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FINAL REPORT

LIGHTWEIGHT FUEL CELL POWERPLANT COMPONENTS PROGRAM

BY

R. E. MARTIN

22 February 1980

UNITED TECHNOLOGIES CORPORATION
Power Systems Division

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS8-30637

George C. Marshall Space Flight Center
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NOTICE

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FOREWORD

This final report describes the system definition and component development work completed in defining an alkaline lightweight fuel cell powerplant under NASA contract no. NAS8-30637 from 18 March 1974 through 31 December 1979.

The NASA Project Manager for this contract was Mr. L. J. George. The contributions of Mr. George and other members of the Electrical Power Branch at George C. Marshall Space Flight Center are gratefully acknowledged.

The Project Manager for Power Systems Division was Mr. Ronald E. Martin. Principal Power Systems Division personnel who directed the tasks performed in this program were.

L. M. Handley
A. P. Meyer
B. Gitlow
W. F. Bell

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

ABSTRACT

An analytical and experimental development program was conducted on a lightweight hydrogen-oxygen alkaline fuel cell incorporated into the design of a Lightweight Fuel Cell Powerplant (LFCP). The powerplant operates with passive water removal which contributes to a lower system weight and extended operating life.

A preliminary LFCP specification and design table were developed. A lightweight power section for the LFCP design, consisting of repeating two-cell modules was designed.

Two, four-cell modules were delivered to Marshall Space Flight Center. These modules incorporated 0.508 ft^2 ($471.9 cm^2$) active area Space Shuttle technology fuel cells.

During the program over 1,200 hours of single-cell and over 8,800 hours of two-cell module testing was completed. The 0.25 ft^2 ($232.3 cm^2$) active area lightweight cell design was shown to be capable of operating on propellant purity reactants out to a current density of 600ASF (645.8 mA/cm^2). Endurance testing of the two-cell module configuration exceeded the 2,500-hour LFCP voltage requirements out to 3700-hours.

A two-cell module capable of operating at increased reactant pressure completed 1000 hours of operation at a 30 psia (20.7 N/cm^2) reactant pressure.

A lightweight power section consisting of fifteen, two-cell modules connected electrically in series was fabricated. A performance demonstration of the power section is planned under a Lewis Research Center advanced technology fuel cell program.

I. SUMMARY

This final report documents the activity and results of a long-range analytical and experimental program leading to the definition of an Lightweight Fuel Cell Powerplant (LFCP). The advanced technology lightweight fuel cells of the LFCP design operate with passive water removal which offers significant savings in powerplant weight and extends life. Passive water removal eliminates the requirement for a hydrogen circulating pump and dynamic water separator.

Objective

The objective of the program was to define the design of a fuel cell powerplant which would meet the requirements of future NASA missions. The design was based upon the advanced technology lightweight fuel cells developed under NASA Lewis Research Center programs.

The design shall be substantiated, and the readiness of the technology for development will be demonstrated by testing of powerplant elements, such as single cells and multi-cell power sections.

Scope

A lightweight fuel cell powerplant preliminary specification was identified and a lightweight fuel cell powerplant preliminary design table was specified.

Three, two-cell modules, repeating unit of the lightweight power section design were fabricated and tested. In addition, two-single cells and an additional two-cell module of a design capable of increased reactant pressure operation were fabricated and tested.

A lightweight 30-cell power section of the LFCP design was fabricated and a performance demonstration test under a future NASA program is planned.

Results

Two, four-cell modules incorporating 0.508 ft^2 (471.9 cm^2) active area Space Shuttle technology fuel cells were constructed, performance checkout tested and delivered to Marshall Space Flight Center for acceleration testing and to investigate low power density operation.

An Lightweight Fuel Cell Powerplant (LFCP) was defined which would be capable of satisfying NASA requirements for advanced space vehicles. A Powerplant Specification and Design Table were established for the LFCP.

A power section for the LFCP design based upon a repeating two-cell module unit was defined.

A total of 8,855 hours of two-cell module testing and 1,222 hours of single-cell testing was completed. Endurance testing of the two-cell module configuration exceeded the 2500 hour design voltage requirement of the LFCP design.

A two-cell module configuration demonstrated that the effect of propellent purity gases on cell performance was very small. The evaluation was conducted at current densities to 600 ASF (645.8 mA/cm^2) with hydrogen and oxygen being diluted with up to 0.5 percent Helium to simulate gases that might be obtained from space vehicle propellent tanks.

A two-cell module incorporating a passive water removal assembly capable of operating at increased reactant pressure, completed over 1000 hours of operation at a 30 psia (20.7 N/cm^2) reactant pressure.

A 30-cell lightweight power section consisting of fifteen, two-cell modules was constructed. A performance demonstration test of the power section is planned under a Lewis Research Center advanced technology fuel cell program.

Conclusions

- Performance and endurance testing of the two-cell modules has shown that the design will:
  - Satsify the 2500 hour voltage requirements of the Lightweight Fuel Cell Powerplant Design.
  - Operate with propellent purity reactants with no significant impact upon cell performance.
- Additional endurance testing of two-cell modules incorporating passive water removal assemblies capable of increased reactant pressure operation will be required to demonstrate long-term performance stability.
- A performance demonstration test of the 30-cell lightweight power section designed and constructed during this contract period of performance will be necessary to verify cell reactant distribution, product water removal operation, thermal characteristics, performance with time and structural integrity.

II. INTRODUCTION

Background

Power Systems Division (PSD) of United Technologies Corporation has developed several hydrogen-oxygen alkaline fuel cell powerplants for space and undersea applications. PSD has built upon the experience and the lessons of the Apollo program by continuously upgrading and expanding the capabilities of the alkaline fuel cell powerplants through parallel development of basic technology and powerplant hardware. The powerplants which PSD has developed and the improvements in technology they have incorporated are shown in Figure 1.

The Apollo PC3A-2 powerplant, the first in a series, was a complete powerplant successfully qualified for manned space flight. Ninety Apollo fuel cell powerplants were delivered, successfully completing sixteen flights including nine lunar, three skylab and a Apollo-Soyuz mission. A total of 10,750 hours of flight time was completed without incident.

The PC8B series of powerplants was developed under in-house sponsored programs to improve performance, startup characteristics, operating characteristics, endurance, and reduce powerplant weight beyond the achievements of Apollo. The PC8B-1 was the first powerplant incorporating low-temperature, matrix-type alkaline cells configured for space applications. Cell active area of 0.4 ft^2 (371.6 cm^2) was the same as Apollo. For compatibility with the Apollo Service Module, the PC8B-1 retained the Apollo ancillaries and mounting structure. The PC8B-2 was identical to PC8B-1 except that the interface panel and mounting structure were modified for compatibility with the Air Force Manned Orbiting Laboratory (MOL) vehicle.

In 1969, the PC8B was repackaged with a stack of 0.5 ft^2 (464.5 cm^2) active area cells. Designated the PC8B-3, this powerplant was operated as a demonstration unit for more than a year, accumulating 97 starts and more than 6000 hours on reactants. The cooling system was improved, its rating was raised from 2.5 to 4.5kW and it was designated the PC8B-4.

The 5kW PC8C was built in 1971 with a stack of 0.5 ft^2 (464.5 cm^2) active area cells of the high power density type. This cell was developed in the late 1960's in Air Force and in-house IR&D programs. Originally developed for operation at high current densities, typically 3000 ASF (3229 mA/cm^2), the cell was found to have superior endurance as well. Endurance testing of this cell configuration in a NASA-LeRC program demonstrated over 11,000 hours of operation and a subscale laboratory cell in a PSD IR&D program exceeded 35,000 hours of testing. This cell configuration has been used in all subsequent low-temperature alkaline fuel cell powerplants. The PC8C was used as a demonstrator powerplant for almost two years. During this period it accumulated 100 self-energized starts.

The Navy 20kW PC15B, the NASA 5kW DM-2, the PSD 15kW demonstrator X-712, and the Space Shuttle PC17B all incorporate low-temperature, alkaline electrolyte fuel cells of the high power density type, a pumped liquid thermal control subsystem, a circulating hydrogen water removal subsystem and a reactant control subsystem with coupled regulators.

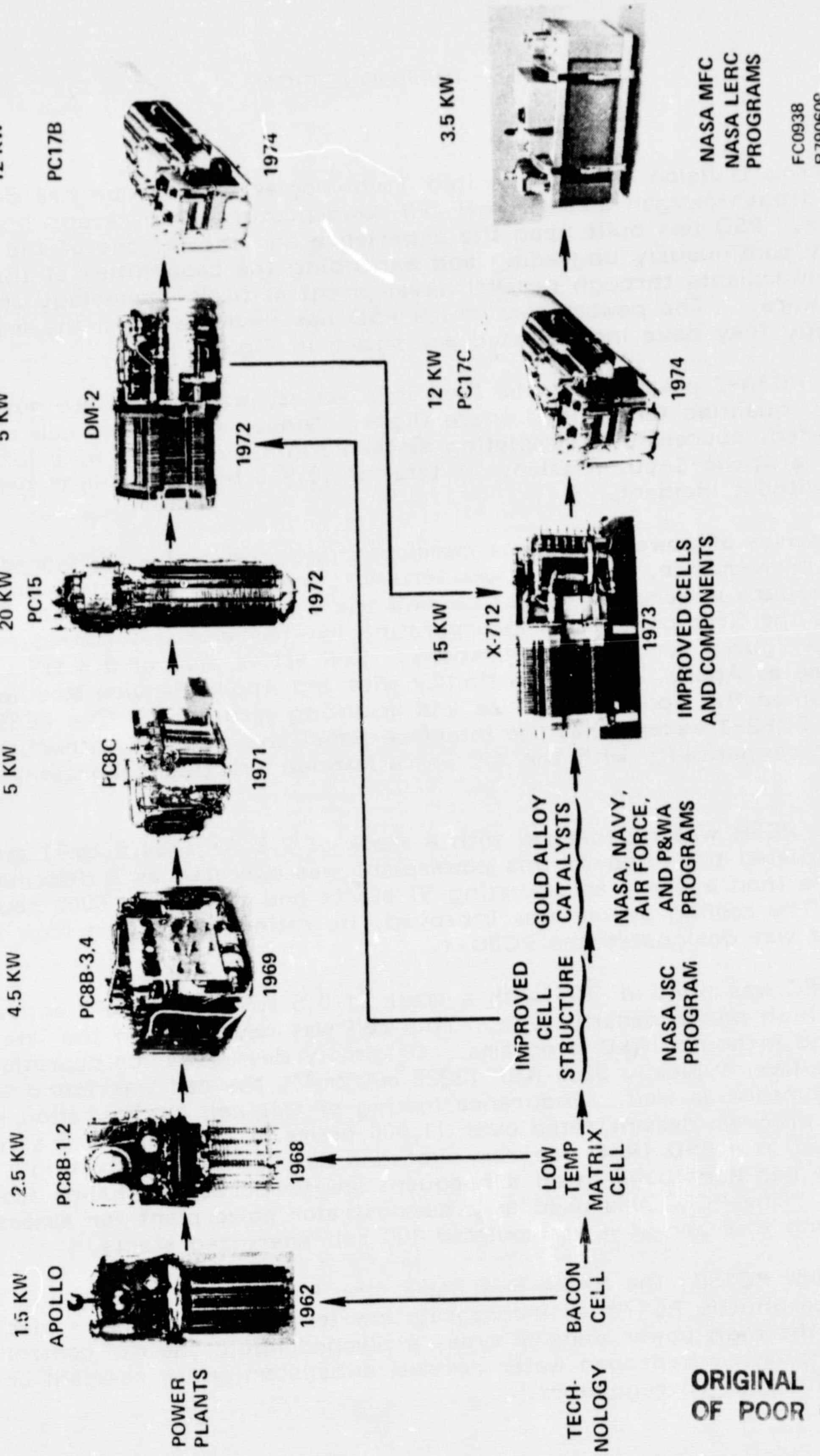

Figure 1. Powerplant Development History

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The largest powerplant in the series is the 20kW PC15 hydrogen-oxygen powerplant developed under the Navy sponsored Deep Submergence Rescue Vehicle (DSRV) program. It was designed to supply propulsion and hotel power for deep-diving manned submersibles. Three, 20kW, 128 cell powerplants were built and tested for 877 hours during the program. A total of 137 hours of field operation has been completed.

The DM-2 was developed for NASA-JSC to demonstrate Space Shuttle fuel cell technology, Its continuous output rating was 5kW and has a 7.5kW short duration overload capability, limited by its coolant pump and condenser capacity. The DM-2 power section consisted of 34, 0.5 ft^2 (464.5 cm^2) active area cells. The powerplant operated over a simulated Space Shuttle power profile for 5072 hours, Figure 2, the equivalent of 31 missions. The powerplant demonstrated 21 self-energized ten minute starts. Two six-cell power sections tested under this program accumulated 10,000 and 10,500 hours of operation, Figure 3, and a hydrogen circulation pump was tested for 10,000 hours.

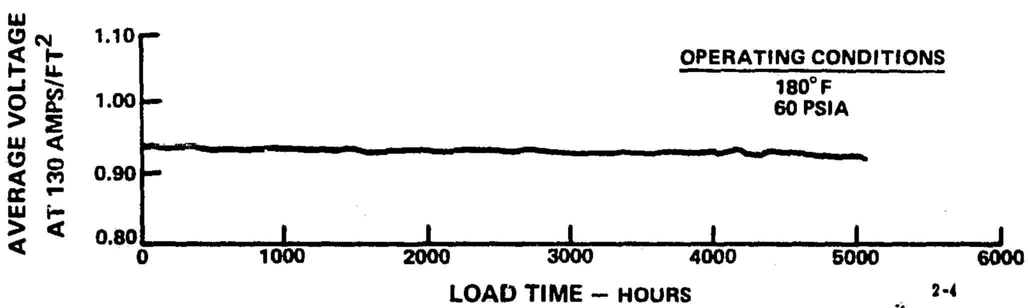


Figure 2. DM-2 5000 Hour Test Summary

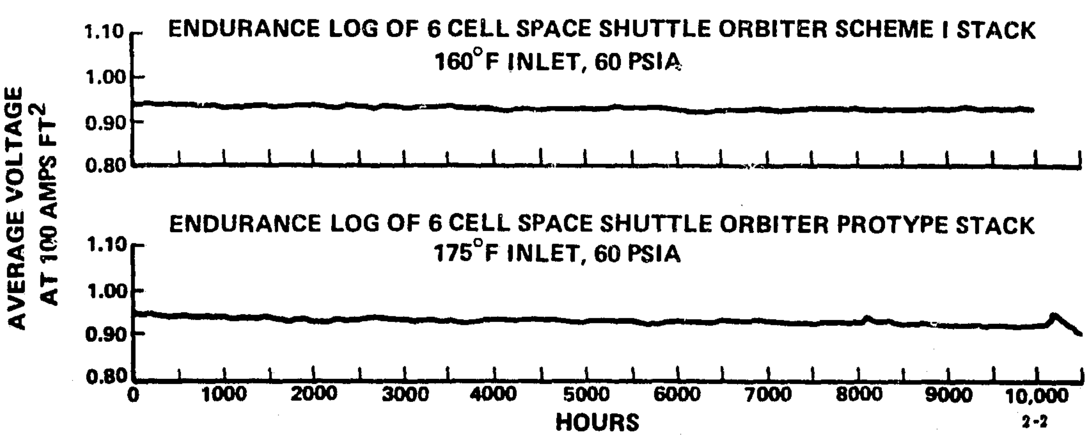


Figure 3. 10,000 Hour Power Section Tests

The X712 Demonstrator powerplant was similar to the DM-2 but incorporated a stack of 36, 0.5 ft^2 (464.5 cm^2) active area single cells with a higher performing gold-alloy cathode catalyst replacing the platinum cathode catalyst employed on the DM-2 cell. X712 has a greater capacity coolant system than the DM-2, giving it a continuous output rating of 15kW. X712 has been employed as a demonstrator powerplant for four years accumulating 115 self-energized starts.

The space shuttle PC17C powerplant incorporates two power sections comprised of 32, 0.5 ft^2 (464.5 cm^2) active area cells connected electrically in parallel. A total of 8 Orbiter fuel cell powerplants have been delivered to date, successfully completing 182 hours of operation during atmospheric testing of the Space Shuttle vehicle. The PC-17C design has accumulated over 10,147 hours of operation with over 450 self-energized starts. A PC-17C development powerplant which operated to a power profile for over 4200-hours, Figure 4, exceeding the 2,000-hour, 27.5 volt design requirement.

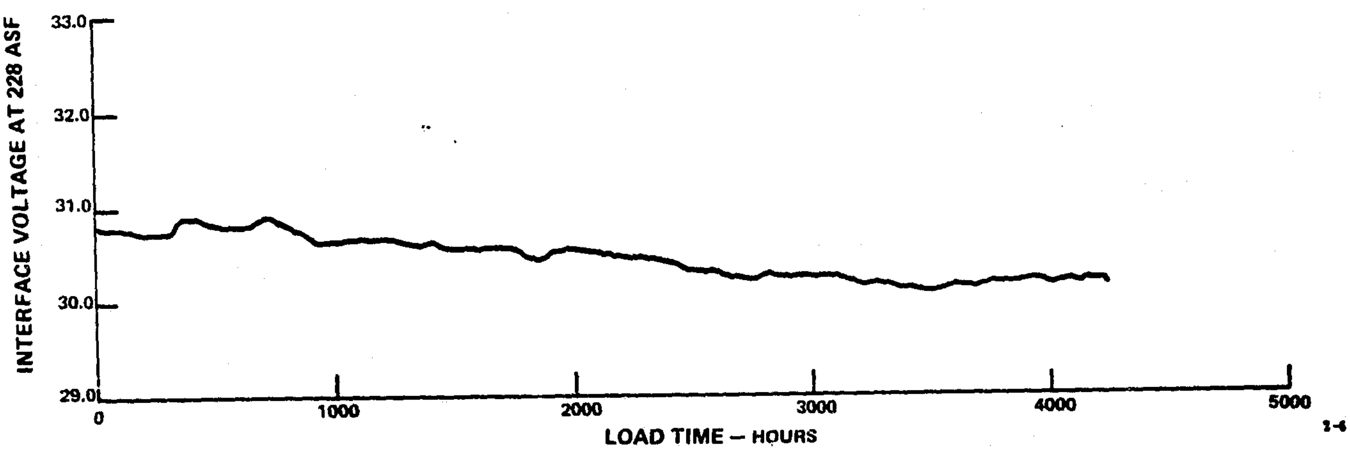


Figure 4. PC-17C Development Powerplant X-706 Test Summary

In addition a 64-cell PC-17C power section completed 3500-hours of operation to a simulated Orbiter power profile exceeding the 2,000-hour, 27.5 design voltage requirement.

An Advanced Lightweight Alkaline Fuel Cell Technology program conducted by PSD under the direction of the Lewis Research Center has identified and demonstrated a low weight cell design with increased performance and extended life.

- The lightweight cell design has a specific weight of 4 lbs/kW (1.89g/W) compared to the PC-17C cell design specific weight of 8 lbs/kW (3.69g/W).
- A gold-platinum catalyst cathode was developed which demonstrated increased cell performance and improved stability for long life.

- The lightweight cell design has accumulated over 138,000 cell-hours of operation with one cell operating continuously for 10,021 hours and another cell operating at a current density of 200 $AMPS/ft^2$ (215.3 mA/cm^2) for 6,680-hours.

PSD has been conducting a program under the direction of George C. Marshall Space Flight Center since March 1974 to develop a fuel cell powerplant design based upon the advanced lightweight alkaline fuel cell developed under the Lewis Research Center program.

Scope

The objective of this program was to define the design of a generic fuel cell powerplant which will meet the requirements of future NASA missions. The design will be based upon the advanced lightweight future fuel cell developed in previous programs by NASA. Ancillary components shall be similar to Space Shuttle Orbiter Powerplant components to minimize eventual delta qualification requirements.

The design shall be substantiated, and the readiness of the technology for development will be demonstrated by testing of powerplant elements, components, and sub-sections.

Relevance/Significance

Performance and endurance testing of the two-cell module configuration, repeating unit of the lightweight fuel cell power section has shown:

- The configuration will satisfy the 2500-hour voltage requirements of the Lightweight Fuel Cell Powerplant design.
- The capability to operate on propellent purity reactants with only a slight affect on cell performance.

Purpose/Objective

An analytical and experimental development effort was conducted to translate the lightweight fuel cell technology resulting from the Lewis Research Center program into a lightweight powerplant design to satisfy future NASA mission requirements. A lightweight powerplant design was developed which incorporated a 34, 0.25 ft^2 (232.3 cm^2) active area cell power section, comprised of 16 repeating two-cell modules.

Four, two-cell modules were fabricated and endurance tested to verify the power section design.

Three, 0.25 ft^2 (232.3 cm^2) active area single cells were fabricated and endurance tested to establish the increased reactant operating pressure capability of a modified lightweight cell design.

A 30-cell power section consisting of 15 repeating, two-cell modules was fabricated. A 2,500-hour performance demonstration test is planned under a future NASA program.

Test Conditions and Facilities

The performance evaluation tests were conducted in test stands originally built for the Apollo fuel cell program in 1963 and modified to meet the requirements of the lightweight cell design.

Performance evaluation tests were conducted at current densities out to 600 ASF (648.8 mA/cm^2). The capability of the two-cell module design to operate on propellant purity reactants was demonstrated by diluting the reactants with up to 0.5% helium.

The operating reactant pressure of the lightweight fuel cell powerplant design is 19 psia (13.1 N/cm^2) at a nominal cell temperature of 180°F (82.2°C). Endurance tests of two-cell modules and single-cells were conducted at cell temperature of 165°F (73.9°C) and 180°F (82.2°C) at reactant pressures up to 60 psia (41.4 N/cm^2). A controlled vacuum is maintained in the water cavity of the passive water removal assembly to achieve product water removal and maintain operating electrolyte concentration.

