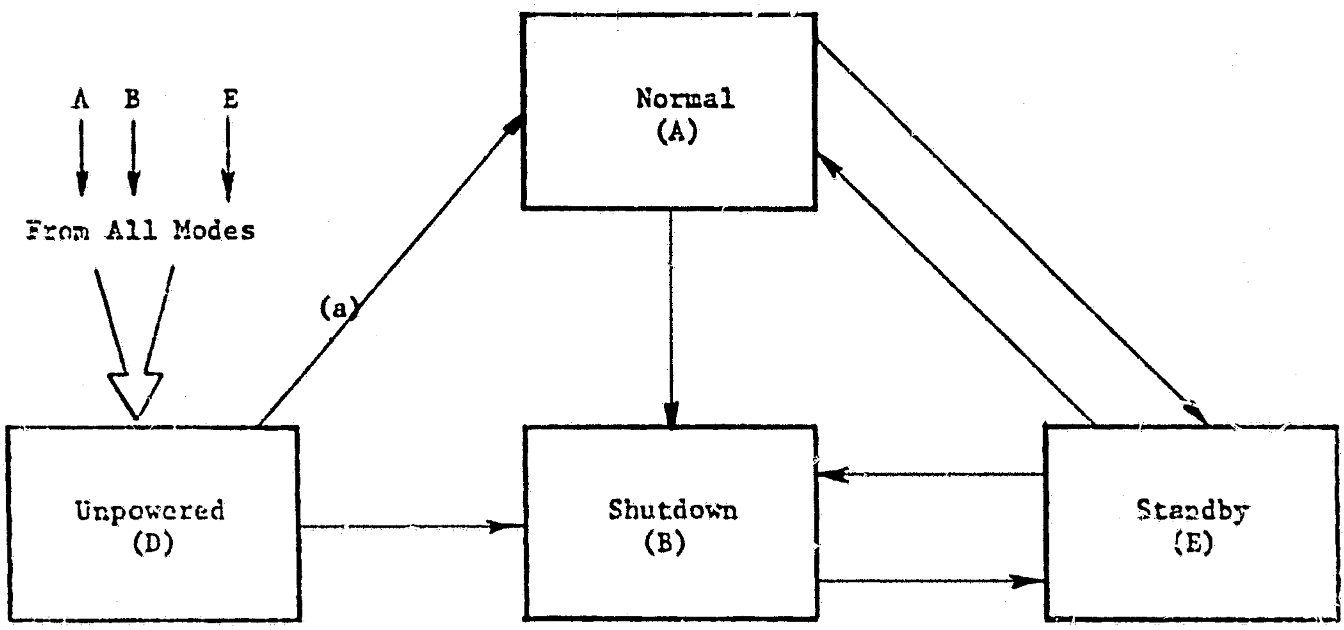


FIGURE 2-2 FOUR SWEC TEST STANDS

TABLE 4 SWEC TEST STAND BASELINE OPERATING CONDITIONS

Product Gases	
Oxygen	
Flow, cm^3/min[a]	56.7
Temperature, K (F)	294 (70)
Pressure, kPa (in H_2O)	7.5 (30)
Hydrogen	
Flow, cm^3/min[a]	113.4
Temperature, K (F)	294 (70)
Pressure, kPa (in H_2O)	3.8 (15)
Test Stand Fluids	
KOH (25%)	
Flow, cm^3/min	35
Temperature, K (F)	355 (180)
Pressure, kPa (psia)	94.5 to 97.9 (13.7 to 14.2)
Coolant	
Flow, cm^3/min	300
Temperature, K (F)	355 (180)
Pressure, kPa (psia)	101 to 205 (14.7 to 29.7)
Current, A	15

(a) Flow is the dry volumetric rate at 294 K (70 F) and 101 kPa (14.7 psia).



(a) Allowable Mode Transition only if Auto reset option is selected on to automatically restart test stand in the event of momentary power loss.

- 4 Modes
- 3 Operating Modes
- 10 Mode Transitions

FIGURE 11 SWEC/TS OPERATING MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 5 OPERATING MODES AND UNPOWERED MODE DEFINITIONS

Mode (Code)	Definition
Shutdown (B)	The SWEC is not generating gases. Cell current is zero and all valves are deenergized. The Test Stand is powered and all sensors are working. The Shutdown Mode is called for by: • Manual actuation • High or low SWEC coolant temperature • High or low SWEC feed water temperature • Low cell voltage • High O_2 outlet temperature • Power on reset from Unpowered Mode (D)
Normal (A)	The SWEC is performing its function of generating gases at the design rate. The Normal Mode is called for by: • Manual actuation
Standby (E)	The SWEC is ready to generate gases. The system is powered at operating pressure and maximum temperature possible (but less than setpoint) and the module current is off. The Standby Mode is called for by: • Manual actuation
Unpowered (D)	No electrical power is applied to the Test Stand. The Unpowered Mode is called for by: • Manual actuation (circuit breaker in TS) • Electrical power failure

Figure 12 shows a functional block diagram of the SWEC test stand electrical instrumentation. Control of the SWEC and feed water circulation temperatures is done with two Temperature Control and Monitors (TeCM), and the DC power supply controls and regulates cell current. A Single Cell Voltage Monitor (SCVM) and Temperature Monitor (TeM) are used to monitor the SWEC voltage (E1) and O_2 outlet temperature (T3), respectively. Other SWEC and test stand tmperatures are monitored using thermocouples and a pyrometer. The operation of the test stand itself is accomplished with the Operation Control (OpC). Appendix 4 further defines the roles of the TeCM, SCVM, TeM and OpC on the SWEC Test Stand. Appendices 5 and 6 detail the control/monitor setpoints used in conjunction with the TeCM, SCVM, TeM and OpC instrumentation.

PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance including design, purchasing, fabrication and testing.

Quality Assurance

Quality Assurance activities were included during the design studies, interface requirement definitions and during inspection of fabricated and purchased parts. The objective was to search out quality weaknesses and provide appropriate corrective action.

Quality Assurance activities for the program consisted of the following:

1. Establishing and implementing a parts receiving inspection program, maintaining a record of nonconforming articles and materials and their disposition, implementing control over the special processing required in the fabrication of certain cell parts, quality workmanship and controlling configuration to the Life Systems' standard drawing and change control procedure.