III. FOUR CELL DELIVERY MODULES

Two, four-cell modules were delivered to Marshall Space Flight Center (MSFC). MSFC planned to conduct an acceleration test and investigate low power density operation. These modules incorporated 0.508 ft^2 (471.9cm^2) active area Space Shuttle technology fuel cells.

- Environmental Test Module delivered to MSFC on 17 July 1974
- Low Power Density Module delivered to MSFC on 17 December 1974

A. Environmental Test Module

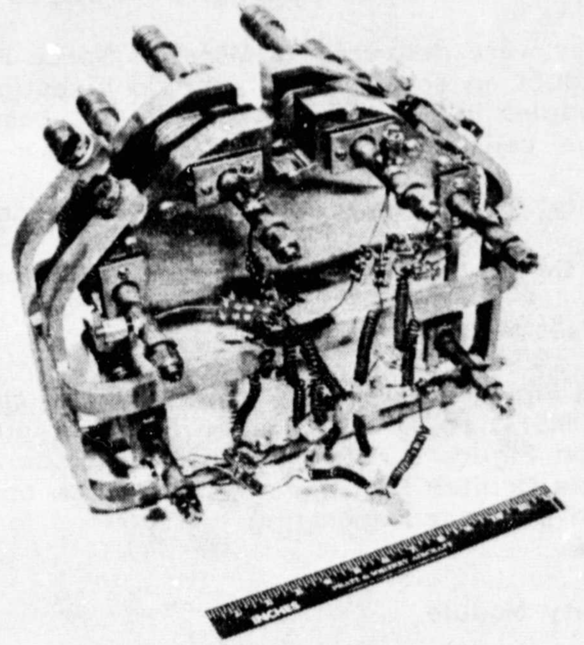
The module shown on Figure 5 completed a performance checkout test of 18 hours and was delivered to MSFC on 17 July 1974. The checkout test performance of the module is presented on Figure 6. The unitized electrode assemblies are the same as those of the Shuttle Orbiter PC17B powerplant. An operations manual, Reference 6 was prepared which presented operating instructions for the module and checkout test performance data.

B. Low Power Density Module

The Low Power Density Module shown on Figure 5 completed a performance checkout test of 25 hours and delivered to MSFC on 17 December 1974. The checkout test performance of the module is presented on Figure 6. The unitized electrode assemblies (UEA) are the same as those of the Shuttle Orbiter PC-17C powerplant. The gold-platinum catalyst cathodes incorporated into this UEA was responsible for the higher performance demonstrated by the low power density module.

The initial checkout test identified a lower than expected performance. Data analysis suggested that the cause to be inadequate mechanical compression of the cells. The module was disassembled and inspected. Both the fiberglass/epoxy cell edge frames of the UEA and the cell-coolant separator plates were found to deviate from dimensions required for proper compression. The dimensional deviations of the cell frames was traced to a change in measuring technique used in UEA fabrication. The separator plate deviations were traced to a vendor manufacturing problem.

The module was rebuilt with all new UEA's and cell-coolant separator plates which were within dimensional tolerances required for proper cell impression. The module was performance tested and delivered to MSFC. An operations manual, Reference 7 was prepared which presented operating instructions and checkout test performance for this module.



Environmental Test Module

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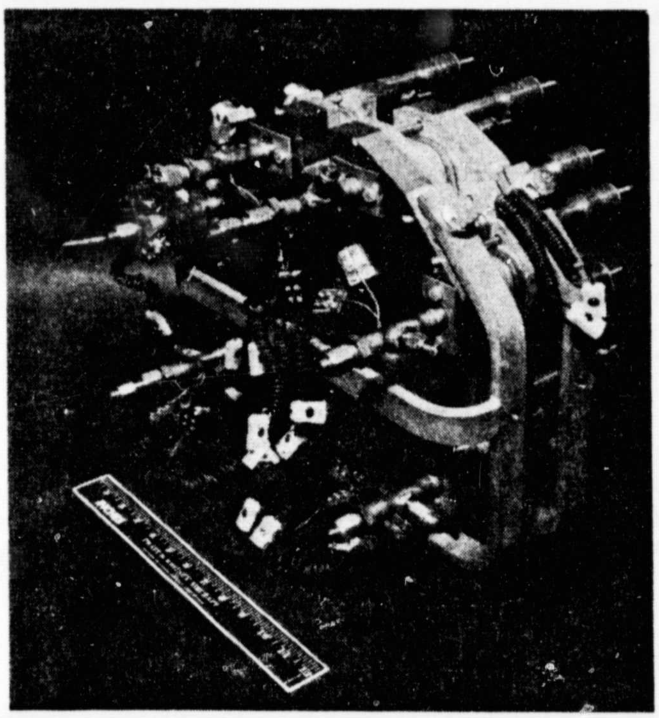

Low Power Density Module

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Figure 5. Multi-Cell Delivery Modules

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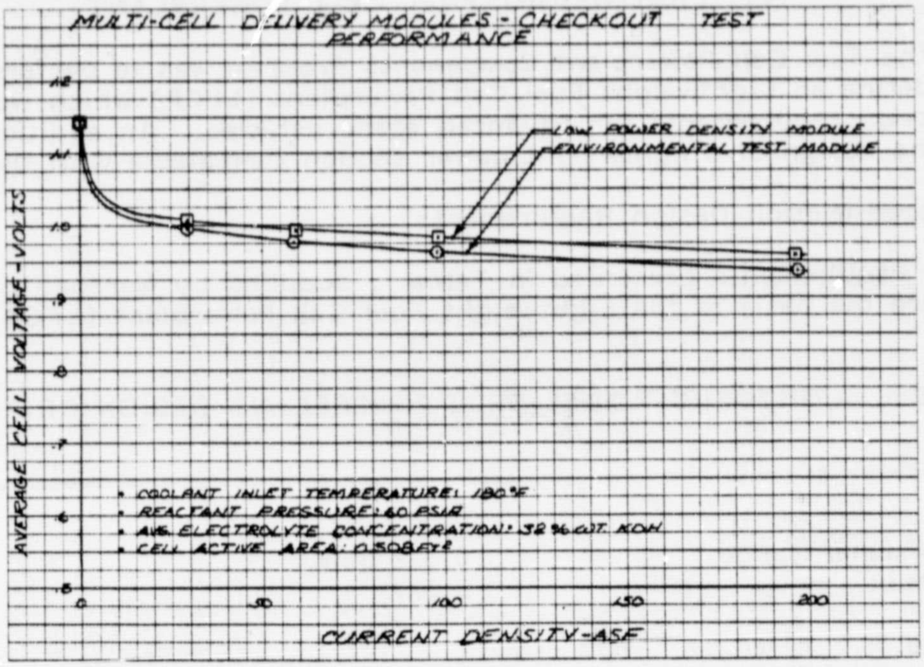

Figure 6. Multi-Cell Delivery Modules Checkout Test Performance

IV. LIGHTWEIGHT FUEL CELL POWERPLANT

A task of the Fuel Cell Powerplant Components Program was to perform a system design to define an Lightweight Fuel Cell Powerplant (LFCP) which would meet NASA's mission requirements for advanced space vehicles. An additional task was to define the design of a lightweight power section compatable with the LFCP.

A. Advanced Mission Design Requirements

The design requirements presented in Table I, supplied by Marshall Space Flight Center, were the basis of the Lightweight Fuel Cell Powerplant (LFCP).

TABLE I. LIGHTWEIGHT FUEL CELL POWERPLANT DESIGN CRITERIA

Power	
Nominal Range	0.5-2.0kW
Peak	3.5kW
Voltage	
Nominal Power Range	24.0-32.5 volts
Peak Power	18 volts
Reactant Purity	Propulsion Grade*
Reactant Supply Pressure	
Hydrogen	19.0-21.5 psia (13.1 - 14.8 N/cm^2)
Oxygen	29-32 psia (20.0 - 22.1 N/cm^2)
Endurance	
Total Operating Time	2500 hours**
Time at Peak Power	8 hours

* Possibility contaminated with several percent Helium
** Composed of missions averaging several days duration

The design requirements for the LFCP were directed toward advanced space missions such as Space Tug and Orbital Transfer Vehicle (OTV).

A preliminary specification for the lightweight Fuel Cell Powerplant is presented in Appendix A.

B. System Operation

The fluid schematic of the Lightweight Fuel Cell Powerplant (LFCP) is shown in Figure 7.

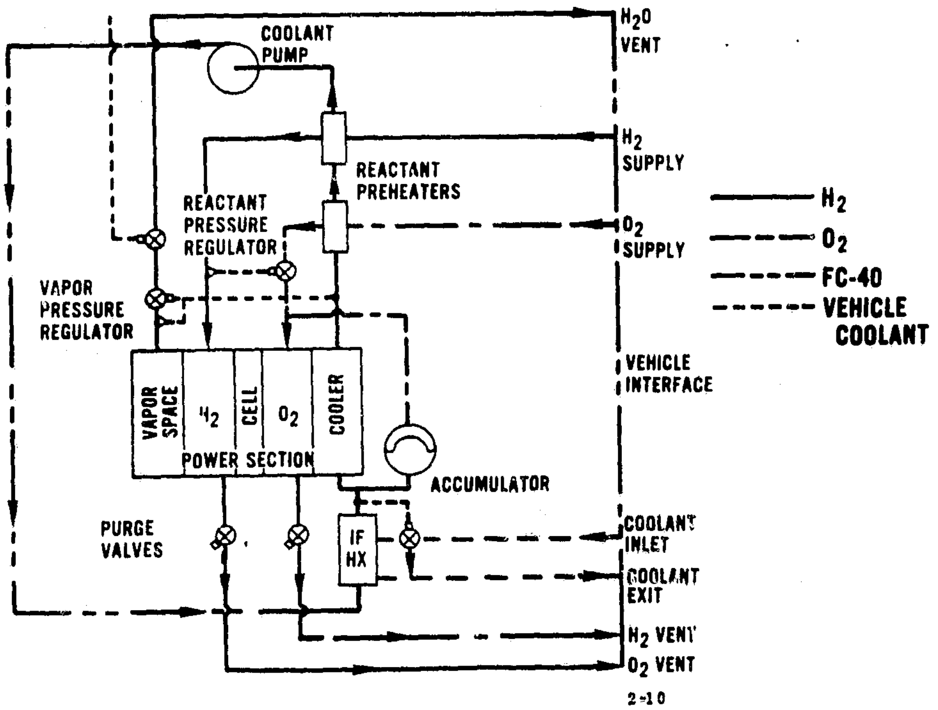

Figure 7. Lightweight Fuel Cell Powerplant Fluid Schematic

Reactants are supplied to the power section by demand-type pressure regulator valves. Reactant preheaters before these valves raise reactant temperature to the 180°F (82.2°C) nominal operating temperature of the power section. The valves assure that the oxygen pressure in the power section is maintained 2 psia(1.4 N/cm^2) above the hydrogen pressure at 19 psia (13.1 N/cm^2) over the full range of reactant flows. Fixed-size orifices in the reactant vent lines maintain a constant reactant purge rate, preventing the accumulation of inerts, from the propellent grade reactants, within the power section.

Product water is removed by the passive water removal method. Product water from the cell diffuses through a gas-tight passive water removal assembly and evaporates into a 4 psia (2.8 N/cm^2) cavity. A temperature-biased vapor pressure regulator controls this pressure, thereby maintaining the proper water balance in the cells over the full operating range. This regulator is temperature biased to power section coolant exit so that product water generated during startup is vented from the powerplant. This feature reduces the cell electrolyte reservoir plate volume requirements, resulting in powerplant weight savings. Product water is vented to the vehicle interface as a vapor.

Waste heat is removed from the power section by circulating a liquid dieletric coolant, FC-40, through cooler assemblies adjacent to each cell. The waste heat is rejected through an intereface heat exchanger to the space vehicle cooling system. A thermal control valve adjusts coolant flow from the space vehicle system to maintain a desired cell inlet temperature. An accumulator is provided in the powerplant coolant system to handle volume changes occurring over the load range. The coolant system is pressurized to oxygen system pressure via the accumulator reference line to the oxygen system.

The powerplant design was based upon the advanced lightweight-alkaline fuel cell design developed by Lewis Research Center of NASA. A powerplant based upon this technology could effect significant economies in vehicle weight and development cost. Figure 8 shows a model of the LFCP design.

A preliminary design table for the Lightweight Fuel Cell Powerplant is presented in Appendix B.

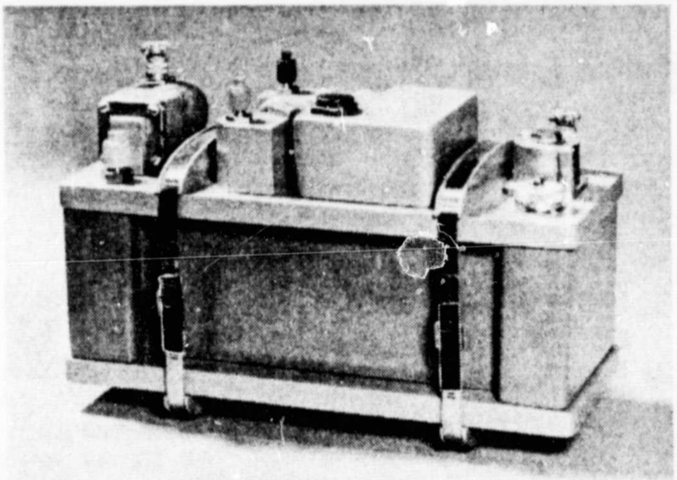

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Figure 8. Lightweight Fuel Cell Powerplant

C. Power Section Design

The power section for the Lightweight Fuel Cell Powerplant (LFCP) is a 23 pound (10.4 kg), 14.5 x 7 x 10 inch (36.8 x 17.8 x 25.4 cm) unit. This unit consists of 34, 0.25 ft^2 (232.3 cm^2) active area, liquid-cooled, low temperature, matrix-type, passive water removal alkaline fuel cells. Transfer of current between cells is accomplished by soldering the appropriate electrode screens together at the sides of the power section. The use of lightweight plastic, non-electically conducting components throughout the power section requires edge current transfer. The cells are packaged in two-cell modules which are connected electrically in series and are maintained in a rigid structure between end-plates that are secured by tierods.

The two-cell module consists of two, 77-mil (2mm) thick unitized electrode assemblies (UEA), a 35-mil (0.9mm) thick cooler assembly and two, 77-mil (2mm) thick passive water removal assemblies bonded into a rigid fiberglass epoxy edge frame. Teflon screens are used as the hydrogen and product water flow fields. The oxygen flow field consists of a 15-mil (.38mm) thick nickel electroform sheet with a nubbin pattern flow field. The components of the two-cell module assembly is shown on Figure 9. The design of each of these elements, with a few exceptions, are the same as the advanced technology lightweight fuel cell design developed under the NASA-LeRC program.

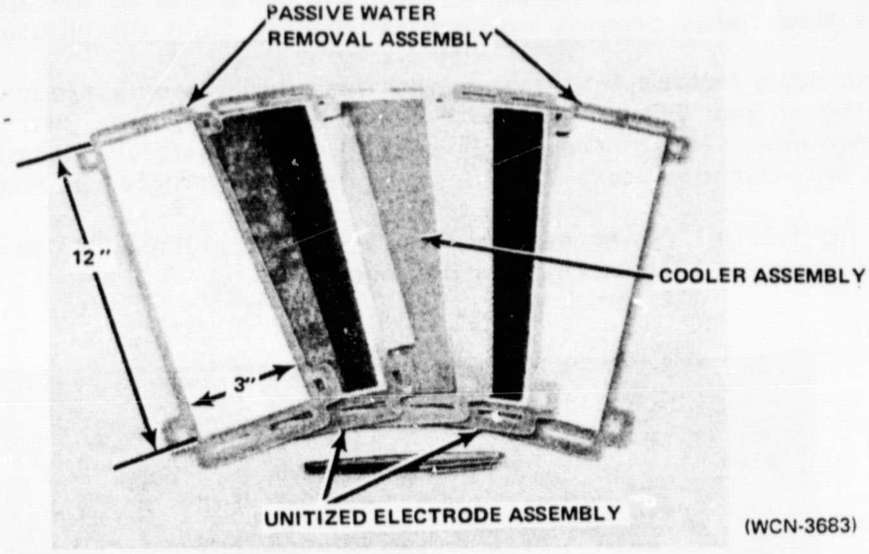

Figure 9. Two-Cell Module Assembly

The UEA consists of a cathode, a 10-mil (.25 mm) reconstituted asbestos matrix, an anode, and a 30-mil (.76 mm) porous nickel plated polysulfone electrolyte reservoir plate, all laminated into a rigid fiberglass/epoxy edge frame. The cathode catalyst is a gold-platinum alloy and the anode catalyst is a platinum alloy. The UEA is the electrochemical power generating unit of the power section.

The cooler assembly consists of a teflon screen sandwiched between two nickel electro-form sheets bonded into a rigid fiberglass/epoxy edge frame. The cooler assembly is located between cells, providing a coolant channel for cell waste heat removal.

The passive water removal (PWR) assembly consists of a protective screen, 10-mil (.25 mm) reconstituted asbestos gas barrier, support screen, 30-mil (.76 mm) nickel plated polysulfone electrolyte reservoir plate, and a porous Teflon electrolyte barrier membrane. The functions of the PWR assembly are to allow diffusion of product water from the cell to the vapor cavity and seal the 19 psia (13.1 N/cm^2) hydrogen from the 4 psia (2.76 N/cm^2) water vapor. The fine pore structure of the asbestos gas barrier provides the gas seal and offers a low resistance path for diffusion of product water. The electrolyte reservoir plate is provided for the gas barrier to accomodate the electrolyte volume changes that occur during different operating conditions assuring that the gas barrier is always filled with electrolyte. To prevent electrolyte loss from the PWR assembly during power section operation, the electrolyte barrier is provided. This fine pore hydrophobic membrane allows water vapor to pass through its pores while retaining electrolyte.

Holes in the fiberglass/epoxy edge frames of the UEA, Cooler, and PWR assembly form a continuous manifold in the assembled power section for reactant, coolant, and product water. Metering ports from the manifolds to the appropriate reactants or coolant flow fields provide uniform cell-to-cell fluid distribution.

Elastomeric seals molded into a specially designed fiberglass/epoxy frame, identified as the Integral Seal Frame, form the seal between adjacent PWR assemblies of the two-cell modules. Within the power section these seals are compressed by the endplates and tierods into a rigid leak-tight unit of high structural integrity.

A 30-cell lightweight power section was fabricated during the program. Figure 10 shows the assembled lightweight power section.

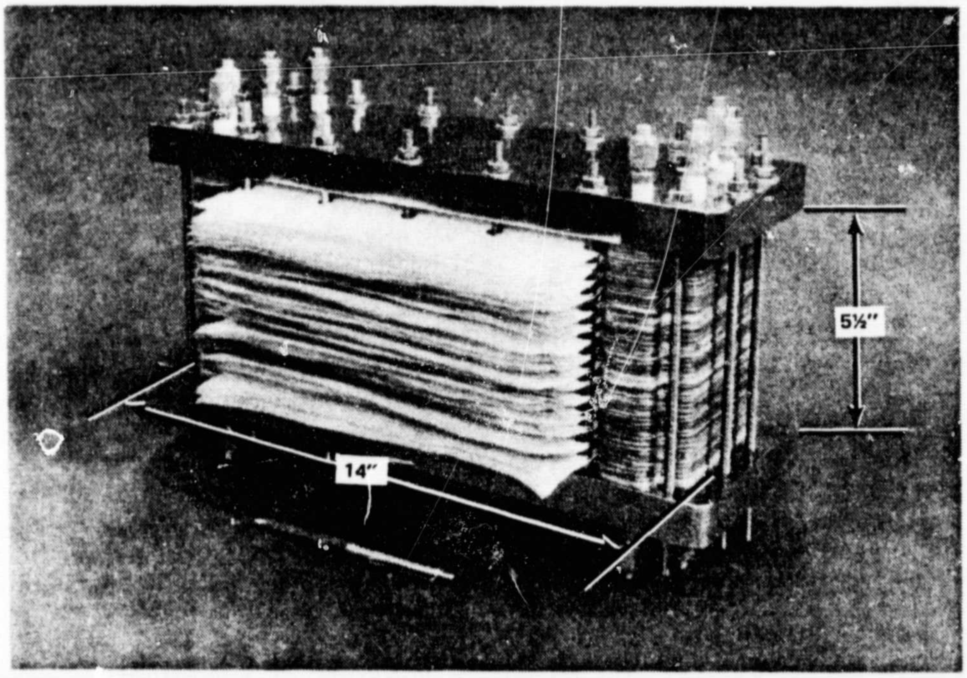

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Figure 10. Lightweight 30-Cell Power Section

V. LIGHTWEIGHT CELL CONFIGURATIONS

This section describes the two-cell module and single-cell configurations tested during the program. The two-cell module is the "basic" repeating unit of the lightweight power section incorporated into the Lightweight Fuel Cell Powerplant design. A two-cell module design was defined, based upon the NASA-Lewis advanced technology lightweight fuel cell configuration. Four, two-cell modules were constructed and tested.

Two, single cells capable of increased reactant pressure operation were constructed and tested. The fourth, two-cell module tested was constructed to a design capable of increased reactant pressure operation.

The two-cell modules and single cells tested incorporated the following similar features:

- Strip Cell, high length to width ratio
- Edge Current Collection
- Lightweight Plastic Cell Components
- Passive Water Removal

A. Two-Cell Module Assembly

The two-cell module (TCM) assembly shown in Figure 11 is the "basic" repeating unit of the lightweight power section. The TCM consists of two, unitized electrode assemblies (UEA) and passive water removal assemblies (PWR) bonded to a center cooler assembly. Table II presents a complete description of the Two-Cell Module Assembly.

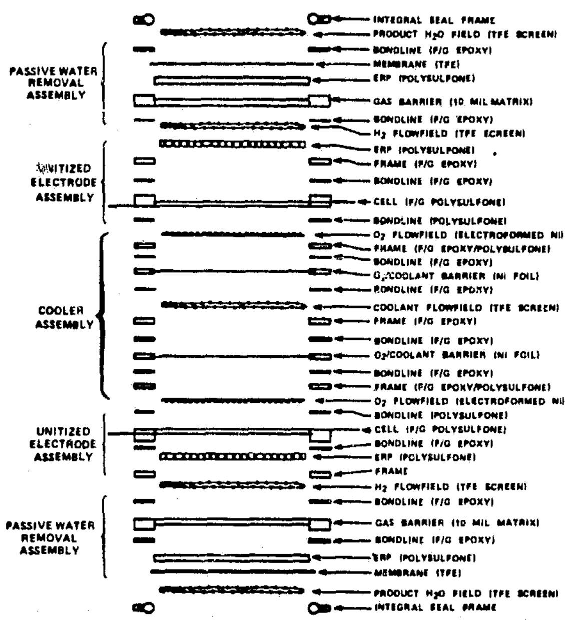

Figure 11.

Two-Cell Module Cross Section Description

TABLE II. TWO-CELL MODULE ASSEMBLY COMPONENT DESCRIPTION

Unitized Electrode Assembly
- Anode - Platinum-Palladium Catalyst on Silver Plated Nickel Screen
- Cathode - Gold-Platinum Catalyst on Gold Plated Nickel Screen
- Matrix - Reconstituted Asbestos
- Electrolyte Reservoir Plate - Nickel Plated Porous Polysulfone
- Cell Edge Frame - Resin Impregnated Fiberglass

Passive Water Removal Assembly
- Matrix - Reconstituted Asbestos
- Electrolyte Reservoir Plate - Nickel Plated Porous Polysulfone
- Membrane - Porous Teflon
- Protective Screen - Silver Plated Nickel Screen
- Edge Frame - Resin Impregnated Fiberglass

Cooler Assembly
- Oxygen/Coolant Separator - Electro-deposited Nickel foil
- Edge Frame - Resin Impregnated Fiberglass

Flow Fields
- Hydrogen - Teflon Screen
- Oxygen - Electroform Nickel
- Water Vapor - Teflon Screen
- Coolant - Teflon Screen

An integral seal frame, see Section VII.B, provides the seal between the product water cavity of adjoining Two-Cell Modules.

The UEA has an active area of 0.25 ft^2 (232.3cm^2) with planar dimensions of 3 x 12 inches (7.6x30.5cm). Nickel inlet reactant foils are used at both reactant inlets and on the PWR support screen at the hydrogen inlet. This feature prevents localized drying from the unhumidified reactants allowing water vapor diffusion to prevent port blockage.

There were four, two-cell modules tested during the program. A detailed description of these TCM's is shown in Table III. A summary of the performance evaluation tests is presented in Section VI.A.

TABLE III. SUMMARY OF TWO-CELL MODULE DESIGNS

Two-Cell Module (TCM) Identification	UEA Description	PWR Description	Oxygen Field	Hydrogen, Coolant Product Water
TCM-I	90Au-10Pt Cathode I0mil(0.25mm) Matrix Pt Pd Anode 30mil(0.76mm) Nickel-Polysulfone ERP Hybrid-Polysulfone Epoxy Glass-Fiber Frame	5 mil(0.127mm) Protective Screen I0mil(0.25mm) Matrix 30mil(0.76mm) Nickel-Polysulfone ERP Teflon Membrane Epoxy-Glass Fiber Frame	15mil(.38mm) Field-Electroform Nickel	Teflon Screen 30mils(0.76mm)
TCM-2	90Au-10Pt Cathode 10mil(0.25mm) Matrix Pt Pd Anode 30mil(0.76mm) Nickel Polysulfone ERP Hybrid-Polysulfone Epoxy Glass-Fiber Frame	5mil(0.127mm) Protective Screen I0mil(0.25mm) Matrix 5mil(0.127mm) Support Screen 30mil(0.76mm) Nickel-Polysulfone ERP Teflon Membrane Epoxy-Glass Fiber Frame	I5mil(0.38mm) Field-Electroform Nickel	Teflon Screen 30mils(0.76mm)
TCM-3 and TCM-4	90Au-10Pt Cathode I0mil(0.25mm) Matrix Pt Pd Anode 30mil(0.76mm) Nickel Polysulfone ERP Hybrid-Polysulfone Epoxy Glass-Fiber Frame	5mil(0.127mm) Protective Screen I0mil (0.25mm) Matrix 5mil(0.127mm) Teflon Impregnated Support Screen 30mil(0.76mm) Nickel-Polysulfone ERP Teflon Membrane Epoxy-Glass Fiber Frame	I5mil(0.38mm) Field-Electroform Nickel	Teflon Screen 30mils(0.76mm)

B. Single Cells

The 0.25 ft^2 ($232.3cm^2$) active area single cell design was based upon the advanced lightweight fuel cell technology developed under Lewis the Research Center program. (References 1, 2, 3, 4, 5, 8 and 9) A description of the single cell design is presented in Table IV.

TABLE IV. SINGLE-CELL COMPONENT DESCRIPTION

Unitized Electrode Assembly
- Anode - Platinum-Palladium Catalyst on Silver Plated Nickel Screen
- Cathode - Gold-Platinum Catalyst on Gold Plated Nickel Screen
- Matrix - Reconstituted Asbestos
- Electrolyte Reservoir Plate - Nickel Plated Porous Polysulfone
- Cell Edge Frame - Resin Impregnated Fiberglass

Passive Water Removal Assembly
- Protective Screen - Silver Plated Nickel Screen
- Matrix - Reconstituted Asbestos
- Support Screen - Teflon impregnated Nickel Screen
- Electrolyte Reservoir Plate - Nickel Plated Porous Polysulfone
- Membrane - Porous Teflon
- Edge Frame - Resin impregnated Fiberglass

Cooler Assembly
- Oxygen/Coolant Separator - Electro-deposited Nickel foil
- Edge Frame - Resin impregnated Fiberglass

Flow Fields
- Hydrogen - Teflon Screen
- Oxygen - Electroform Nickel
- Water Vapor - Teflon Screen
- Coolant - Teflon Screen

A typical single cell is shown in Figure 12.

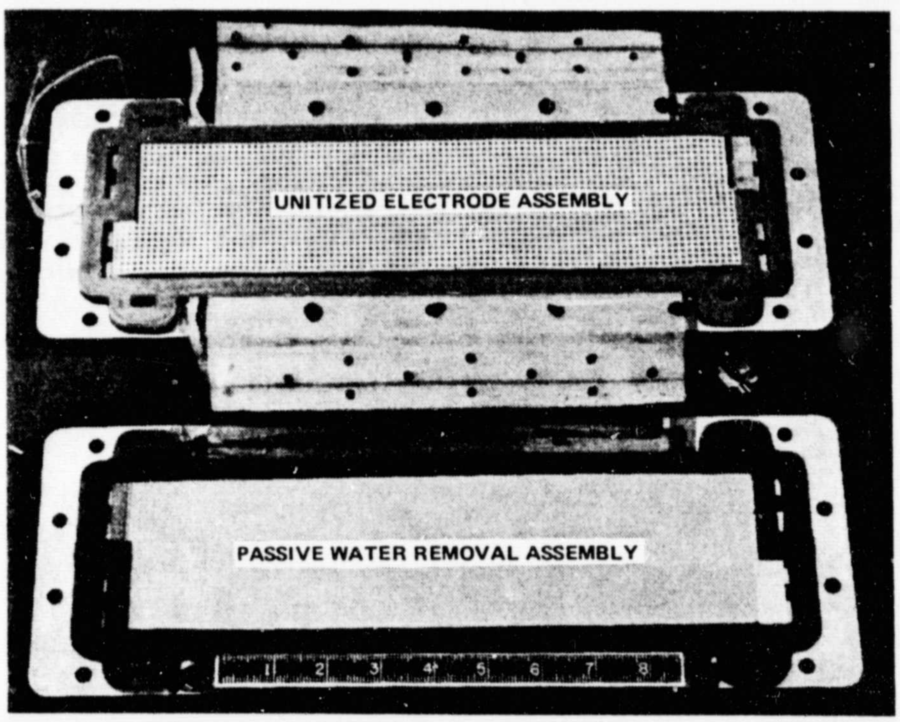

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Figure 12. Lightweight Single Cell Configuration

The cell includes a passive water removal (PWR) assembly modified for increased reactant pressure. The introduction of a Teflon impregnated nickel screen between the gas barrier matrix and polysulfone electrolyte reservoir plate of the PWR assembly allows higher reactant pressure operation, see Figure 13.

The UEA has an active area of 0.25 ft^2 (232.3cm^2) with planar dimensions of 3 x 12 inches (7.6x30.5cm).

There were two single cells fabricated and tested during the program. A detailed description of these single cells is shown in Table V. A summary of the performance evaluation tests is presented in Section VI.B.

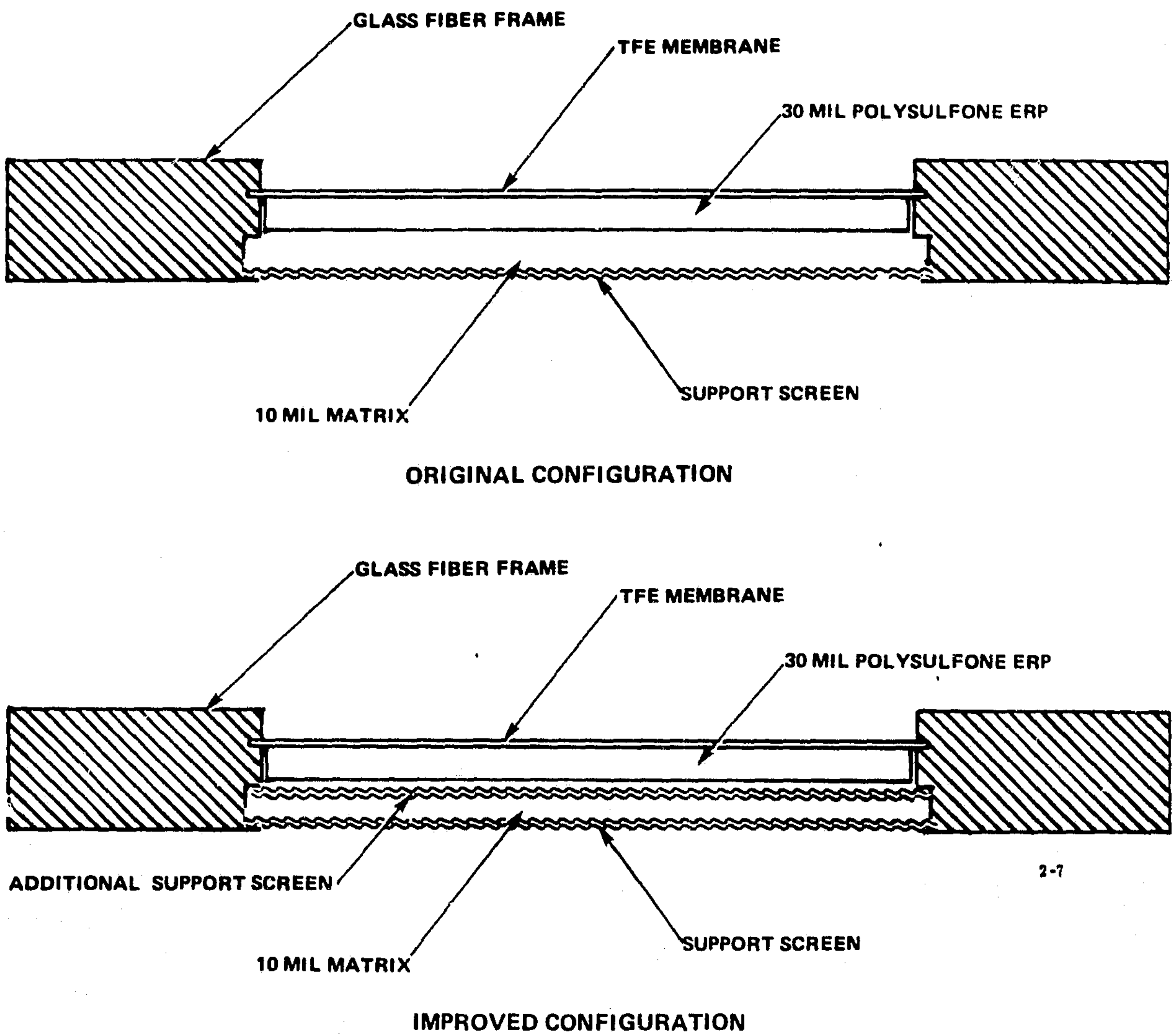

Figure 13. Passive Water Removal Assembly Configurations

TABLE V. SUMMARY OF SINGLE-CELL DESIGNS

Single-Cell Identification	UEA Description	PWR Description	Oxygen Field	Hydrogen, Coolant Product Water
HP-1 and HP-2	90Au-10Pt cathode 10mil(0.25mm) Matrix Pt Pd Anode 30mil(0.76mm) Nickel Polysulfone ERP Hybrid-Polysulfone Epoxy Glass Fiber Frame	5mil(0.127mm) Protective Screen 10mil(0.25mm) Matrix 5mil(0.127mm) Teflon Impregnated Support Screen 30mil(0.76mm) Nickel Polysulfone ERP Teflon Membrane Epoxy-Glass Fiber Frame	15mil(0.38mm) Field-Electroform Nickel	Teflon Screen 30mils(0.76mm)

VI. LIGHTWEIGHT CELL EVALUATION TESTS

This section summarizes each of the two-cell modules and single cells tested during the program.

A. Two-Cell Modules

A summary of the Two-Cell Module tests is presented in Table VI.

TABLE VI. TWO-CELL MODULE TEST SUMMARY

TCM* No.	Load Time-Hrs	Endurance Load Amps/ft²	Endurance Load mA/cm²	Nominal Cell Temperature °F	Nominal Cell Temperature °C	Reactant Pressure psia	Reactant Pressure N/cm²	Avg. Cell Performance - volts
2	5,051	33.7	36.3	165	73.9	16	11	.917
3	2,793	25.0	26.9	180	82.2	16	11	.929
4	1,011	33.7	36.3	165	73.9	30	20.7	.915

*TCM No. 1 Used To Evaluate Module Fabrication Techniques.

1. Two Cell Module No. 1

Two-cell module No. 1 (TCM-1) was constructed to the configuration identified in Section V.A. TCM-1 was scheduled to undergo an endurance test to evaluate module fabrication techniques and structural integrity. However following fabrication of TCM-1, reactant pressure tests identified leakage between the hydrogen and product water cavities through the passive water removal assembly (PWR).

Inspection of the PWR identified the leakage to be through the edge of the gas barrier matrix in an area unsupported by the electrolyte reservoir plate (ERP). The ERP apparently had contracted as a result of the multiple bonding heat cycles necessary for module fabrication. ERP shrinkage had not been encountered during single cell fabrication because only a single heat cycle is required. On all subsequent two-cell modules a protective support screen was included between the gas barrier matrix and ERP to provide support for the gas barrier. Figure 13 shows the location of the additional support screen in the PWR. This screen allows some shrinkage of the ERP without resulting in the loss of gas barrier matrix support.

2. Two-Cell Module No. 2

The test objective of two-cell module No. 2 (TCM-2) was to conduct an endurance test to verify that the two-cell module design meets performance and operating characteristics of the Lightweight Fuel Cell Powerplant (LFCP) design. A description of TCM-2 construction can be found in Section V.A. A total of 5,051 hours of performance evaluation testing was completed. TCM-2 was operated to a simulated mission profile through the first 2000-hours of testing. The performance history of TCM-2 is presented on Figure 14.

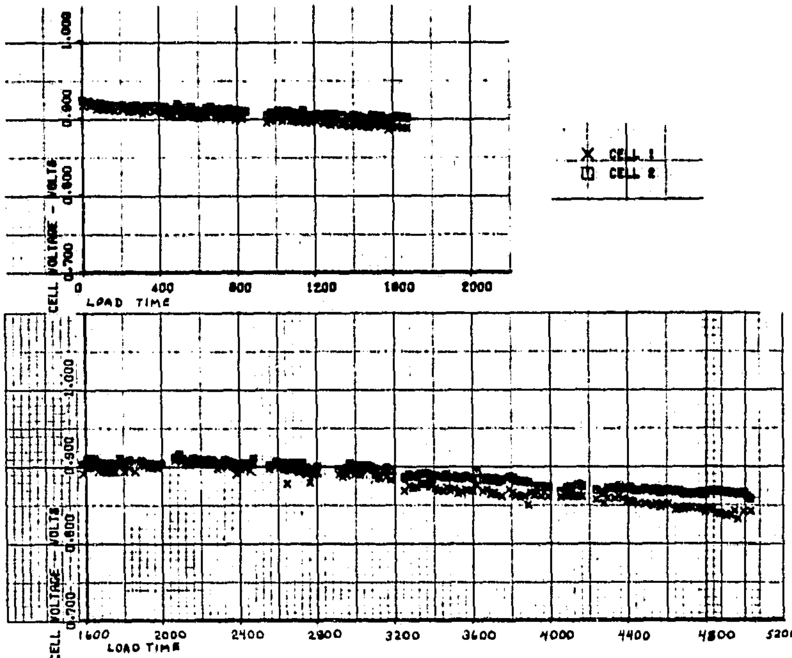

Figure 14. Two-Cell Module No. 2, Performance History

Figure 15 summarizes the test data from performance calibrations. As shown on Figure 15 the performance of TCM-2 exceeded the requirements of the LFCP design out to 3712 hours. The LFCP design life was 2,500 hours.

Electrolyte excursion test data, summarized on Figure 16, was obtained periodically during the endurance program. The cell electrolyte concentration was varied by changing product water cavity vacuum. The gradual change in performance response over the concentration range of 34% wt KOH to 40% KOH is an indication of a reduction in cell electrolyte inventory. A loss of cell electrolyte can be caused by carbonation of the electrolyte or by a physical loss of electrolyte from the cell. A carbonate analysis of the electrolyte at the completion of the test, 5051 load hours, revealed only 14.8% KOH converted to K_2CO_3, consistent with past NASA-LeRC single cell test experience, Figure 17. A loss of cell electrolyte to the PWR unit by the electrolyte transfer mechanism described in Reference 3 was more than likely the cause of the abnormal performance response to concentration variation. The loss of electrolyte from the cells is further supported by requirement throughout the test to lower product water cavity vacuum to control cell electrolyte inventory.

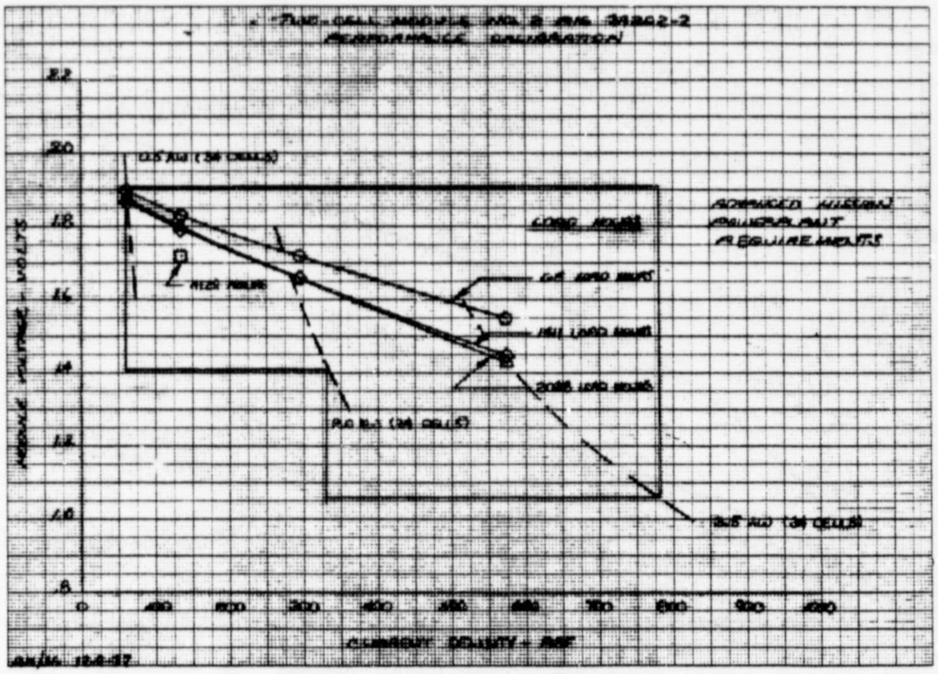

Figure 15. Two-Cell Module No. 2, Performance Calibrations

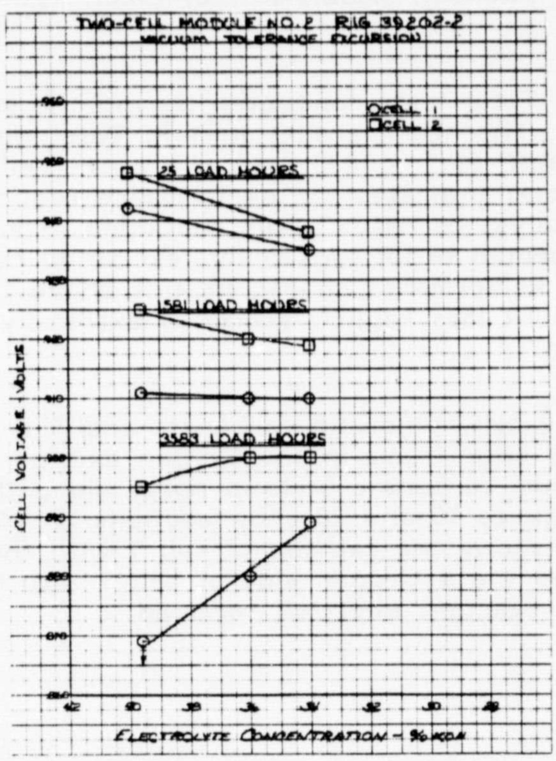

Figure 16. Two-Cell Module No. 2, Electrolyte Excursion Data

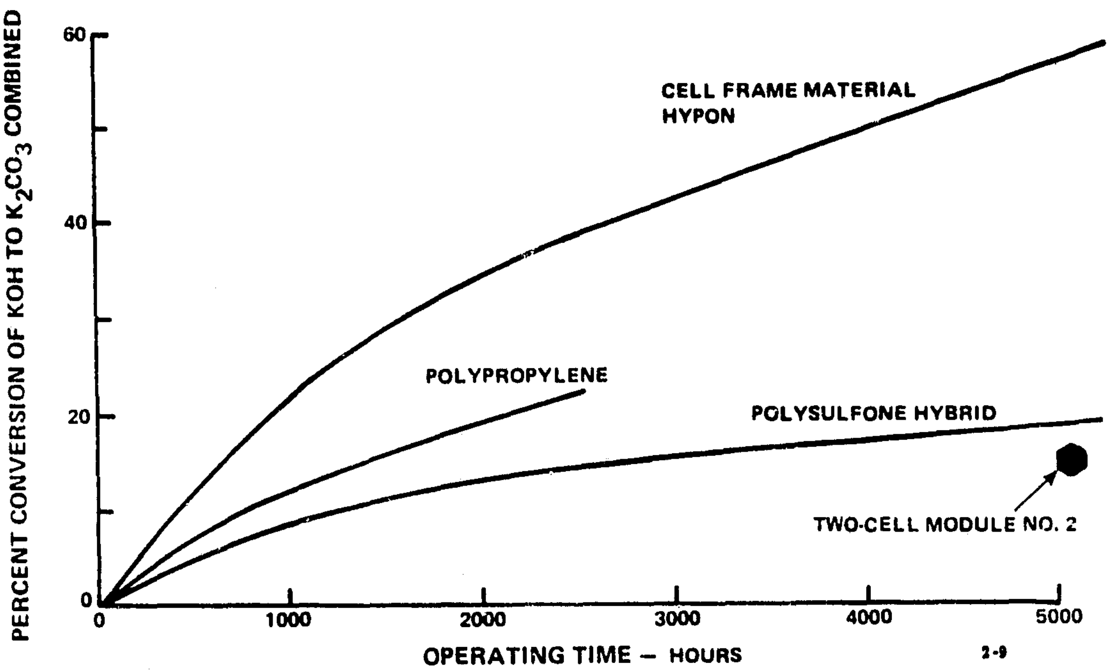

Figure 17. Two-Cell Module No. 2, Electrolyte Carbonation Data

Test data from oxygen Tafel tests conducted during the endurance test are summarized on Figure 18. The near parallel shift in Tafel slopes, voltage response in the load range of 1-10ASF (1.1 - 10.8 mA/cm^2) where cell IR and electrode diffusion losses are negligible, indicates the performance reduction with time was due to changes in cathode catalyst activity. This reduction in activity was greater than expected and was suspected to be caused by test stand contaminants introduced by the shutdown cycles. Performance characteristics above 10ASF (10.8 mA/cm^2), electrode diffusion and IR loss region, remained extremely stable throughout the 5051 hours of operation.