2. Performing the receipt and final inspection of components.

3. Ensuring that workmanship was consistent with the program at the development level.

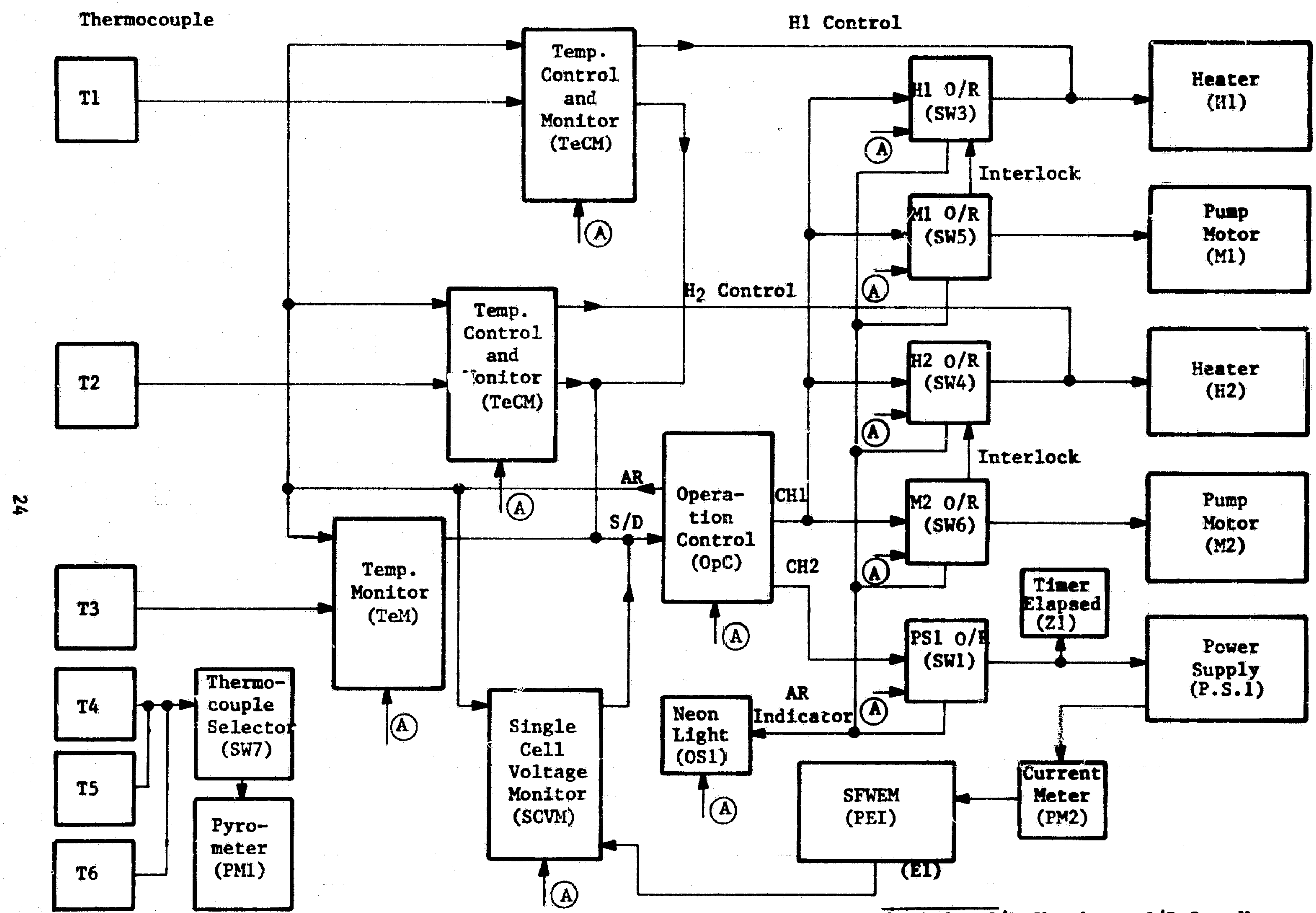
4. Evaluating all data acquisition equipment to determine its accuracy, stability and repeatability.

5. Calibrating and maintaining the data acquisition equipment to ensure its accuracy and reliability.

Reliability

Reliability provisions and studies were included as part of the overall product assurance activities to ensure equipment reliability and long-life SWEC performance. Reliability program activities consisted of the following:

1. Conducting design reviews for the purpose of critical evaluation of all aspects of SWEC and SWEC test stand design pertinent to the



1. Contains: (a) electrical sensors only (b) electrical and electrically powered components (c) items to be tested.

2. Code: S/D=Shutdown; S/B=Standby; O/R=Override; CH=Channel; AR=Auto Reset

FIGURE 12 SWEC TEST STAND ELECTRICAL FUNCTIONAL BLOCK DIAGRAM overall objectives of the program. These included interdepartmental design reviews and a formal final design review which included both Life Systems and NASA personnel.

2. Establishing and maintaining an integrated failure reporting analysis and corrective action procedure to support all phases of the program.

Maintainability

A maintainability program was carried out as part of the Product Assurance program to document needs for unplanned maintenance, corrective action taken, time interval required to determine problem source, time interval required to correct failure and the operations necessary to complete the corrective action. The maintainability program activities consisted of the following:

1. Analyzing SWEC failures or test stand failures which might impact program testing.

2. Implementing the failure reporting procedures established as part of the reliability activities.

Safety

A safety program was initiated to assure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted of performing safety analyses for the purpose of identifying and resolving possible adverse SWEC or SWEC test stand characteristics by reviewing design and design changes for potential safety hazards. Those potential safety hazards include electrical overload, electrical shock, inadvertant actuations, current limiting and other safety devices, fire suppression, toxicity, caution/warning devices, time constraints, emergency procedures, power source failure, and other malfunctions.

PROGRAM TESTING

The SWEC testing was designed and carried out as the first phase of an assessment of the current state of alkaline water electrolysis technology and its capability potential as part of a regenerative fuel cell system of a multi-kW orbiting power plant. The specific objective of the SWEC testing was to demonstrate the operational readiness of the concept and cell hardware while accumulating a data base of parametric and endurance test data upon which to assess the potential of the alkaline electrolyzer. This was done by:

1. Endurance testing four alkaline water electrolysis cells for over 23,450 hours per cell (an average of 5,862 hours per cell).

2. Characterizing the cell's performance with voltage versus current density data.

3. Testing both the advanced and super electrodes to assess the low cell voltages capabilities (1.7 V and 1.5 V, respectively) of these electrodes.

Cell Voltage Versus Current Density

The voltage versus current density span characterizes the cell performance since the cell voltage dictates the power consumption level of the water electrolysis cell at any given current. In particular, the performance of the anode (O_2 electrode) is characteristic since the anode accounts for the most significant overvoltage of the SWEC. Figures 13 and 14 illustrate the cell voltage versus current density for the two cells (105A and 105B) constructed with advanced anodes and the two cells (105C and 105D) constructed with super anodes, respectively.

Cells 105A and 105B exceeded the performance expected of advanced anodes. The cell voltages for the two cells at 162 mA/cm^2 (150 ASF) were 1.54 and 1.60 V. The cell voltage range expected was between 1.6 and 1.7 V. This improvement is representative of the additional efforts incorporated in refining the manufacturing processes of the advanced electrodes which have been Life Systems' baseline electrode since 1974.

Cells 105C and 105D met the performance expected of the super electrodes. The cell voltages at 162 mA/cm^2 (150 ASF) were both 1.49 V. At this voltage the cells are very close to the theoretical 100% thermal efficiency voltage of 1.48 V where no wasted heat exists which has be be rejected. This represents a weight savings in heat rejection equipment over higher voltage cells.

The operating point of the cells at the end of the endurance testing is also shown in Figures 13 and 14. Due to deflections in the polysulfone end plates additional mechanical strength (using either steel braces or stainless steel end plates) was necessary at the conclusion of endurance testing to accurately demonstrate the cell performance at its nominal operating point.

Cell Performance Versus Time

The purpose of the endurance test was to continuously operate the cells at a constant set of operating conditions and observe any departures from initial performance, especially departures in the cell voltage levels.

Cell Voltage Versus Time

Beyond the contractual goal of 5,000 hours per cell of endurance testing an average of 5,862 hours per cell was completed. The cell voltage is plotted against time for each of the four cells in Figures 15 through 18. Cell 105A completed 7,900 hours of operation. As can be seen from Figure 15, the voltage remained stable at 1.54 to 1.58 V for the first 4,500 hours. Between 4,500 and 6,800 hours the voltage increased from 1.56 V to 1.66 V. Similar increases in cell voltage were observed in all of the cells. Deflections in the polysulfone end plates due to the creep of the thermoplastic under thermal and mechanical loads were suspected of causing loss of good electrical contact within the cells. External steel braces were attached to cell 105A at about 7,500. The 70 mV drop in cell voltage from 1.66 V to 1.59 V confirmed the end plate problem.