Visual inspection of the cell, following carbonate analysis identified some swelling of the fiberglass epoxy edge frame in the oxygen exit port area. In addition there was some potassium carbonate buildup noted along the periphery of the reactant inlet foil. Figures 19 and 20 show sections of TCM-2 during the teardown inspection. Figure 19 shows the cathode of cell 1 with the inlet reactant foil in place. Figure 20 shows the hydrogen side of cell 1 with the anode electrolyte reservoir plate (ERP), reactant inlet foil removed.

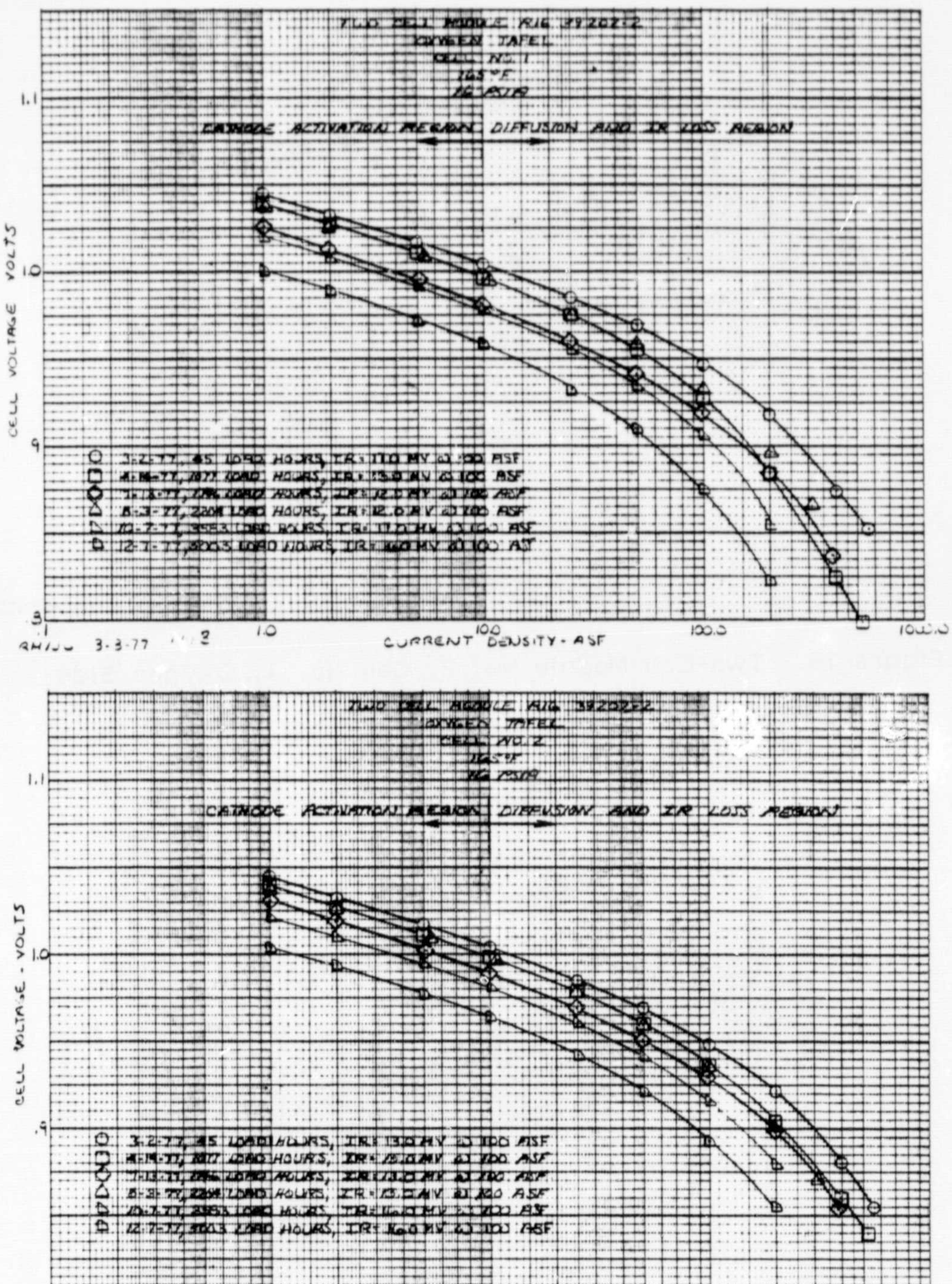

Figure 18. Two-Cell Module No. 2, Oxygen Tafel Test Data

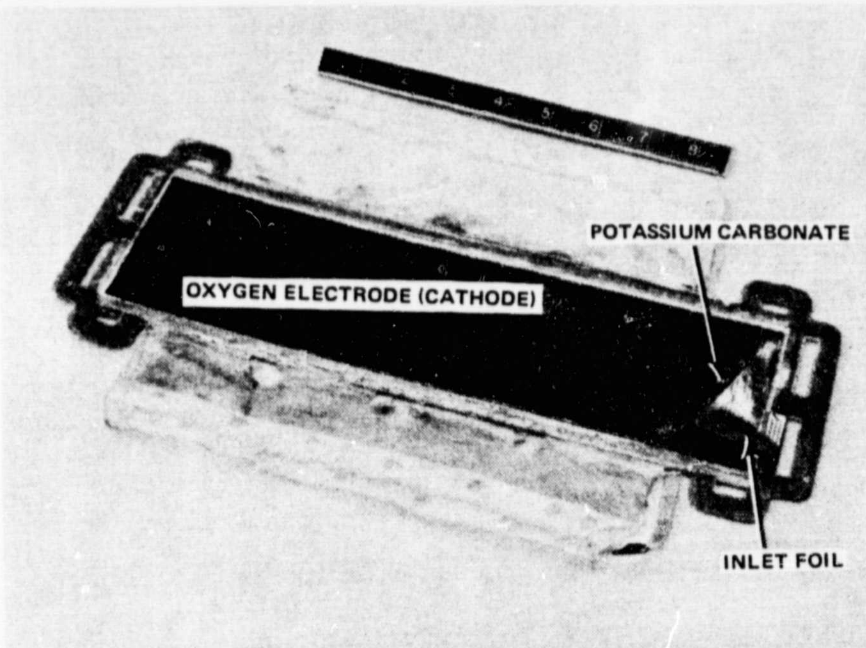

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Figure 19. Two-Cell Module No. 2, Cell No. 1, Oxygen Side

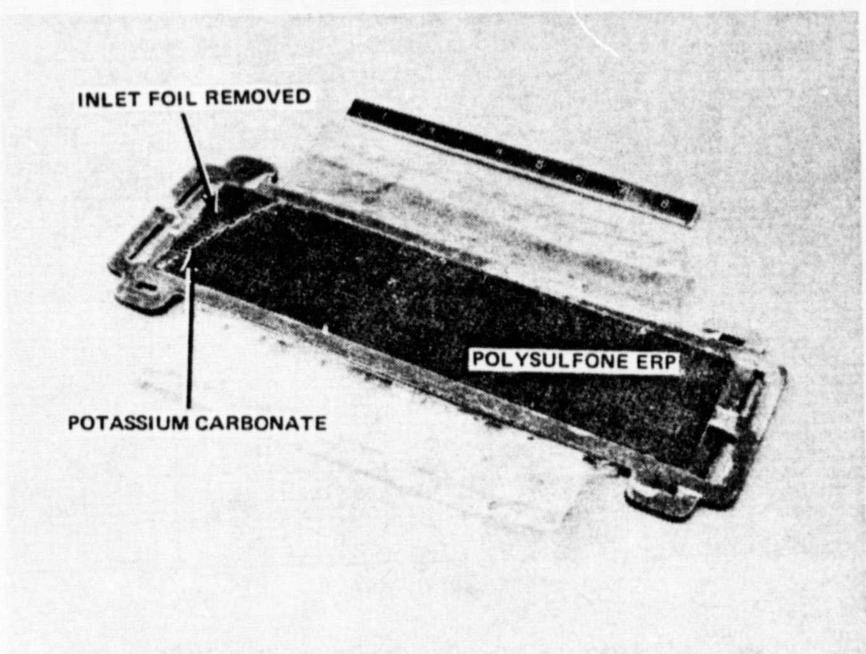

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Figure 20. Two-Cell Module No. 2, Cell No. 1, Hydrogen Side

3. Two-Cell Module No. 3

The test objectives of Two-Cell Module No. 3 (TCM-3) were to establish.

- Two-Cell Module Baseline Performance
- Performance Effects of Helium Diluted Reactants
- Performance Effects of Dry Reactant Operation

A detailed description of TCM-3 construction can be found in Section V.A. A total of 2793 hours of performance evaluation testing was completed. Testing was stopped following completion of all program test objectives. The performance history of TCM-3 is shown on Figure 21. As shown the performance of TCM-3 exceeded design voltage requirements during the entire 2793 hours of operation.

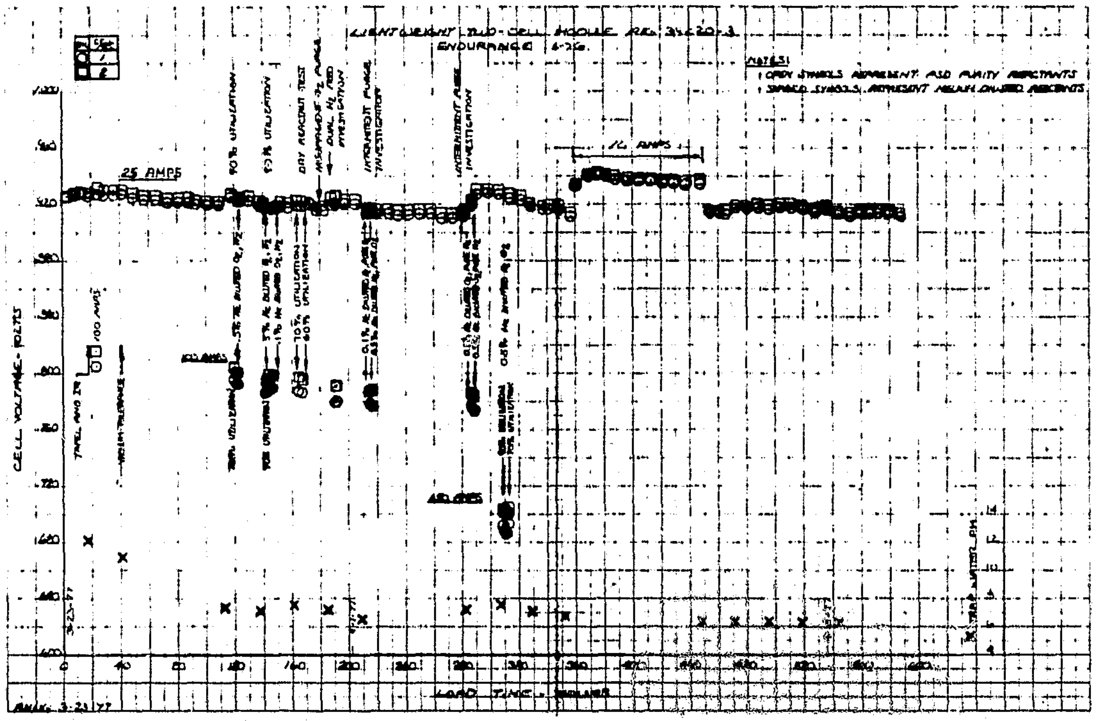

Figure 21. Two-Cell Module No. 3, Performance History (1 of 5)

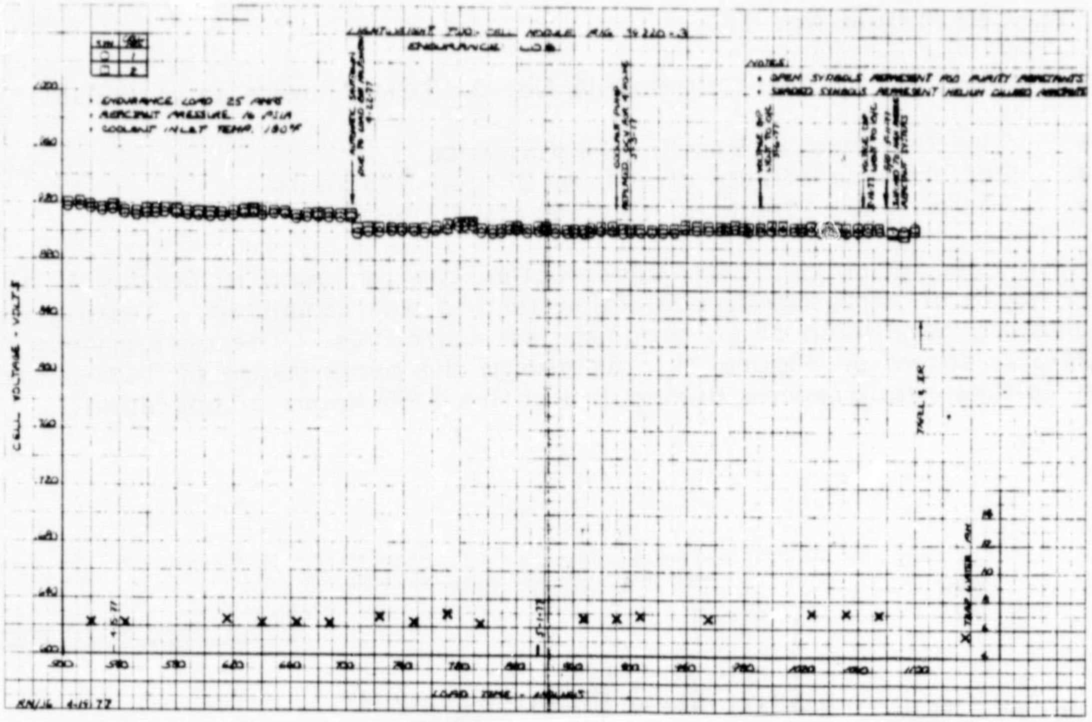

Figure 21. Two-Cell Module No. 3, Performance History (2 of 5)

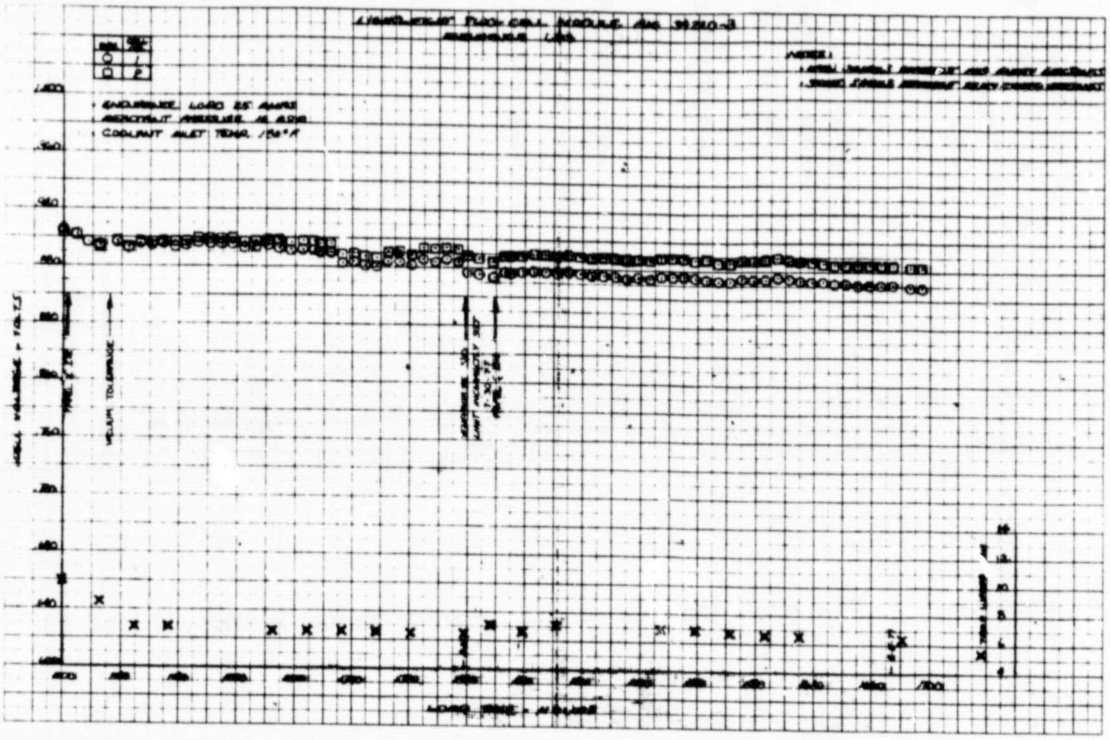

Figure 21. Two-Cell Module No. 3, Performance History (3 of 5)

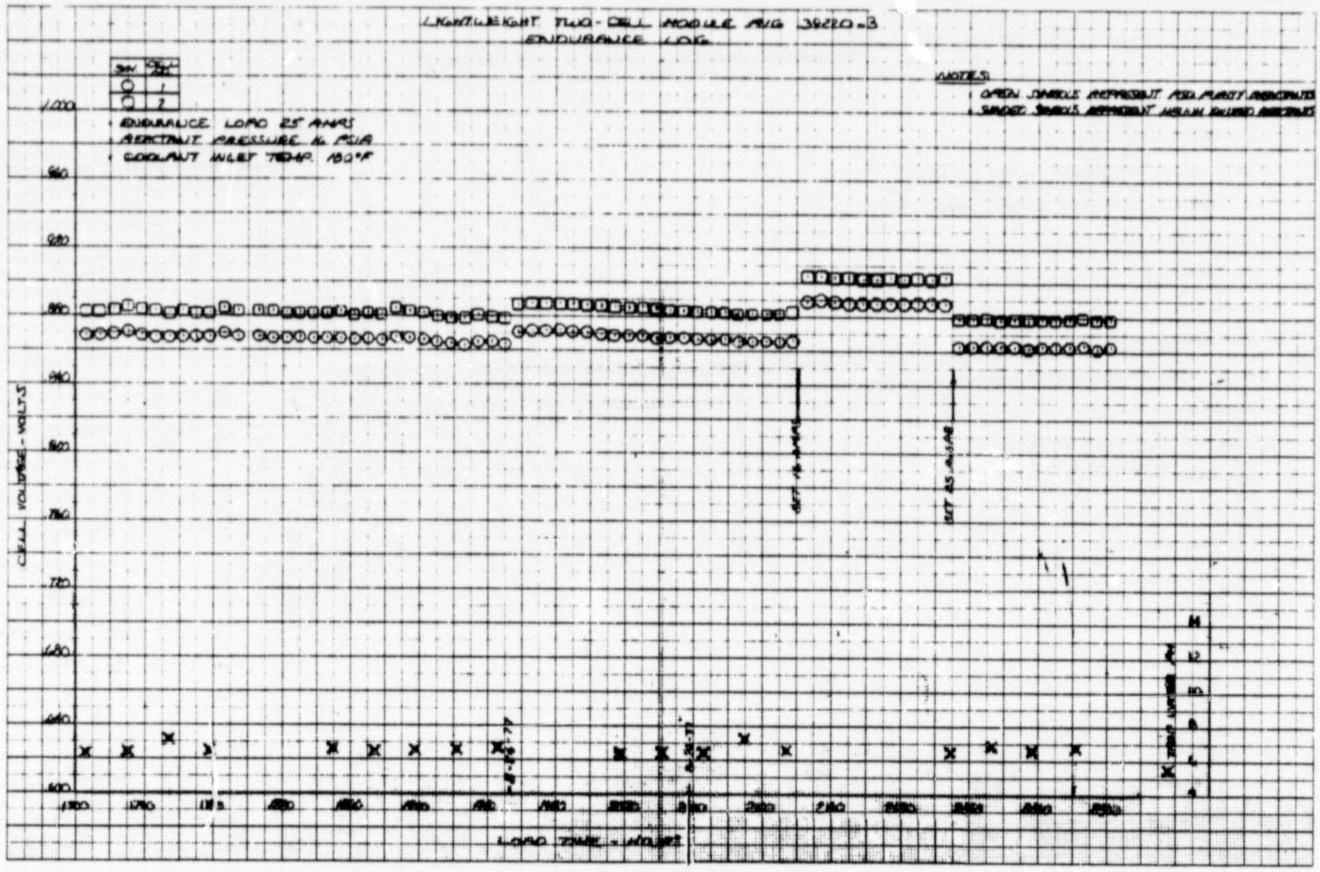

Figure 21. Two-Cell Module No. 3, Performance History (4 of 5)