Cell 105B completed 6,010 hours of operation. Similar to 105A, the performance of the cell remained stable at 1.55 to 1.60 V for the first 5,000 hours.

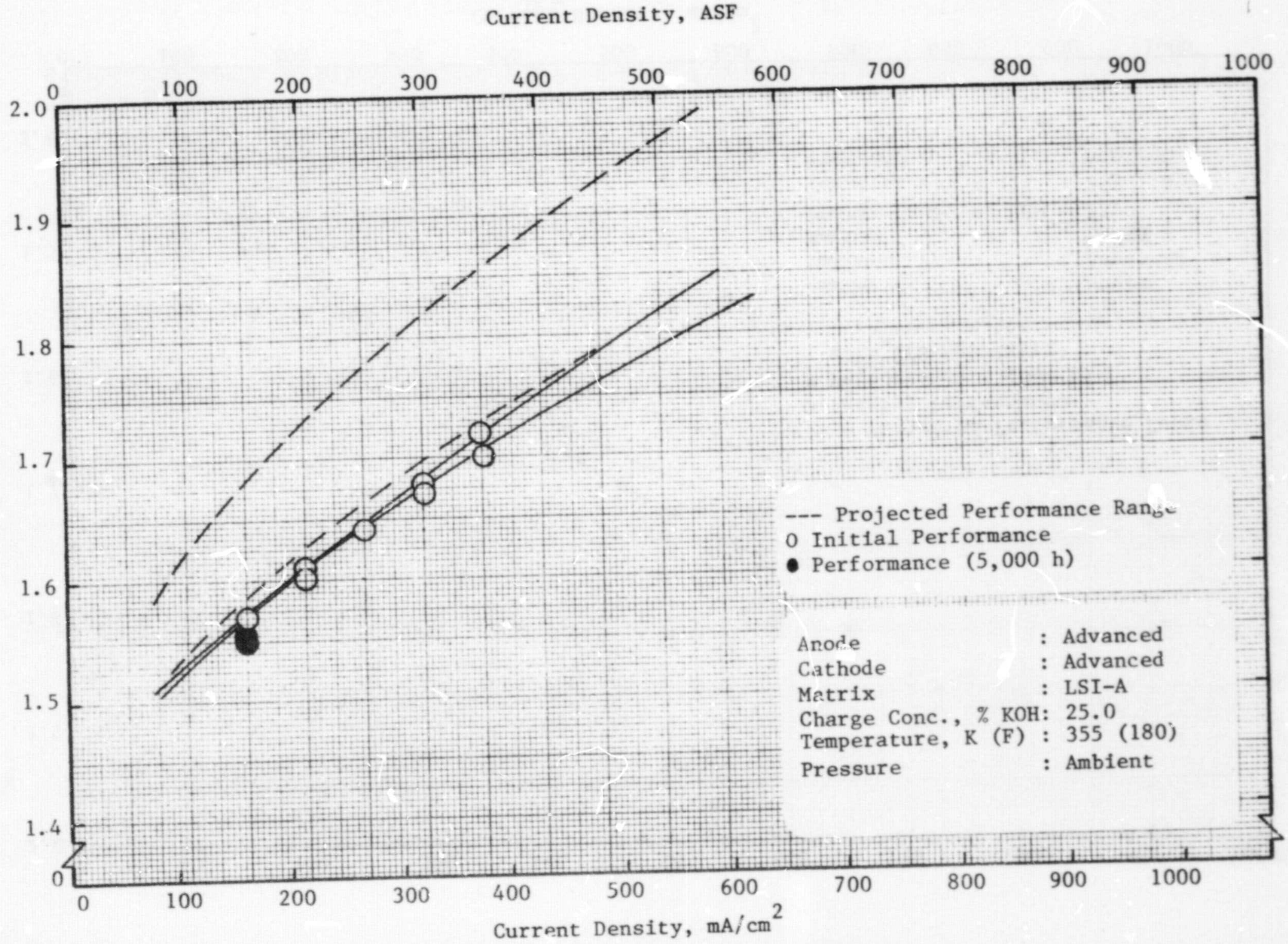


FIGURE 13 CELL VOLTAGE VERSUS CURRENT DENSITY

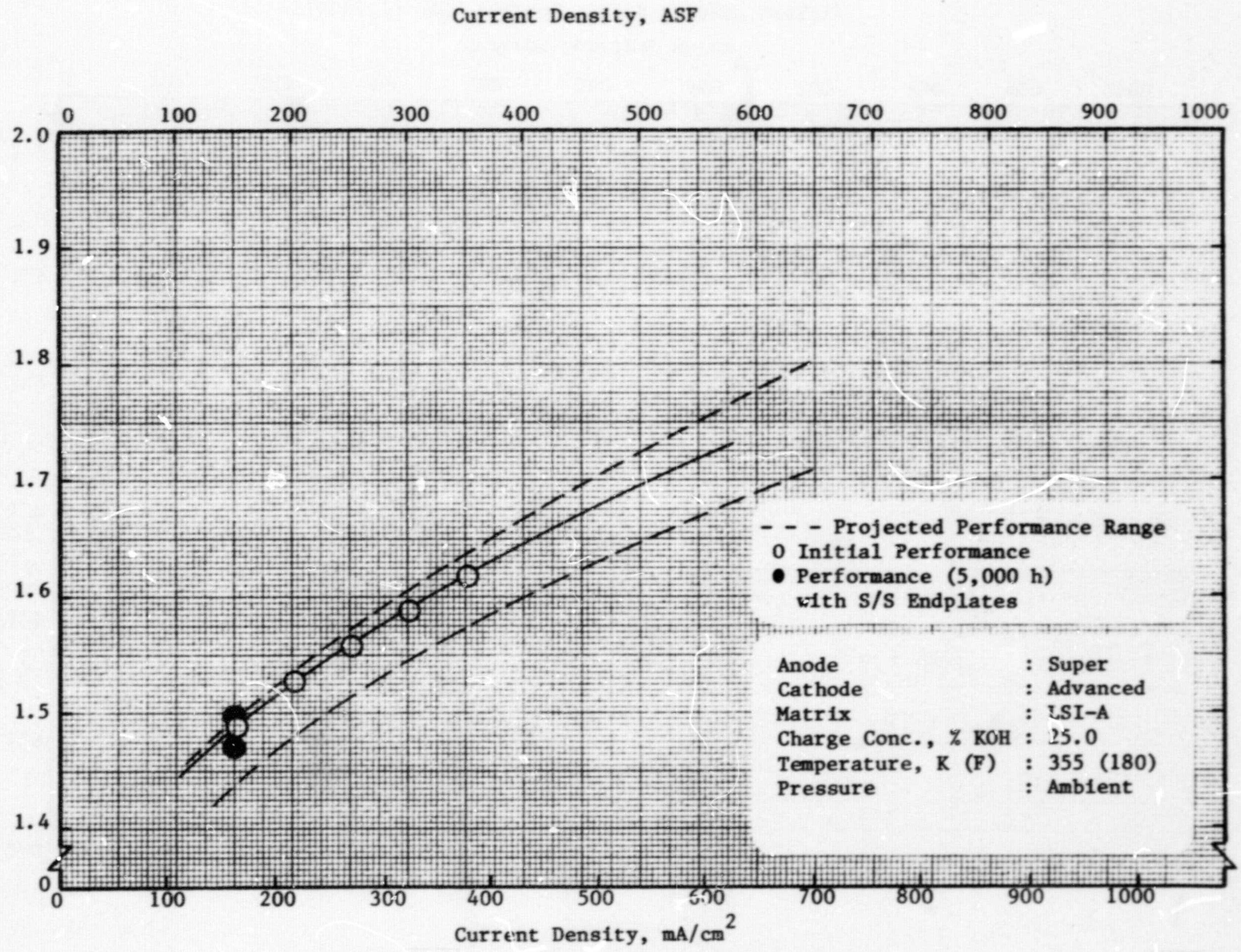


FIGURE 14 CELL VOLTAGE VERSUS CURRENT DENSITY

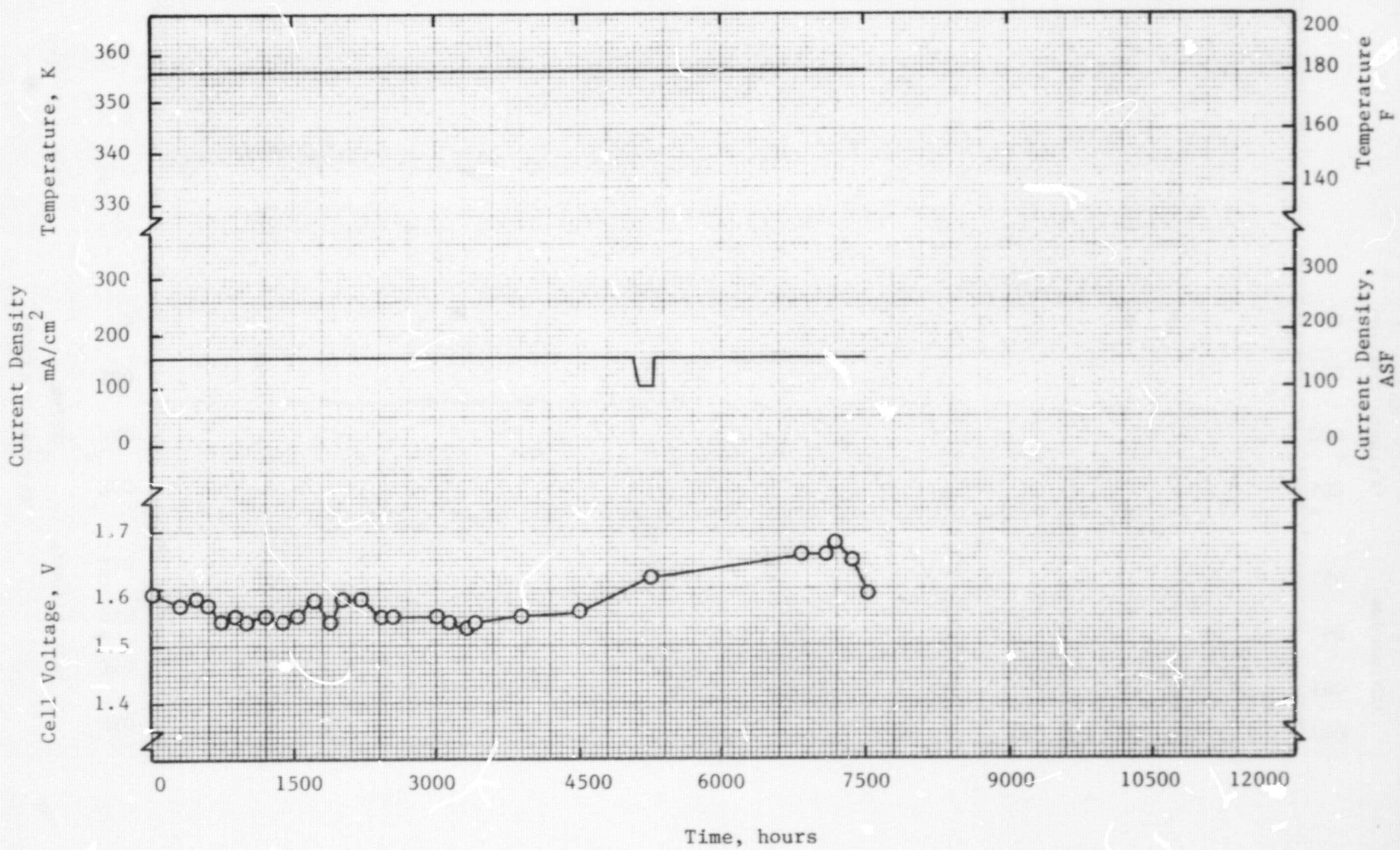


FIGURE 15 SINGLE CELL PERFORMANCE VS TIME, CELL NO. 105A, ADVANCED ANODE

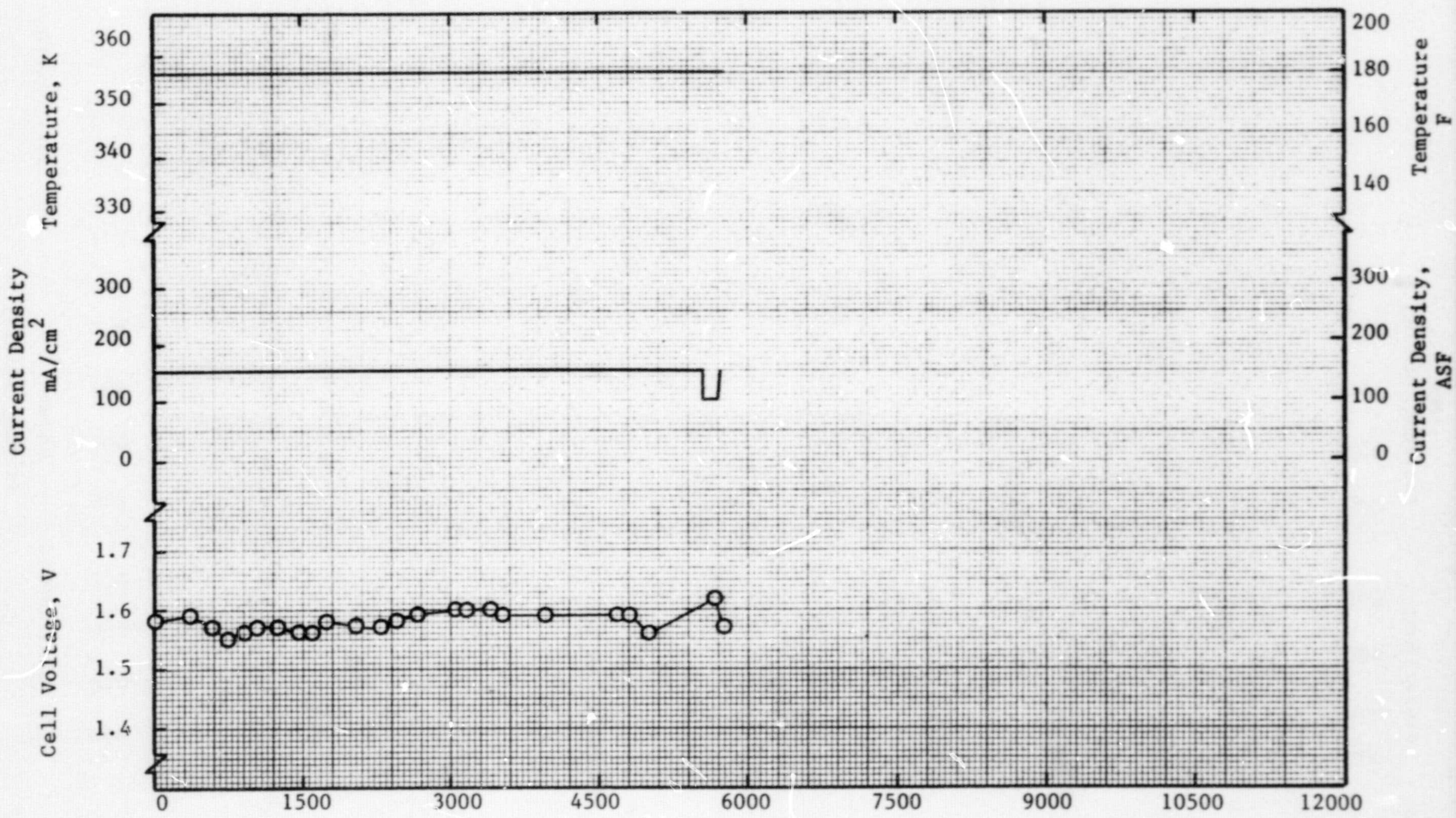


FIGURE 16 SINGLE CELL PERFORMANCE VERSUS TIME, CELL NO. 105B, ADVANCED ANODE

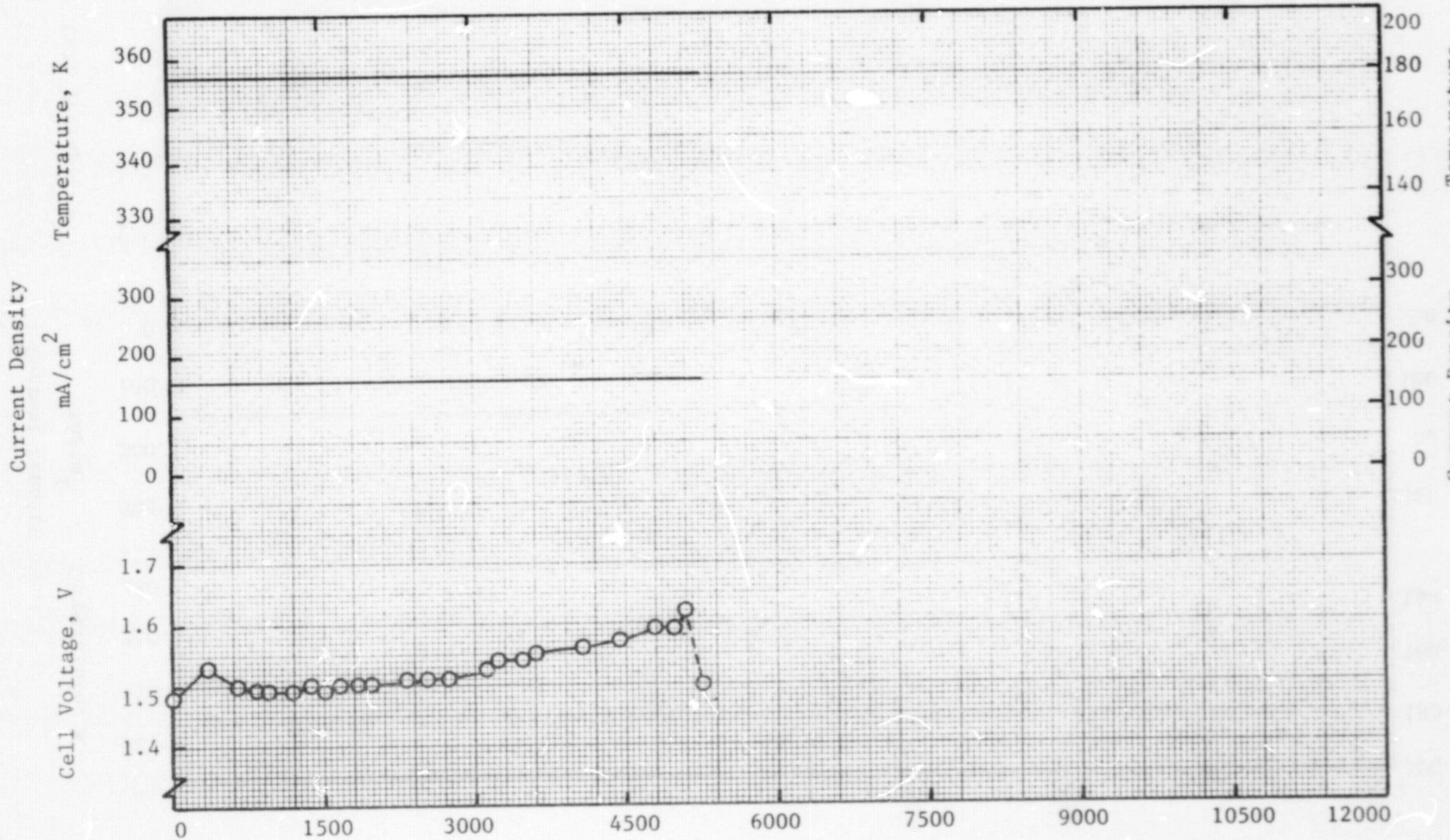


FIGURE 17 SINGLE CELL PERFORMANCE VERSUS TIME, CELL NO 105C, SUPER ANODE

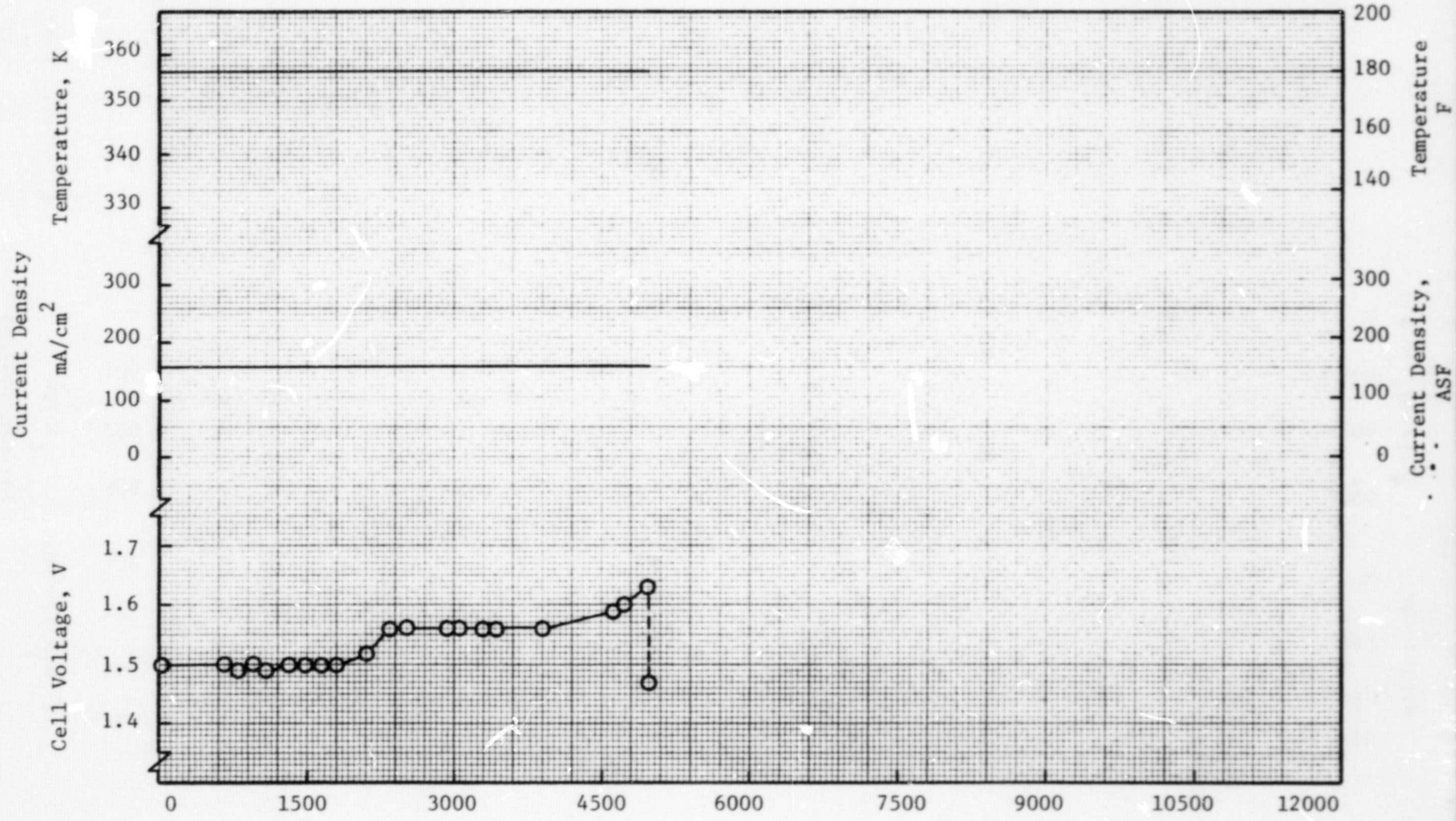


FIGURE 18 SINGLE CELL PERFORMANCE VERSUS TIME, CELL NO. 105D, SUPER ANODE

Between 5,000 and 5,700 hours the voltage increased from 1.56 V to 1.62 V. When steel braces were attached to this cell at 5,700 hours, the cell performance improved by 50 mV to 1.57 V.

As scheduled, testing on 105C and 105D was stopped at the 5,000 hour mark. To verify that the voltage increases of these cells at 2,200-2,300 hours was also due to polysulfone end plate deflection with time, the super electrodes were characterized under an Internal Research and Development (IRAD) program. No degradation of the cell or electrodes was found. The IRAD tests used the cell hardware of cells 105C and 105D, but replaced the polysulfone end plates with rigid stainless steel end plates. Under these conditions cell 105C stabilized at a voltage of 1.50/1.51 V at 352 K, 161 mA/cm^2 (175 F, 150 ASF) and 105D stabilized at a voltage of 1.47 V 355 K, 161 mA/cm^2 (180 F, 150 ASF). This performance is equivalent or better to the performance initially obtained in the endurance testing program.

These tests combined with the results of continued endurance testing of 105A and B indicate that the reason for the performance change during the testing program was excessive deflection of the polysulfone end plates with time at elevated temperature. This resulted in large increases in contact resistances within the cell.

Added Test Observations

Equally important to the evaluation of the length of useful alkaline cell life in a regenerative fuel cell based power energy system is the performance aspects concerned with cell or module corrosion and current efficiency.

Since the cell was an alkaline electrolyte instead of an acid electrolyte problems with metal corrosion are fewer and less severe thereby allowing more freedom in the metal components selection to optimize performance, weight, strength, volume and cost factors. No corrosion of cell components or external electrolyte leakage was observed during the 5000 hours of operation.

The current efficiency of the cell is calculated as the fraction of the total cell current which can be accounted for theoretically by Faradays law. From regularly measured gas production rates it was determined that the cells operated consistently at 100% current efficiency.

CONCLUSIONS

The following conclusions are direct results of the program activities.

1. Alkaline water electrolysis cells are capable of long-term operation without significant deterioration in performance (greater than three percent change in power consumption per year or 0.0053 mv/h increase).

2. The static feed design used in testing shows consistent reliable performance at 162 mA/cm^2 (150 ASF), 355 K (180 F) and has the potential of lower capital cost because of its simplicity of design and lower cost materials.

3. Both the advanced and super electrodes tested are reliable, low voltage, water electrolysis electrodes.

4. Corrosion or mechanical deterioration of the alkaline cell was not observed after 23,450 total hours of the four cells.

RECOMMENDATIONS

Based on the work completed the following recommendations were made:

1. Continue the performance evaluation of the existing four single water electrolysis cells beyond the present 5,000 hour test goal by operating two of the cells at increased current density (323 versus 161 mA/cm^2 (300 versus 150 ASF)) and two of the cells at cyclic conditions representing typical sunlight/shade time cycles of a low earth orbit. These tests should be done with stainless steel end plates to avoid end plate deflections observed in the initial 5,000 hours of testing.