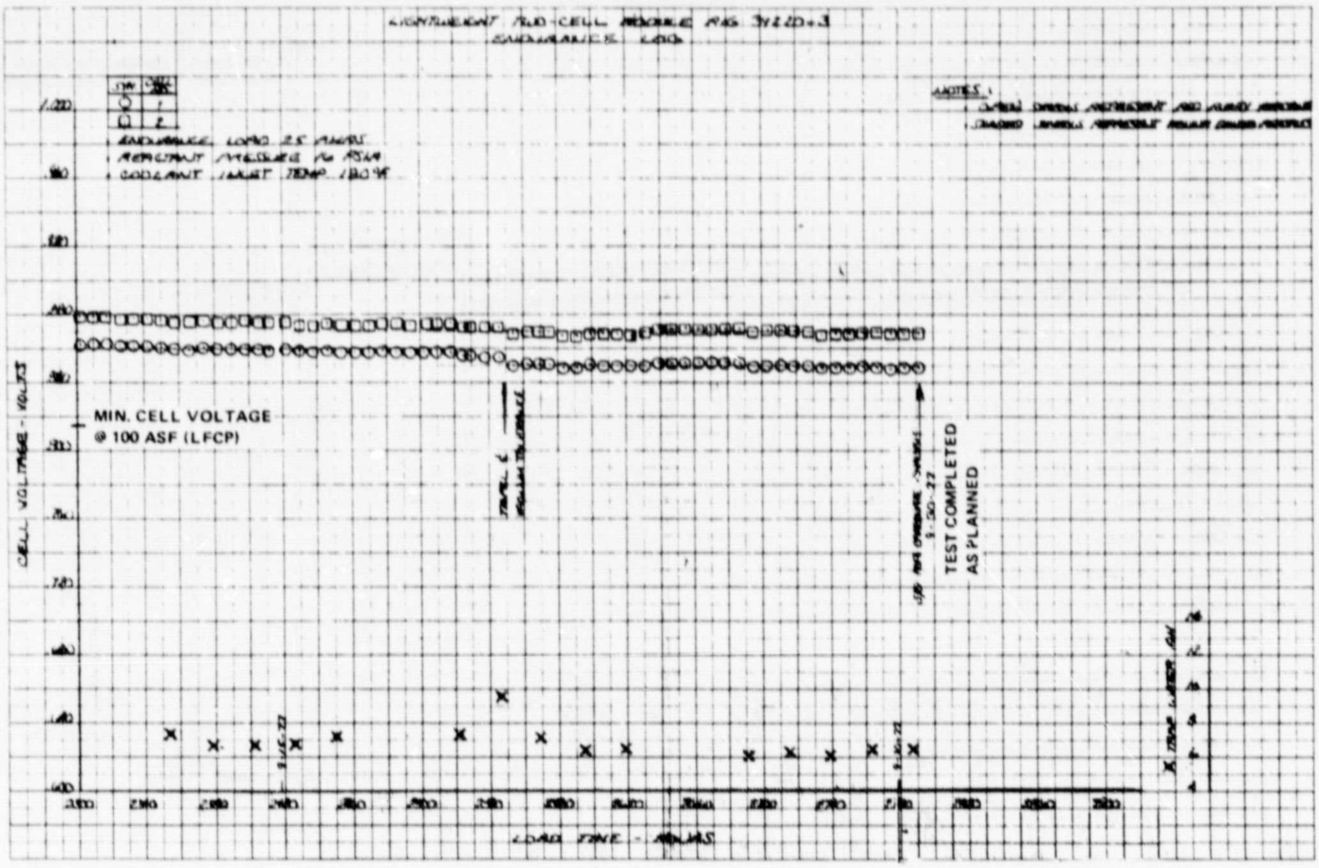

Figure 21. Two Cell Module No. 3, Performance History (5 of 5)

The effect of helium diluted reactants up to 0.5% helium on cell performance was very small. The effect on cell performance of 0.1% helium and 0.5% helium in the reactants was investigated at current densities out to 600ASF (645.8 mA/cm^2) and reactant utilization levels of 70% and 90%. These helium levels are in excess of those expected in Space Vehicle ullage gases. Figure 22 shows the effect on cell performance of helium diluted reactants at 400ASF (430.6 mA/cm^2) as a function of reactant utilization. The cell voltage response to helium diluents was very low and was consistent with NASA-LeRC single cell test experience (Reference 2).

The effect on cell performance of helium diluted reactants at 600ASF (645.8 mA/cm^2) is shown on Figure 23. The cell performance variation due to 0.5% helium diluted reactants was less than 7mV at 600ASF (645.8 ma/cm^2). Dilute reactant testing confirms that the two-cell module design is capable of operating on diluted reactants in excess of that expected from space vehicle propellent gases.

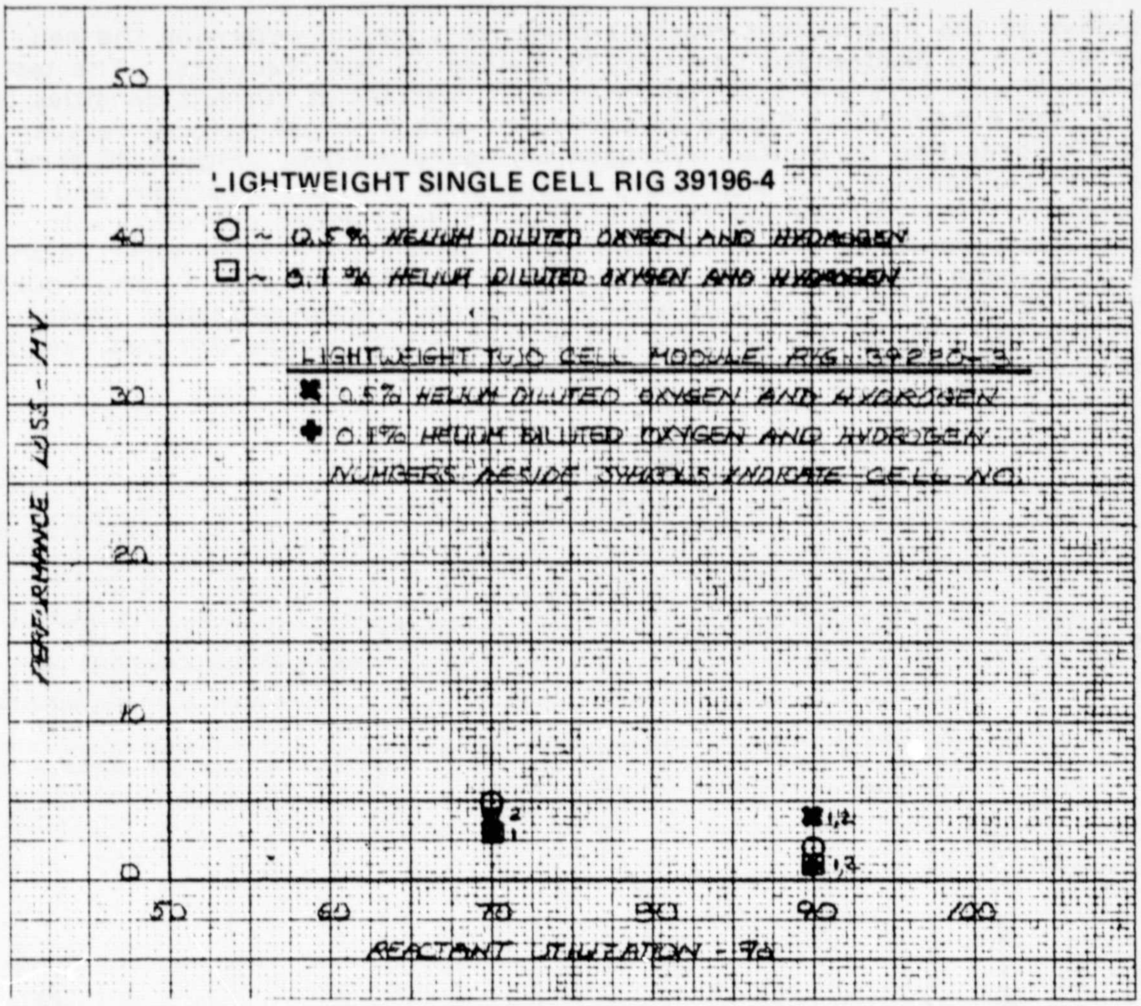

Figure 22. Effect of Diluted Reactants 400ASF

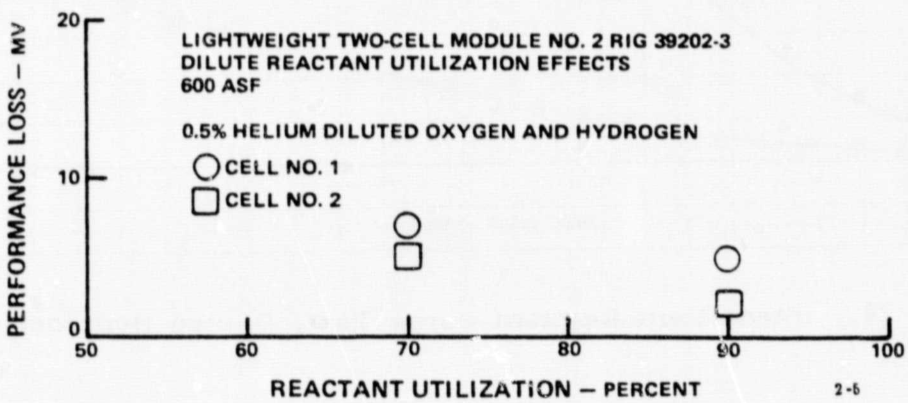

Figure 23. Effect of Diluted Reactants 600ASF

The objective of the intermittent reactant purge test was to determine the cell voltage response to dead-ended operation on helium diluted reactants. The test was conducted with 0.1% and 0.5% helium in each reactant at current densities out to 400ASF (430.6 mA/cm²). Figure 24 shows the effect on cell voltage versus amp-hours of operation on diluted hydrogen and pure oxygen. Figure 25 shows the effect on cell voltage with amp-hours of operation on pure hydrogen and diluted oxygen. The cell voltage reduction due to dead-ended operation with diluted reactants would be the sum of the losses determined from Figures 24 and 25. As an example each cell in the module would lose ~80mV after 30 amp-hours of operation at 100ASF (107.6 mA/cm²) with 0.1% Helium diluted reactants. Intermittent purge test results are consistent with NASA-LeRC single cell test results reported in Reference 2.

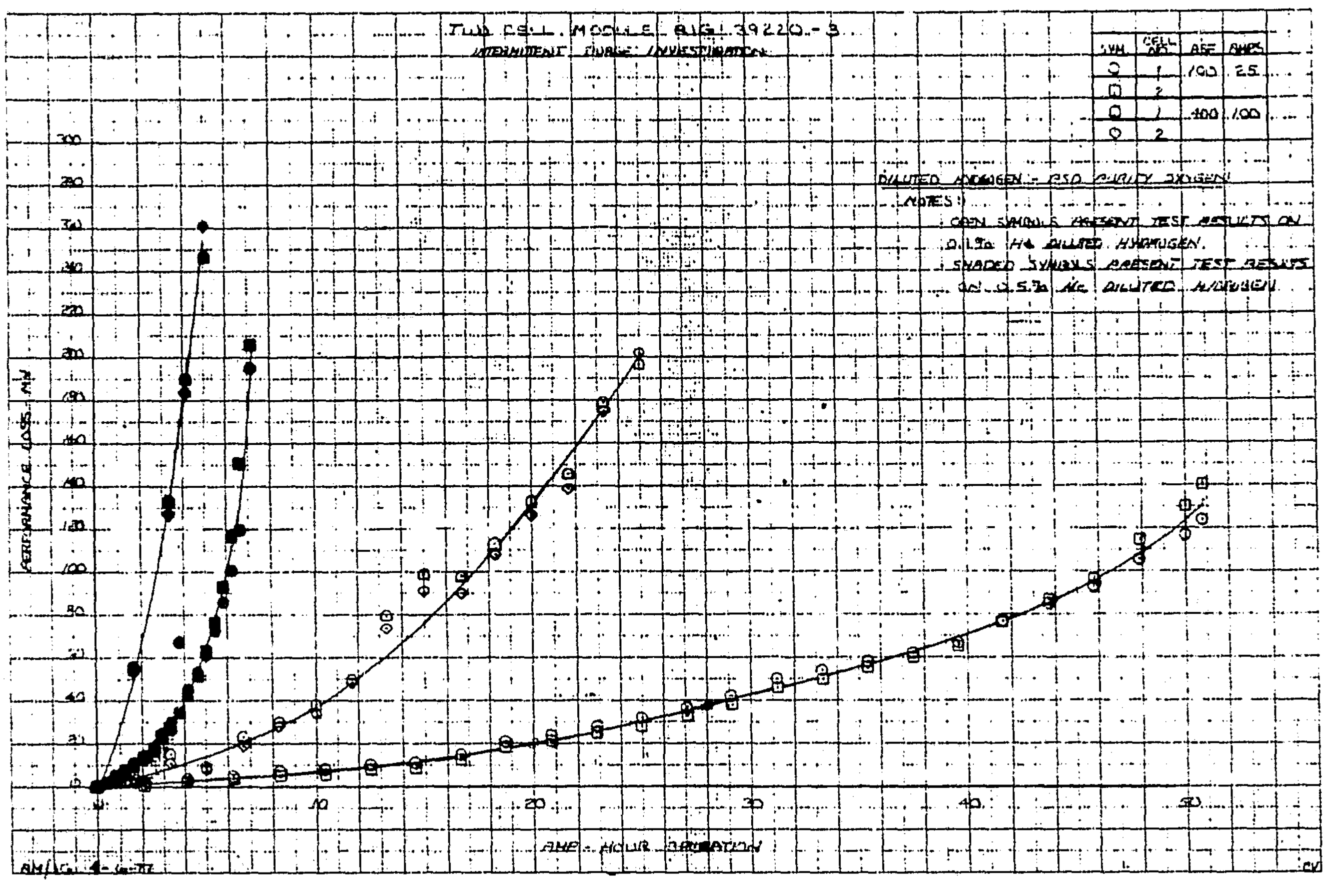

Figure 24. Intermittent Reactant Purge Test, Diluted Hydrogen

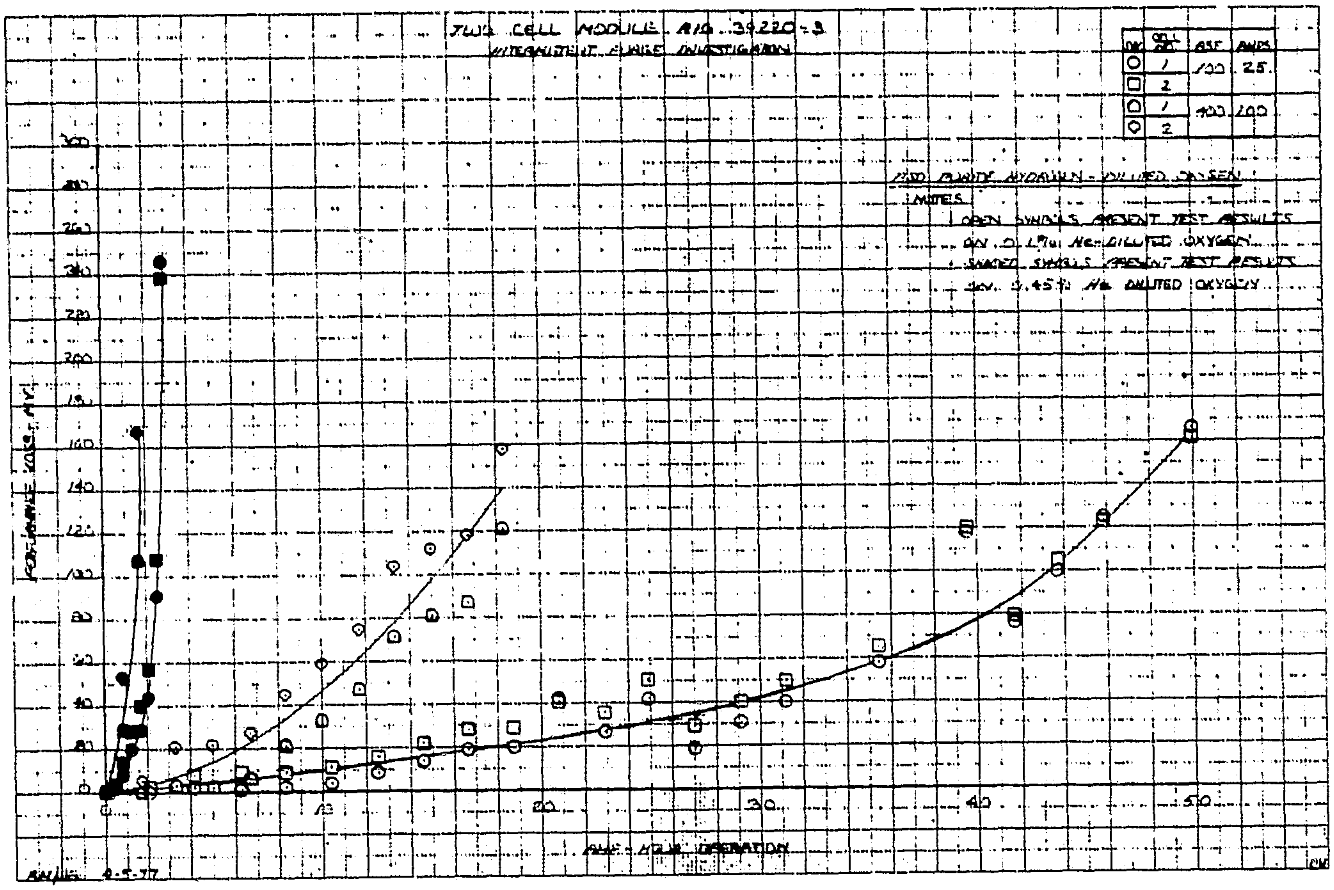

Figure 25. Intermittent Reactant Purge Test, Diluted Oxygen

The two-cell module was operated at reduced reactant utilizations of 60% and 70% to investigate the effect on performance of high flow, dry inlet reactants. As shown on the performance history, Figure 21, at 165 load hours there was no significant effect upon cell voltage. This test result confirms that un-humidified reactant operation of the Lightweight Fuel Cell Powerplant design should not be a problem. Passive water removal operation apparently allows sufficient water vapor back diffusion from the humidified cell exit to the dry inlet, preventing any localized drying.

Electrolyte excursion test data was obtained periodically during the endurance test. Figure 26 presents the data from the electrolyte excursion tests. The cell electrolyte concentration was varied by changing product water cavity vacuum. The gradual change in performance response over the concentration range of 34% wt KOH to 40% KOH on cell 1 is an indication of a reduction in cell electrolyte inventory. A carbonate analysis of the electrolyte at the completion of the test, 2793 load hours, revealed that only 15.4% KOH converted to K_2CO_3, which is consistent with past test experience, Figure 27. A loss of cell electrolyte to the PWR unit by the electrolyte transfer mechanism described in Reference 3 appears to be the cause of the abnormal performance response to concentration variation.