2. Evaluate the performance of the static feed, alkaline electrolyte water electrolysis concept at operating pressures projected for the electrolyzer of a Regenerative Fuel Cell power storage system for low earth orbit application by operating two single water electrolysis cells at greater than 1,378 kPa (200 psia).

3. Perform an applications study to quantify the weight, power and cost savings associated with using the static feed, alkaline electrolyte electrolyzer concept as part of a low earth orbit, regenerative fuel cell power storage concept.

4. Initiate a cell area scale-up from the present 0.0093 m^2 (0.1 ft^2) to a cell area sufficiently large for multi-kilowatt power storage applications.

REFERENCES

1. Wynveen, R. A. and Schubert, F. H., "A Regenerable Fuel Cell System for Modular Space Station Integrated Electrical Power," Paper No. 739055, Eighth Intersociety Energy Conversion Engineering Conference Proceedings, Philadelphia, PA; August, 1973.

2. Powell, J. D.; Schubert, F. H. and Jensen, F. C., "Static Feed Water Electrolysis Module," Final Report, Contract NAS2-7470, CR-137577, Life Systems, Inc., Cleveland, OH; November, 1974.

3. Schubert, F. H.; Wynveen R. A. and Jensen, F. C., "Development of an Advanced Static Feed Water Electrolysis Module," Paper No. 74-ENAs-30, Intersociety Conference on Environmental Systems, San Francisco, CA; July, 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. Schubert, F. H., "Long-Term Operation of a Water Electrolysis Module," Paper No. 690643, National Aeronautic and Space Manufacturing Meeting, Los Angeles, CA; October, 1969.

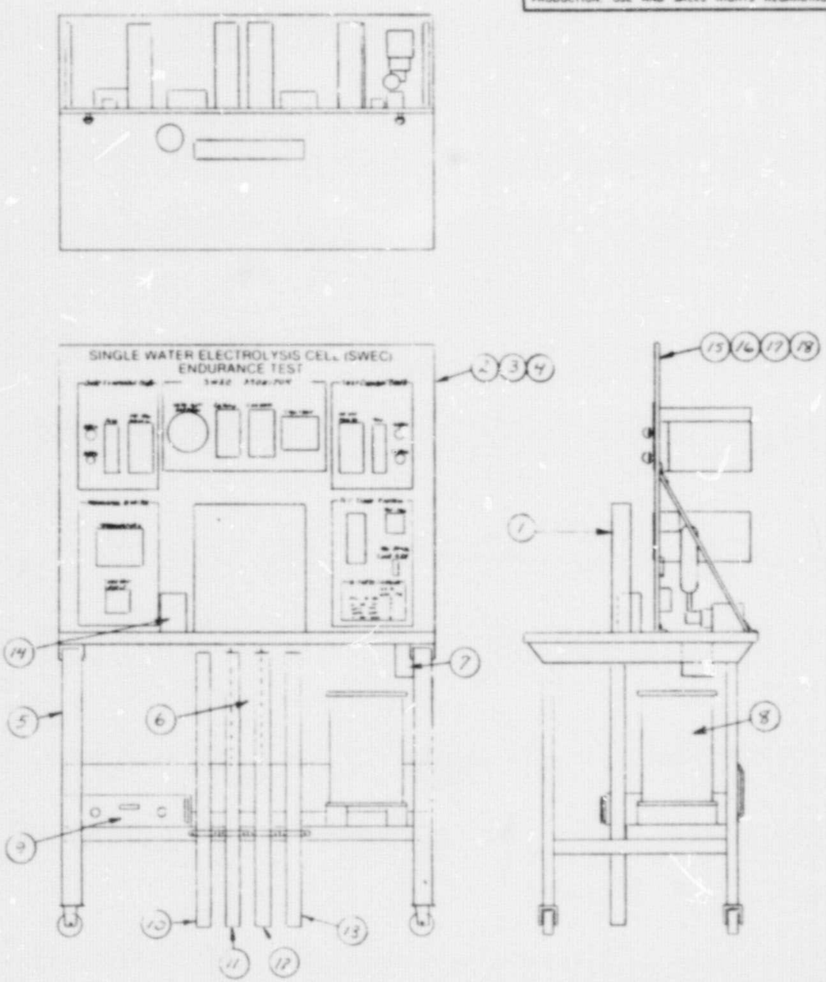
6. Schubert, F. H., "Selection of Electrolytes for Electrolysis Cells: Alkaline or Acid," Paper No. 70-Av/SpT-14, Space Technology and Heat Transfer Conference, Lost Angeles, CA; June, 1970.

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

APPENDIX 1

SWEC TEST STAND

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED



NOTE: IDENTICAL TEST STAND USED FOR TEST STAND NOS 105, 106, 108

ITEM NO.	QTY. REQ'D	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	REFERENCE OR NOTE	CODE IDENT
18	AR	——	FASTENERS	——	——	
17	AR	——	WIRE	——	——	
16	AR	——	TUBING	——	——	
15	AR	——	FITTINGS	——	——	
14	1	WA1	H_2O ACCUMULATOR	SEE DETAIL	C-2483	
13	1	PR2	O_2 BACKPRESSURE REG.	SEE DETAIL	C-2481	
12	1	TR2	O_2 CONDENSATE TRAP	SEE DETAIL	C-2483	
11	1	TR1	H_2 CONDENSATE TRAP	SEE DETAIL	C-2483	
10	1	PR1	H_2 BACKPRESSURE REG.	SEE DETAIL	C-2483	
9	1	PS1	SWEC POWER SUPPLY	SEE DETAIL	D-2485	
8	1	WT1	H_2O FEED TANK	SEE DETAIL	C-2483	
7	1	JB1	JUNCTION BOX	SEE DETAIL	D-2485	
6	1	——	TEST STAND INTERFACE PANEL	SEE DETAIL	SKA-1174	
5	1	C-2379-1	TEST STAND BENCH	SEE DETAIL	C-2379	
4	1	——	ELECTRICAL COMPONENTS	SEE DETAIL	D-2485	
3	1	——	MECHANICAL COMPONENTS	SEE DETAIL	C-2483	
2	1	——	FRONT PANEL	SEE DETAIL	SKA-1402	
1	1	——	ASSY, SINGLE WATER ELECTRO. CELL (SWEC)	SEE DETAIL	J-2229	

LIST OF MATERIALS OR PARTS LIST

NEXT ASSY	USED ON
APPLICATION	

MATERIAL

FINISH

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES
.X ± ANGULAR ±
.XX ±
.XXX ± MACH. SURF. ✓
THREADS: CLASS 2A OR 2B
REMOVE BURRS & SHARP EDGES .020 MAX
MACH. SURF. FLAT WITHIN .001 IN/IN
OTHER SURF. FLAT WITHIN .005 IN/IN
DO NOT SCALE DRAWING

	BY	DATE
DR	M. Parker	9-20-79
CHK	[illegible]	9-25-79
ENGR	[illegible]	9-28-79
APP	[illegible]	9-27-79
APPD		

Life Systems, Inc.
24755 HIGHPOINT ROAD
CLEVELAND, OHIO 44122
USA

TITLE: SINGLE WATER ELECTROLYSIS CELL (SWEC) TEST STAND

SIZE: C | CODE IDENT NO: 55601 | DRAWING NO: 2484

SCALE: NONE | SHEET 1 OF 1

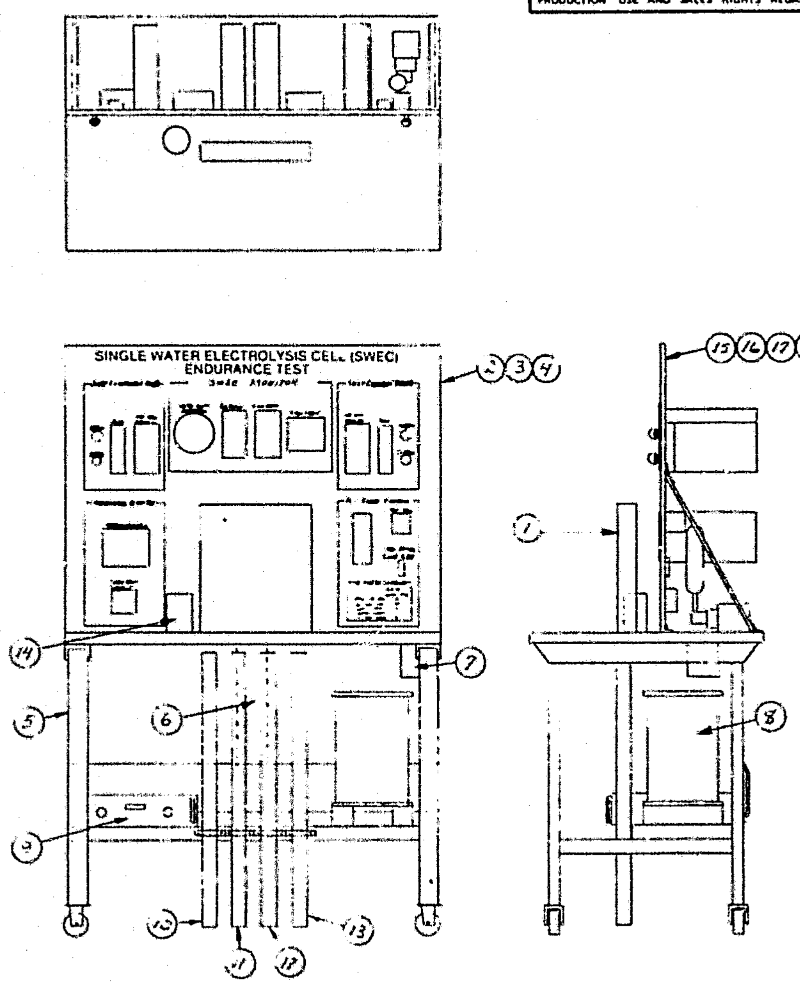
SWEC TEST STAND

PROJECT NO 1160

FIGURE A1-1 SWEC TEST STAND

REPRODUCTION OF THIS DRAWING OR MANUFACTURE OF THE PROPRIETARY PARTS SHOWN HERE WITHOUT WRITTEN CONSENT OF LSI IS ABSOLUTELY PROHIBITED. THIS DRAWING EMBODIES A CONFIDENTIAL, PROPRIETARY DESIGN AND ALL DESIGN, MANUFACTURING PRODUCTION, USE AND SALES RIGHTS REGARDING SAME ARE EXPRESSLY RESERVED