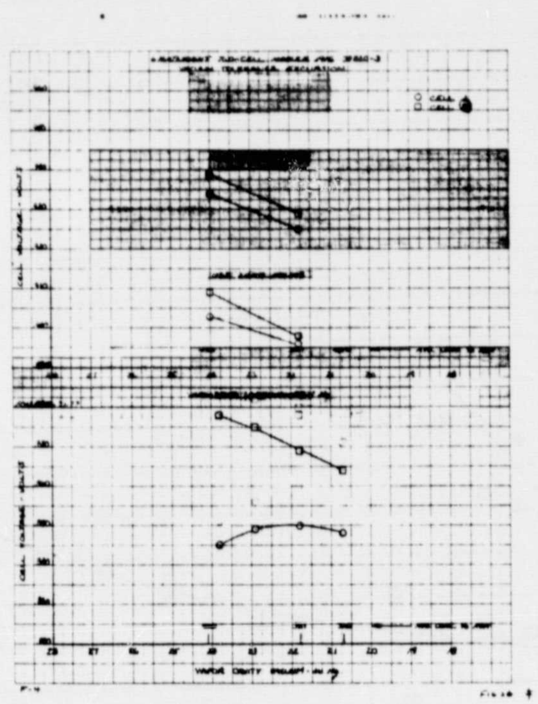

Figure 26. Two-Cell Module No. 3, Electrolyte Excursion Data

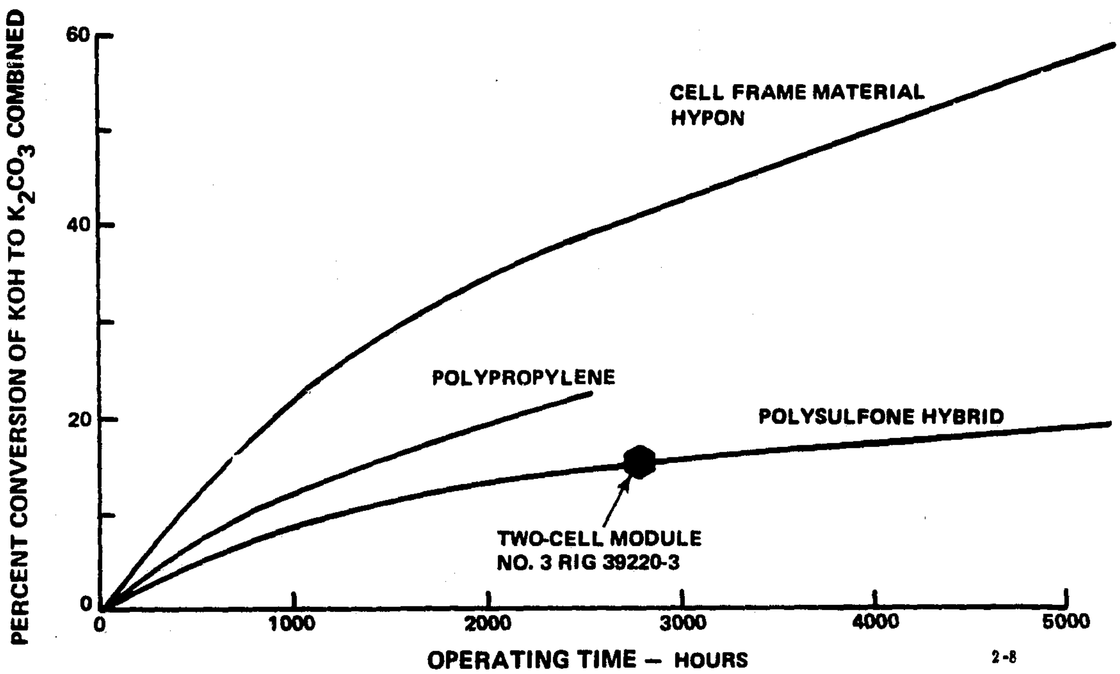

Figure 27. Two-Cell Module No. 3, Electrolyte Carbonation Data

Test data from oxygen Tafel tests conducted during the endurance test are shown in Figures 28 and 29. The near parallel shift in the Tafel performance voltage response in the 1-10ASF (1.1 - 10.7 mA/cm^2) load range, where cell IR and electrode diffusion losses are negligible, indicates the performance loss with time was due to reduction in cathode catalyst activity. This reduction in activity was greater than expected and was suspected to be caused by test stand contaminants introduced during shutdown cycles. Performance characteristics above 100ASF (107.6 mA/cm^2), electrode diffusion and IR loss region, remained extremely stable throughout the 2793 hours of testing.

Tear down inspection of the module, following carbonate analysis of the electrolyte, showed all module components to be in good condition. There was no visual evidence of compression set in any of the plastic components. Virtually no frame corrosion was observed, other than some slight swelling in the oxygen exit port area. Figure 30 shows the hydrogen side of cell I with the Teflon screen flow field on the anode ERP. Figure 31 shows the cathode of cell No. I.

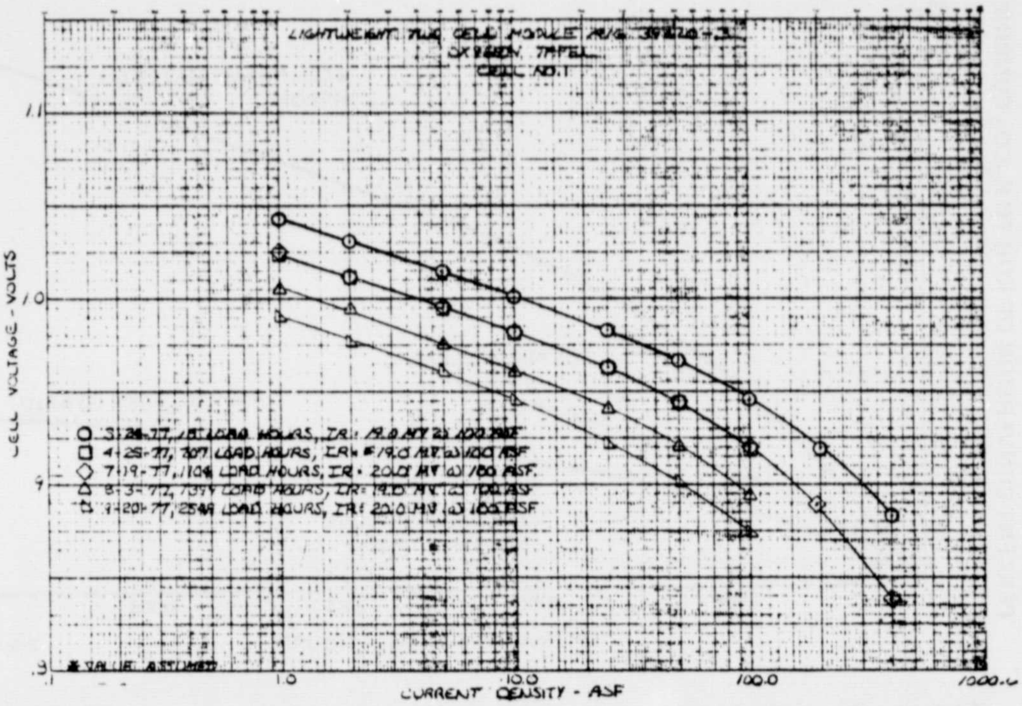

Figure 28. Two-Cell Module No. 3, Cell 1 oxygen Tafel Test Data

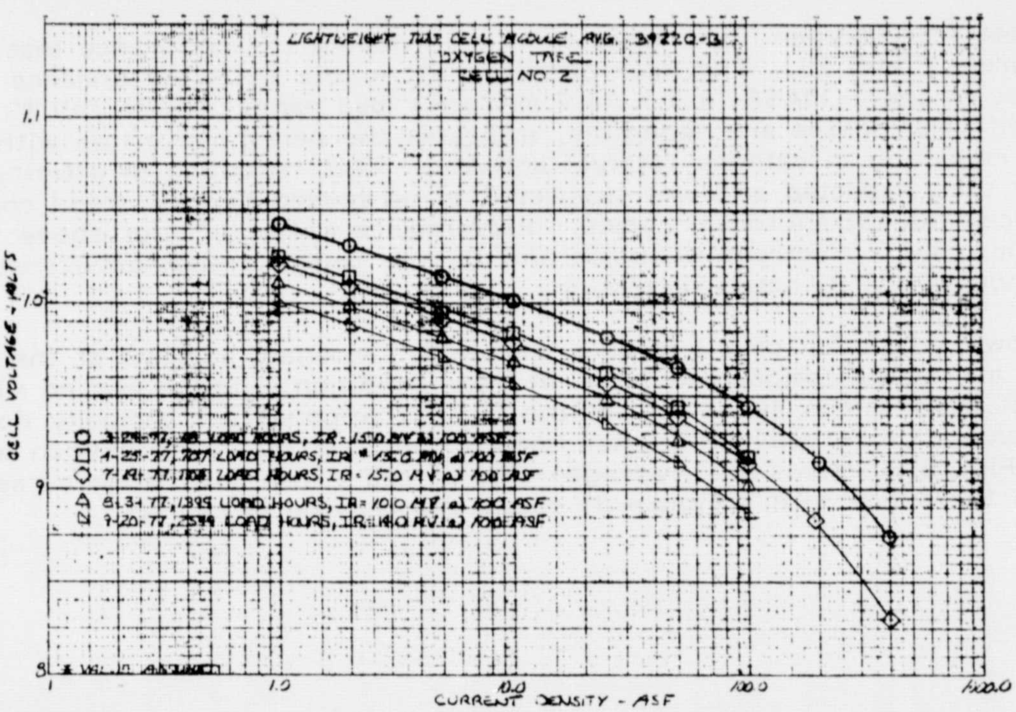

Figure 29. Two-Cell Module No. 3, Cell 2 Oxygen Tafel Test Data

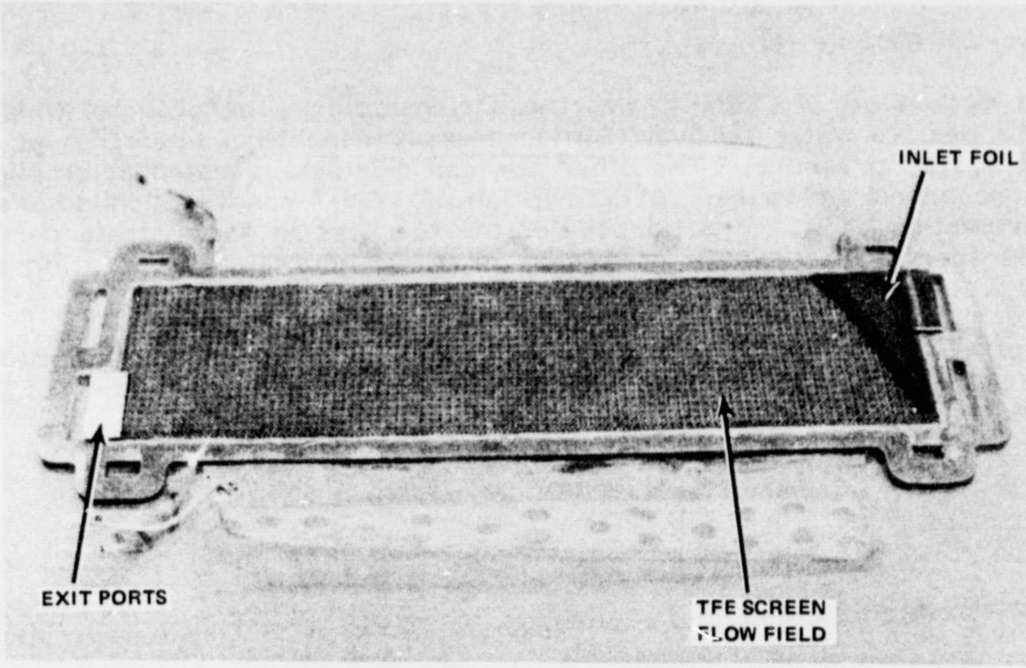

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Figure 30. Two-Cell Module No. 3, Cell No. 1, Hydrogen Side

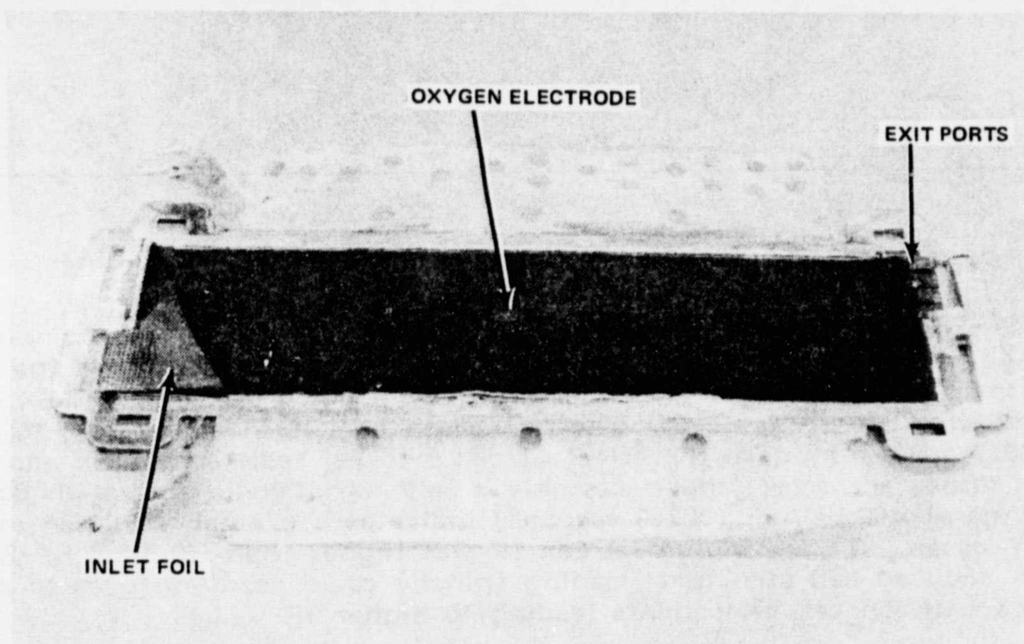

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Figure 31. Two-Cell Module No. 3, Cell No. 1, Oxygen Side

4. Two-Cell Module No. 4

Two-cell module No. 4 (TCM-4) was the only module in the program which incorporated a passive water removal (PWR) assembly capable of operating at increased reactant system pressure. The other two-cell modules operated at or slightly above atmospheric pressure. A description of TCM-4 construction details can be found in Section VI.A. The purpose of the test was to demonstrate performance and endurance characteristics of TCM-4 for 1,000 hours while operating at a 30 psia (20.7 N/cm^2) reactant pressure.

A total of 1,011 hours of operation was completed. The test was stopped following successful completion of the test objective. The performance history of TCM-4 is presented on Figure 32.

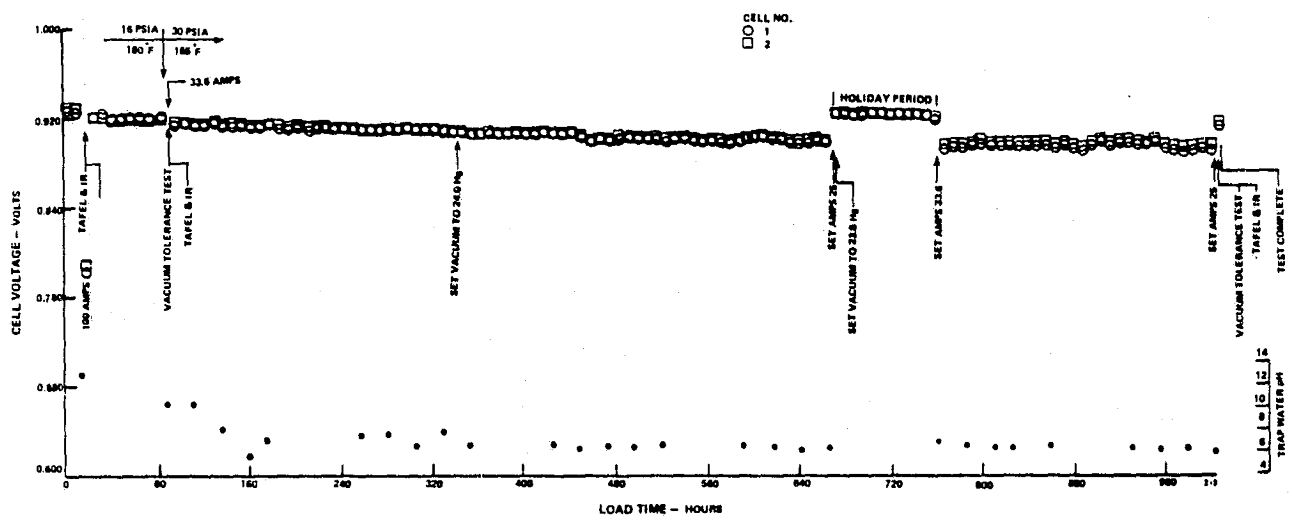


Figure 32. Two-Cell Module No. 4, Performance History

Figure 33 presents the initial oxygen Tafel test results compared to single cell Nos. HP-1 and HP-2, see Section IV.B at comparable load times. At the low reactant pressure of 16 psia (11 N/cm^2) the Tafel performance of TCM-4 cells was consistent with HP-1 and HP-2. The performance in the load range 1 to 10ASF (1.1 - 10.7 mA/cm^2) where the effect of cell internal resistance (IR) and electrode diffusion losses are small, there was only a 5mV variation in activation potential. The voltage above 100ASF (107.6 mA/cm^2) indicates a greater variation in electrode diffusion losses. TCM-4 individual cell IR was higher than HP-1 or HP-2 experience. A reduced cell structural loading (pinch) could result in greater contract resistance between cell components leading to higher IR values.

The effect of increased reactant pressure on cell performance is presented on Figure 34. At 30 psia (20.7 N/cm^2) reactant pressure and 165°F (73.9°C), TCM-4 demonstrated a 48 mV at 400ASF (430.6 mA/cm^2) increase in performance over the performance at 16 psia (11 N/cm^2) reactant pressure and 180°F (82.2°C).

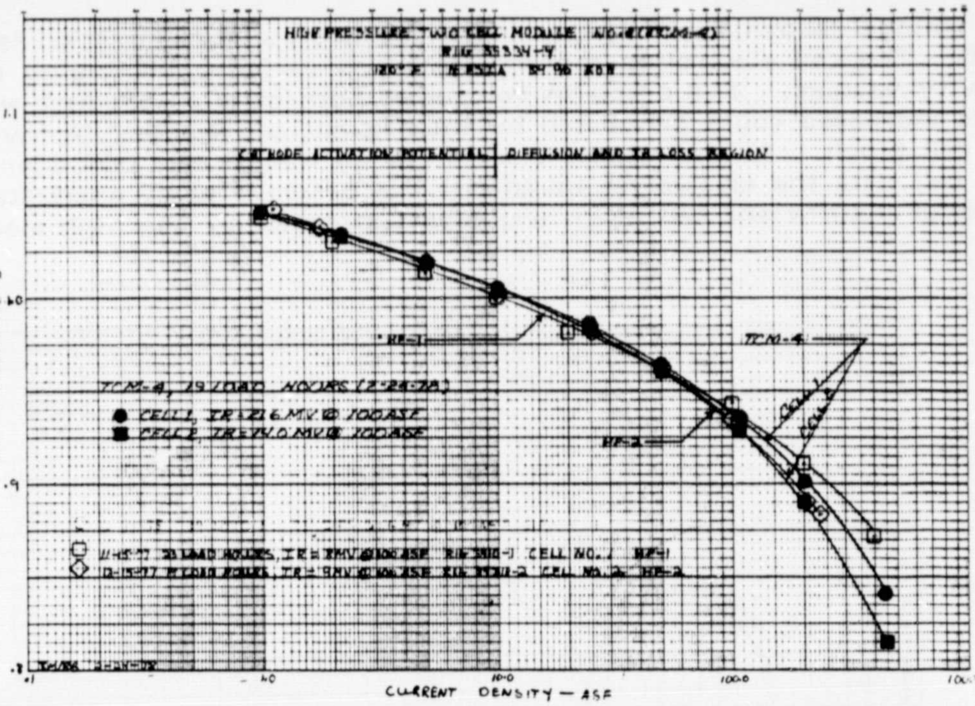


Figure 33. Two-Cell Module No. 4, Oxygen Tafel Test Data

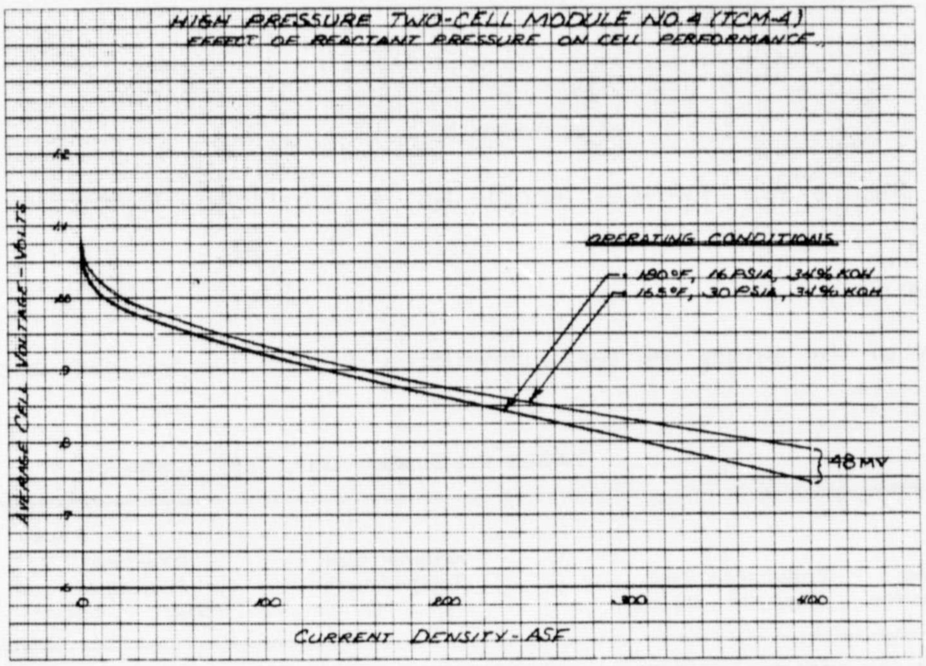


Figure 34. Effect of Reactant Pressure on Cell Performance

The cell voltage response to changes in cell electrolyte concentration is shown in Figure 35. The cell electrolyte concentration was varied by changing the product water cavity vacuum. The droop in voltage of both cells as product water cavity vacuum is increased could be caused by insufficient cell electrolyte inventory or reduced cell pinch. As the module electrolyte fill weight was consistent with previous cell data the electrolyte inventory was assumed to be adequate. The conclusion of insufficient cell pinch was also supported by the high measured IR values.

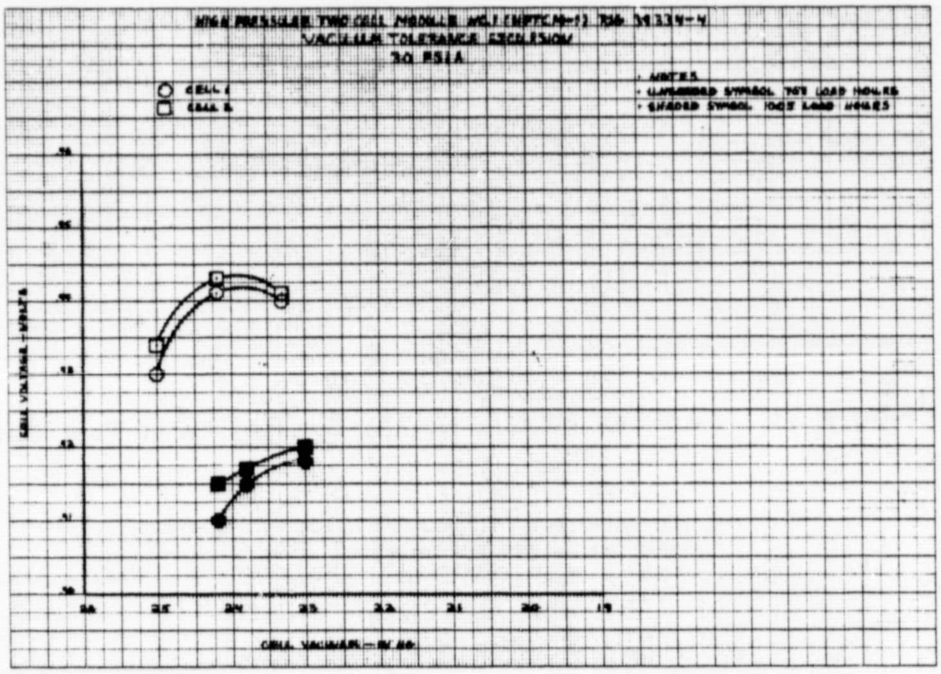


Figure 35. Two-Cell Module No. 4, Electrolyte Excursion Data

B. Single-Cells

A summary of the single cell tests conducted during the program is presented in Table VII.

TABLE VII. SINGLE-CELL TEST SUMMARY

Cell No.	Load Time-Hrs	Endurance Load Amps/ft^2	Endurance Load Ma/cm^2	Nominal Cell Temperature °F	Nominal Cell Temperature °C	Reactant Pressure PSIA	Reactant Pressure N/cm^2	Initial Performance Volts
HP-1	744	134.8	145.1	165	73.9	45	31	.956
HP-2	478	134.8	145.1	165	73.9	60	41.4	.948

1. Single Cell No. 1 (HP-1)

The test objective of single cell No. 1 (HP-1) was to establish the performance characteristic of the 0.25 ft^2 ($232.2 cm^2$) active area cell at a reactant pressure of 45 psia ($31.0 N/cm^2$). The cell was constructed with a passive water removal unit capable of operating at increased reactant pressure. Details of the cell construction are presented in Section V.B. A total of 744 hours of testing was completed. The endurance test was stopped because of a continuing loss of cell electrolyte. The performance history of the cell is shown in Figure 36.

The cell voltage response to changes in product water cavity vacuum at 500 and 692 hours is shown on Figure 37. The decrease in cell voltage with an increase in product water vapor cavity vacuum at 500 hours was the indication of a reduction in cell electrolyte inventory. The capability of HP-1 to operate at an electrolyte concentation below the normal fill electrolyte concentration is an indication of a loss in cell electrolyte. The loss of potassium hydroxide from the cell reduces the electrolyte concentration at which the cell is completely filled. Also beyond 500

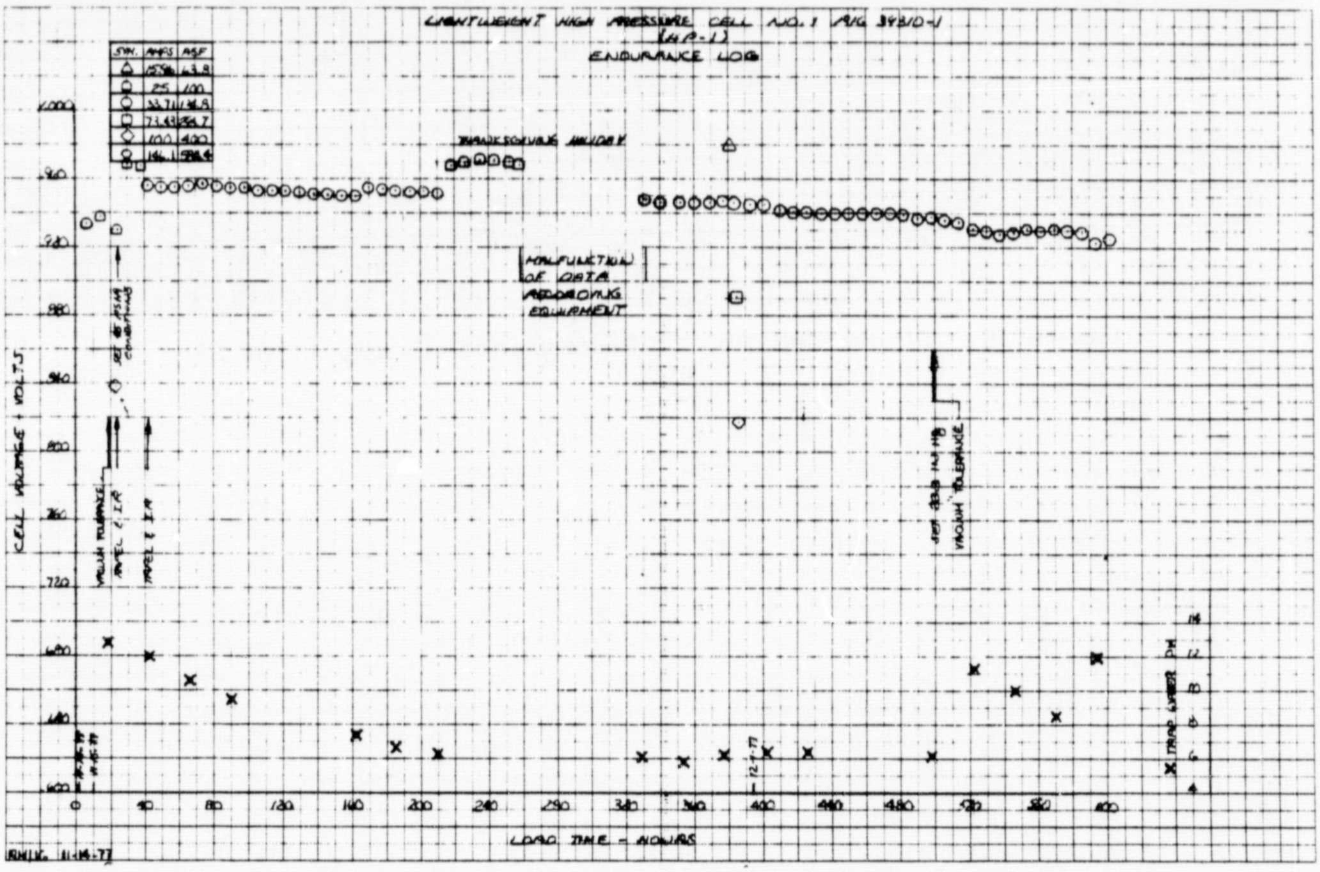


Figure 36. Single Cell No. 1, Performance History (1 of 2)

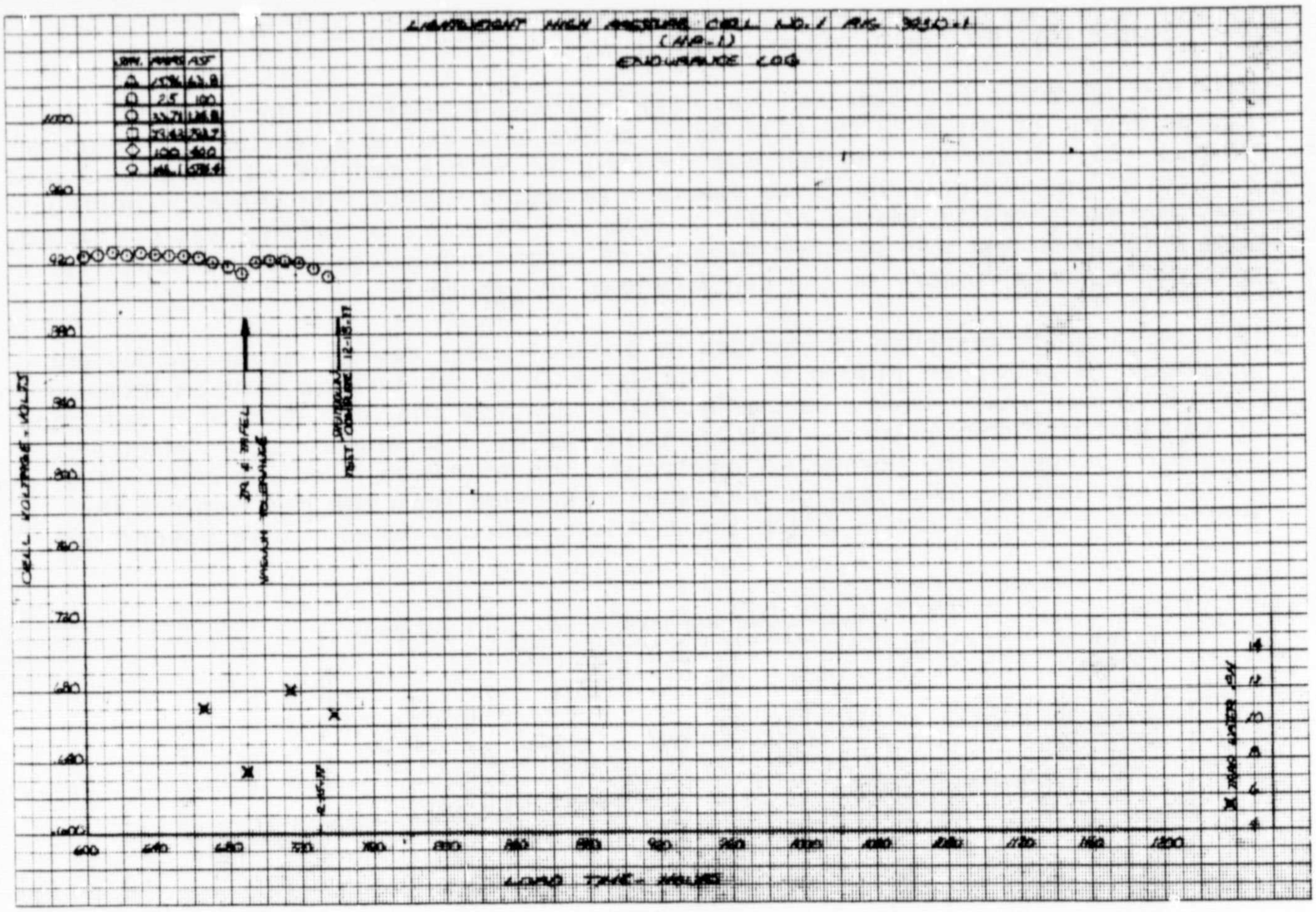


Figure 36. Single Cell No. 1, Performance History (2 of 2)

hours of operation the product water from the cell was contaminated with electrolyte as indicated by high pH values.

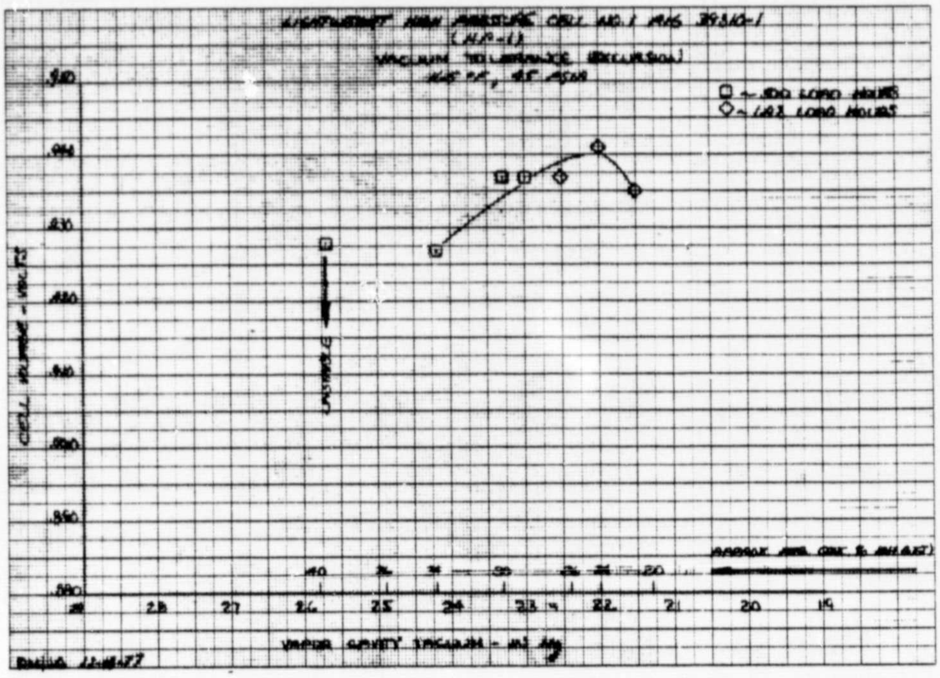


Figure 37. Single Cell No. 1, Electrolyte Excursion Data

Figure 38 presents the oxygen Tafel test data as a function of operating time. The near parallel down-ward shift of the Tafel data probably results from a lowered cell electrolyte concentration necessitated by continuing electrolyte loss.

Tear down inspection of the cell revealed excessive deposits of potassium carbonate (K_2CO_3) along the edge of the cell fiberglass frame at the current collection screens Figure 39 shows the K_2CO_3 deposits on the anode current collector at the edge of the fiberglass frame. Electrolyte that exuded through the cell frame would be a source for the deposits and account for the reduction in cell electrolyte inventory.

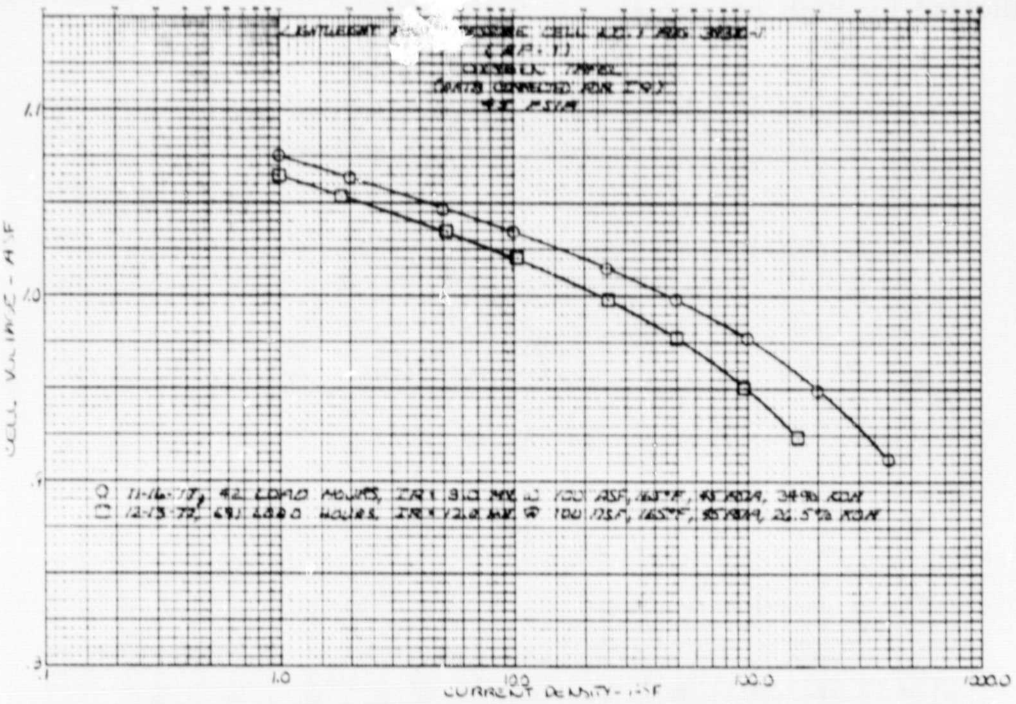


Figure 38. Single Cell No. 1, Oxygen Tafel Test Data

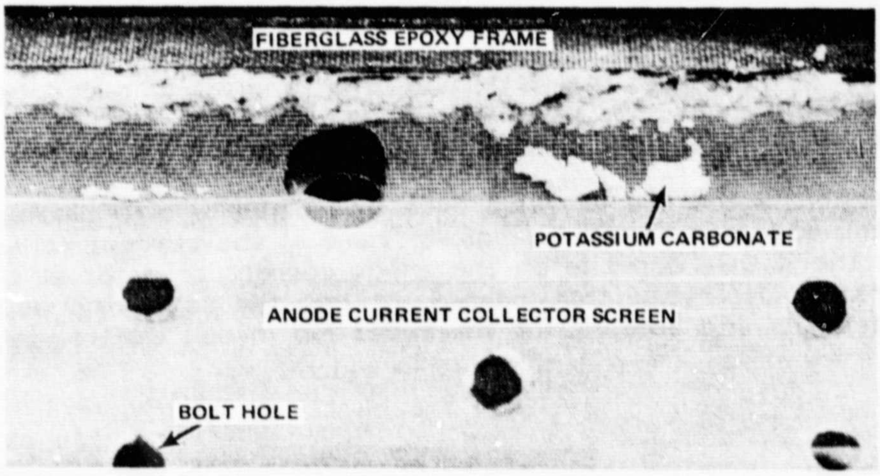


Figure 39. Single Cell No. 1, Anode Current Collector Screen

2. Single Cell No. 2 (HP-2)

The test objective of single cell No. 2 was to establish the performance characteristics of the 0.25 ft^2 ($232.3 cm^2$) active area cell at a reactant pressure of 60 psia ($41.4 N/cm^2$). The cell was constructed with a passive water removal unit capable of operating at increased reactant pressure. Details of the cell construction are presented in Section V.B.

A total of 478 hours of operation was completed. Figure 40 shows the performance history of the cell. The endurance test was stopped because of a hydrogen leak across the passive water removal assembly (PWR). A potential for hydrogen leakage existed from the start of the endurance test as the 60 psia ($41.4 N/cm^2$) reactant pressure was close to the maximum pressure capability of the current design PWR unit.

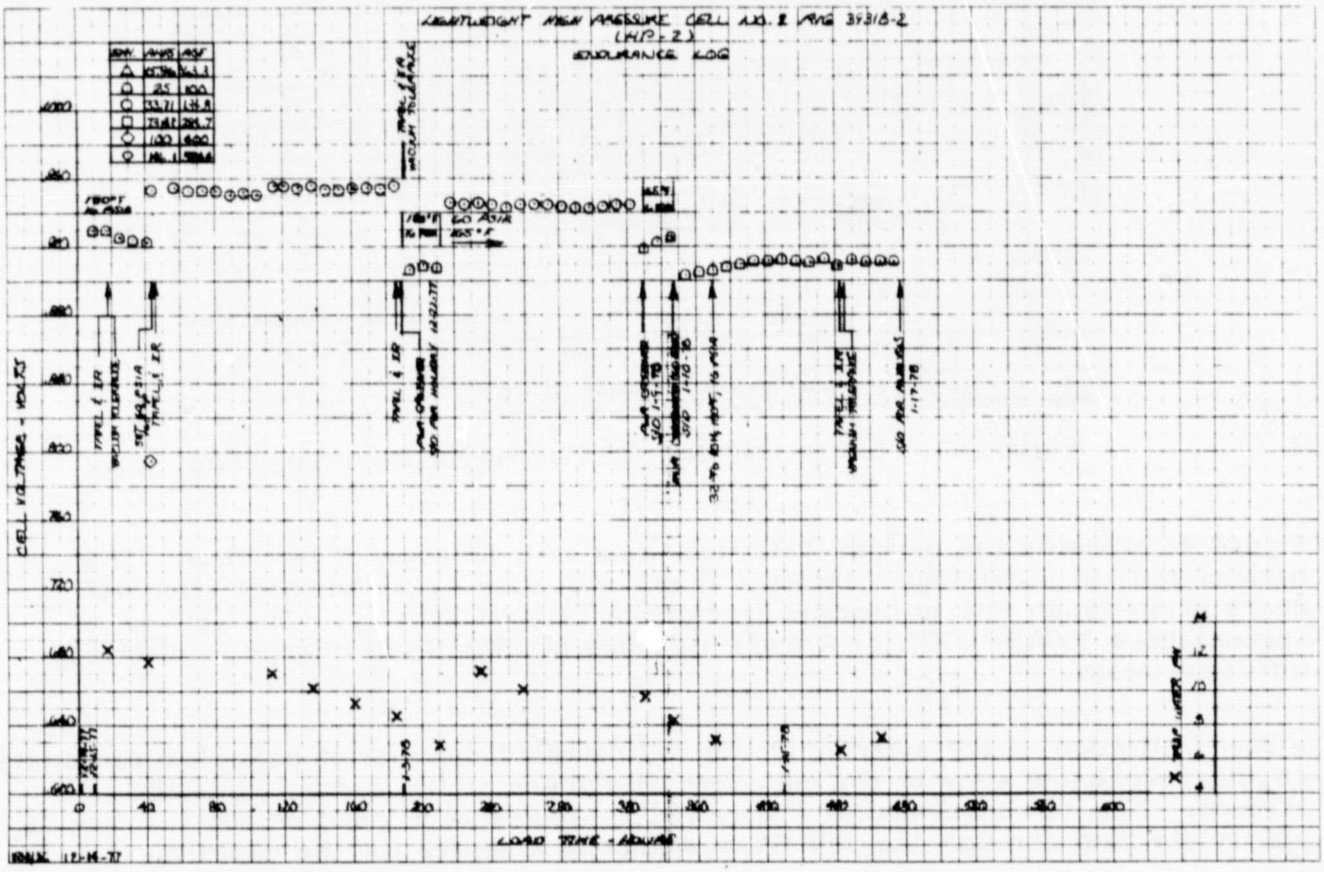


Figure 40. Single Cell No. 2, Perfomance History

The cell voltage response to changes in cell electrolyte operating concentration at 19 and 448 hours is shown in Figure 41. The cell electrolyte concentration was varied by changing the product water cavity vacuum. The increase in cell voltage in response to a change in vacuum from 21.8 in Hg (553.7 mm Hg) to 24.1 in Hg (612.1 mm Hg) indicates that there was no change in cell electrolyte inventory over the course of the endurance test.