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED



NOTE: IDENTICAL TEST STAND USED FOR TEST STAND NOS 105, 106, 108

ITEM NO.	QTY. REQ'D	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	REFERENCE OR NOTE	CODE IDENT
18	AR	——	FASTENERS	——	——	
17	AR	——	WIRE	——	——	
16	AR	——	TUBING	——	——	
15	AR	——	FITTINGS	——	——	
14	1	WA1	H_2O ACCUMULATOR	SEE DETAIL	C 2483	
13	1	PR2	O_2 BACKPRESSURE REG.	SEE DETAIL	C-2483	
12	1	TR2	O_2 CONDENSATE TRAP	SEE DETAIL	C 2483	
11	1	TR1	H_2 CONDENSATE TRAP	SEE DETAIL	C 2483	
10	1	PR1	H_2 BACKPRESSURE REG.	SEE DETAIL	C 2483	
9	1	PS1	SWEC POWER SUPPLY	SEE DETAIL	D-2485	
8	1	WT1	H_2O FEED TANK	SEE DETAIL	C-2483	
7	1	JB1	JUNCTION BOX	SEE DETAIL	D-2485	
6	1	——	TEST STAND INTERFACE PANEL	SEE DETAIL	SKA-1334	
5		C-2379-1	TEST STAND BENCH	SEE DETAIL	C-2379	
4		——	ELECTRICAL COMPONENTS	SEE DETAIL	D-2485	
3	1	——	MECHANICAL COMPONENTS	SEE DETAIL	C-2453	
2	1	——	FRONT PANEL	SEE DETAIL	SKA-1402	
1	1	——	ASSY, SINGLE WATER ELECTRO. CELL (SWEC)	SEE DETAIL	J 2229	

LIST OF MATERIALS OR PARTS LIST

SWEC TEST STAND

NEXT ASSY	USED ON
APPLICATION	
MATERIAL	
FINISH	

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES
.X ± ANGULAR ±
.XX ±
.XXX ± MACH. SURF. √
THREADS CLASS 2A OR 2B
REMOVE BURRS & SHARP EDGES .020 MAX
MACH. SURF. FLAT WITHIN .001 IN/IN
OTHER SURF. FLAT WITHIN .005 IN/IN
DO NOT SCALE DRAWING

	BY	DATE
DR	M. PROKOP	9-20-79
CHK	H. Burke	7-5-79
ENGR	R. Burke	7-28-79
APPD	F.H. Schubert	4-17-79
APPD		

Life Systems, Inc. 24755 HIGHPOINT ROAD CLEVELAND OHIO 44122 USA

TITLE SINGLE WATER ELECTROLYSIS CELL (SWEC) TEST STAND

SIZE	CODE IDENT NO.	DRAWING NO.
C	55601	2484
SCALE NONE		SHEET 1 OF 1

PROJECT NO 1160

FIGURE A1-1 SWEC TEST STAND

APPENDIX 2 STEADY-STATE ACTUATOR CONDITIONS

Operating Mode	Cell Current	Pumps		Heaters	
	PS-1	M1	M2	H1	H2
Shutdown (B)	Off	Off	Off	Off	Off
Normal (A)	On	On	On	On	On
Standby (E)	Off	On	On	On	On
Unpowered (D)	Off	Off	Off	Off	Off

APPENDIX 3 INTERMODE TRANSITION SEQUENCES

Normal to Shutdown (A to B)

1. Push the Shutdown button on the Operation Control (OpC). This de-energizes the cell DC power supply, H1, H2, M1 and M2. In the case of a shutdown caused by tripping any test stand alarm, this sequence happens automatically.

Normal to Standby (A to E)

1. Push the Standby button on the OpC. This de-energizes the cell DC power supply. This transition can only happen manually.

Standby to Normal (E to A)

1. Push the Normal button on the OpC. This energizes the cell DC power supply. This transition can only happen manually.

Shutdown to Standby (B to E)

1. Push the Standby button on the OpC. This energizes M1, M2, H1 and H2 and activates the fault detection of the two fluid circulation loops. This transition can only happen manually.

Standby to Shutdown (E to B)

1. Push the Shutdown button on the OpC. This de-energizes H2, H1, M2 and M1. In the case of a shutdown caused by tripping any of the activated test stand alarms, this sequence happens automatically.

APPENDIX 4 INSTRUMENTATION DEFINITIONS - SWEC TEST STAND

Title	Description	Sensor	Actuator	Control Point	Adjust. Range
TeCM	Control T1 using heater provides shutdown if temperature either too high or too low	T1	H1 OpC	355 K (180 F)	305 to 383 K (90 to 230 F)
TeCM	Control T2 using heater provides shutdown if temperature either too high or too low	T2	H2 OpC	355 K (180 F)	305 to 383 K (90 to 230 F)
TeM	Provides shutdown if T3 too high	T3	OpC	372 K (210 F)	305 to 383 K (90 to 230 F)
OpC	Executes shutdown if either T1, T2, T3 or E1 too high or T1, T2 or E1 too low	TeM, TeCM SCVM	All	---	0 to 5 V
SCVM	Provides shutdown if cell voltage E1 is too high or too low	E1	OpC	1.58 V	0.05 to 2.00 V

Mode ____________

APPENDIX 5 CONTROL/MONITOR SETPOINT TABLE

System Single Cell WES
System Schematic No. C2483
Sheet 1 of 1 Rev. ____

Sensor				Setpoints									
				Control		Monitor						Allowable Range	
						Low			High				
Code	Description	Range	Unit	Low	High	Alarm	Warning	Caution	Caution	Warning	Alarm	Low	High
T1	Cell KOH Outlet Temperature	50-250	F	175	185	100	120	150	190	200	210	90	230
T2	Cell Coolant Outlet Temp.	50-250	F	175	185	100	120	150	190	200	210	90	230
T3	Cell O_2 Outlet Temp.	50-250	F	-	-	-	-	-	190	200	210	90	230

Prepared by [illegible] 11/12/79
Date

Approved by [illegible] 11/1[illegible]/79
Date

F 630 (Rev. 10/31/78)

Mode ______________

APPENDIX 6 CONTROL/MONITOR SETPOINT TABLE

System · Single Cell WES
System Schematic No. C2483
Sheet 1 of 1 Rev. ____

Sensor				Setpoints									
				Control		Monitor						Allowable Range	
						Low			High				
Code	Description	Range	Unit	Low	High	Alarm	Warning	Caution	Caution	Warning	Alarm	Low	High
I1	Cell Current	0-50	A	14.9	15.1	←		NO SETPOINTS			→	0	40
T1	Cell KOH Outlet Temperature	50-250	F	175	185	100	120	150	190	200	210	90	230
T2	Cell Coolant Outlet Temp	50-250	F	175	185	100	120	150	190	200	210	90	230
T3	Cell O_2 Outlet Temp	50-250	F	-	-	-	-	-	190	200	210	90	230
E1	Cell Voltage	0-2.50	V	-	-	1.35	1.40	1.45	1.55	1.60	1.65	0.05	2.00
				-	-	1.40	1.45	1.50	1.65	1.70	1.75	0.05	2.00

Prepared by Ken A. Baker 11/12/79
Date

Approved by Frazzy H Schuker 11/13/79
Date