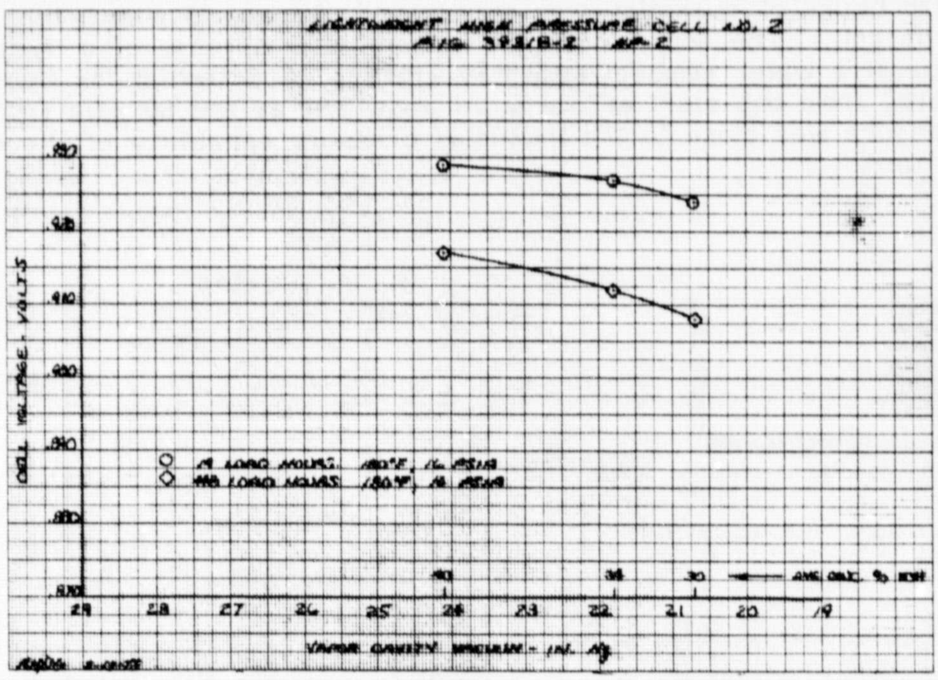


Figure 41. Single Cell No. 2, Electrolyte Excursion Data

Figure 42 presents the oxygen Tafel test data as a function of test time. The parallel shift in Tafel slopes shows a 19 mV reduction in performance after 447 hours of operation due to changes in cathode catalyst activity. The voltage response above 100ASF (107.6 mA/cm^2) indicates no significant change in electrode diffusion losses.

Visual inspection of the exterior of the cell revealed deposits of potassium carbonate (K_2CO_3) along the edge of the cell fiberglass frame at the current collection screens. The carbonate deposits were not as extensive as seen on HP-1. An electrolyte path through the cell frame would be a source for the deposits.

Photomicrographs of cell frame cross-sections were obtained to assist in identifying possible electrolyte paths. Photomicrographs were taken of the cell frame exterior edge and of three separate locations at intervals of approximately 1/8 inch (.318cm) inboard of the frame exterior edge. These photographs reveal no obvious continuous electrolyte path.

In the investigation to identify possible electrolyte paths, a photomicrograph of the cell frame at the current collector screen under increased magnification was taken. The presence of possible crystals of electrolyte among the glass-fiber bundles was noted. The suspected electrolyte crystals among the glass-fiber bundles would form the electrolyte path. A change in the cell manufacturing procedure such as the addition of epoxy rich glass-fiber sheets in the frame laminating step would provide additional epoxy flow around the glass fibers, providing a more complete electrolyte seal.

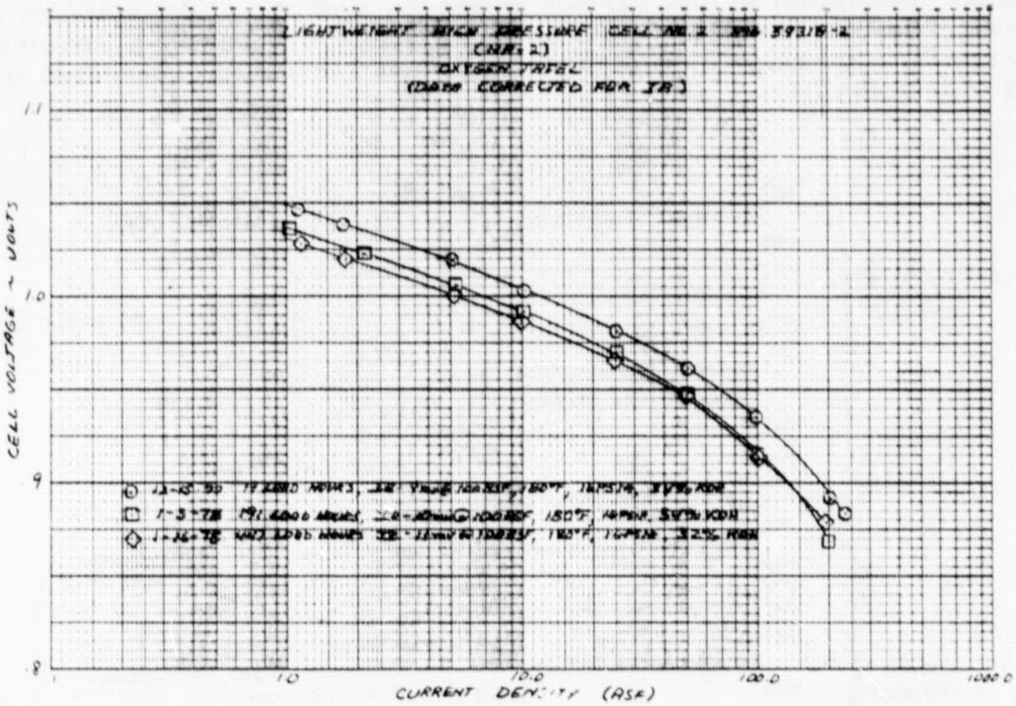


Figure 42. Single Cell No. 2, Oxygen Tafel Test Data

VII. LIGHTWEIGHT 30-CELL POWER SECTION

The final task of the program was to fabricate sufficient lightweight cell components for construction of a lightweight 30-cell power section. This section summarizes the work conducted in fabricating the lightweight power section.

A. Two-Cell Module Component Fabrication

Fabrication of components for the two-cell module (TCM) assembly, basic repeating unit of the power section was completed by Power Systems Division (PSD). A cross-section description of the various components of the TCM is shown in Figure 43. Fifteen, two-cell modules, connected electrically in series are required for the power section. A summary of the TCM component fabrication completed by PSD is presented in Table VIII.

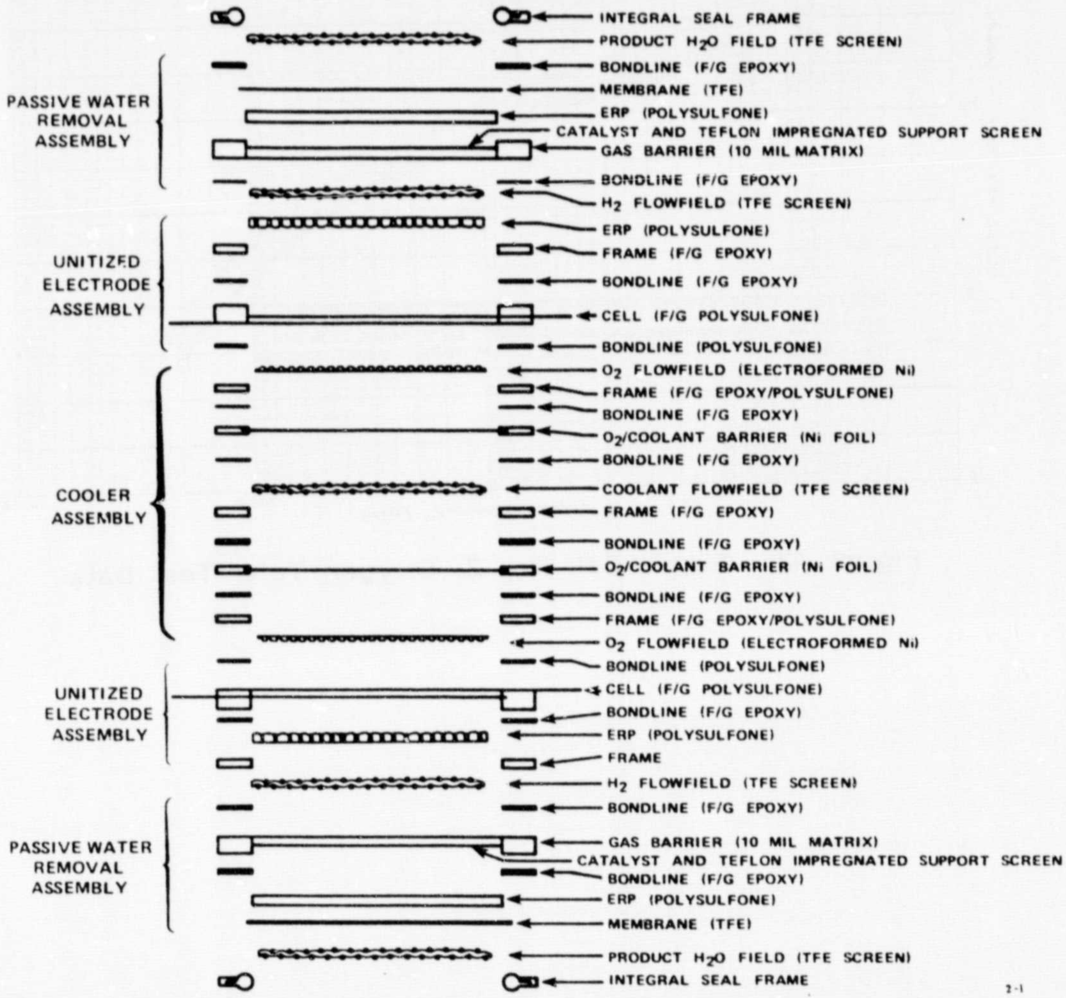


Figure 43. Two-Cell Module, Cross-Section Description

TABLE VIII. TWO-CELL MODULE COMPONENT FABRICATION

Description	Quantity Fabricated
Electrolyte Reservoir Plates (ERP)	
Unitized Electrode Assembly (UEA)	60
Passive Water Removal Assembly (PWR)	60
Anodes	60
Cathodes	60
Fiberglass/Epoxy Frames	
Cooler Frame	24
UEA Frame	53
Hydrogen Cavity Frame	60
PWR Frame	41
Oxygen Cavity Frame	45
Teflon-Catalyst Impregnated Screen	60
Cooler Assembly Components	48

B. Two-Cell Module Component Procurement

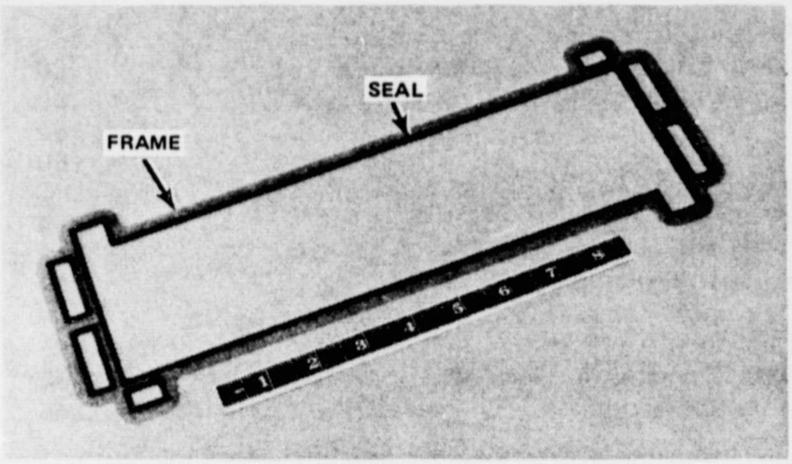
Two-cell module (TCM) assembly components supplied by vendors are identified in this section. A summary of the parts procured from vendors is presented in Table IX.

TABLE IX. TWO-CELL MODULE COMPONENT PROCUREMENT

Description
Cathode Substrate Screen
Anode Substrate Screen
Integral Seal Frame
Electoform Nickel Oxygen Field
Silver Plated Support Screen
Teflon Screen
Nickel foil
Catalyst

There were two unique TCM components designed by PSD and fabricated by outside vendors. These components were the Integral Seal Frame and the Electroform Nickel Oxygen Flow Field.

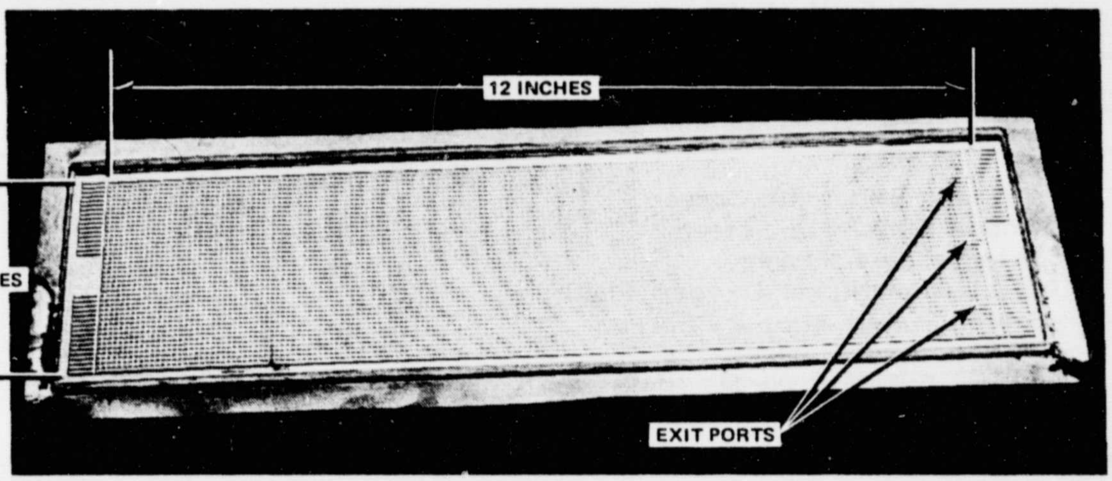
The Integral Seal Frame shown in Figure 44 was designed to provide a seal between the product water cavity of adjoining Two-Cell Modules. This will be the only seal used within the power section. The integral seal assembly consists of a 30mil (.76 mm) thick fiberglass-epoxy frame to which a flanged rubber "O" ring is attached.



(WCN-5331)

Figure 44. Two-Cell Module, Integral Seal Frame

Electroform Nickel Oxygen Flow Field, Figure 45, was designed to be lightweight. The oxygen flow consists of a 15-mil (.38mm) thick nickel electroform sheet with a nubbin pattern flow field.



(WO-1013)

Figure 45. Electro-Form Nickel Oxygen Flow Field

C. Two-Cell Module Assembly

The two-cell module assembly is comprised of a cooler, two passive water removal sub-assemblies and two unitized electrode sub-assemblies. The arrangement of these sub-assemblies within the two-cell module is shown in Figure 46.

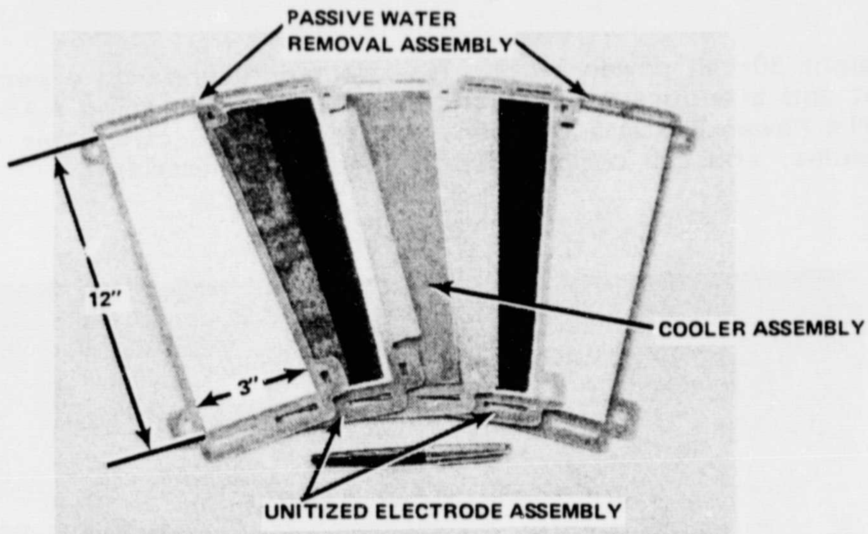


Figure 46. Two-Cell Module Assembly Components

A summary of the Two-Cell Module Assembly is presented in Table X.

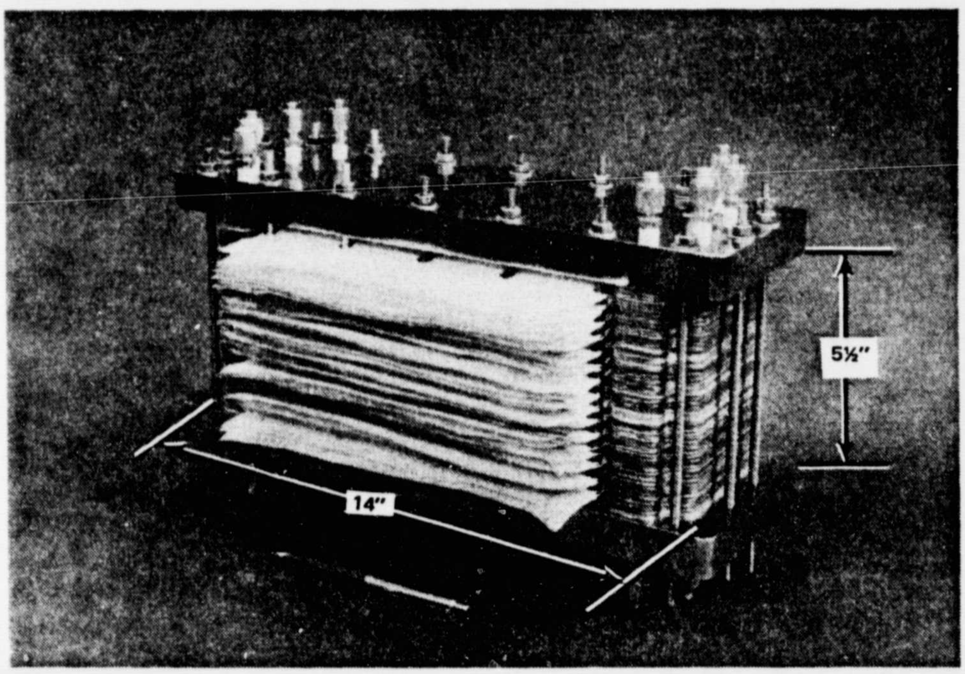
TABLE X. TWO-CELL MODULE ASSEMBLY

Description	Quantity Assembled
Component Parts	
Cooler Assembly	21
Passive Water Removal Assembly (PWR)	34
Unitized Electrode Assembly (UEA)	33
Two-Cell Module Assembly	16

D. Lightweight 30-Cell Power Section

A 30-cell power section was assembled by stacking fifteen two-cell modules with integral seal frames forming the seals between adjacent Passive Water Removal Units of the repeating two-cell modules. Figure 47 shows the assembled power section. The power section was not filled with electrolyte. In addition, the edge current collector screens at the sides of the two-cell modules were not soldered together.

The lightweight 30-cell power section is expected to undergo a performance demonstration test and a endurance evaluation during a forthcoming NASA-LeRC program. In the interim Power Systems Division will store the 30-cell power section, spare two-cell modules, and cell components unfilled with electrolyte.



(WCN-7135)

Figure 47. Lightweight 30-Cell Power Section

APPENDIX A

LIGHTWEIGHT FUEL CELL POWERPLANT PRELIMINARY SPECIFICATION

APPENDIX A
LIGHTWEIGHT FUEL CELL POWERPLANT PRELIMINARY SPECIFICATION

INTRODUCTION

This specification presents the preliminary performance and design criteria for a Lightweight Fuel Cell Powerplant. It is a Power Systems Division (PSD) document generated from conversations and correspondence with NASA and certain potential prime contractors and from the Space Shuttle Specification (North American Rockwell, MC464-0115). It serves as the basic specification on which the Preliminary Design Table, Appendix B, is based.

1. SCOPE

1.1. Scope. This specification defines the performance and design requirements for the Lightweight Fuel Cell Powerplant, referred to herein as the LFCP.

2. REQUIREMENTS

2.1. FCP Definition. The LFCP is the primary source of electrical power for operation of the space vehicle. Two LFCP's are used in the vehicle power generation system.

The LFCP consists of those components, subassemblies, and assemblies necessary to produce electrical power and product water while consuming gaseous hydrogen and oxygen supplied from the vehicle hydrogen and oxygen propellant storage system. Waste heat generated during operation of the LFCP's is rejected to the space vehicle coolant loop. Product water is discharged as a liquid to the vehicle water storage system, or is vented overboard. The LFCP includes a powersection and an accessory section. The accessory section provides the functions of reactant and thermal control, product water management, and automatic startup.

2.1.1. FCP Schematic. The fluid and instrumentation schematic of the LFCP is shown in Figure 48. Figure 49 presents the electrical wiring diagram of the LFCP.

2.1.2. Interface Definition.

2.1.2.1. Envelope. The LFCP shall have the general configuration shown in Figure 50.

2.1.2.2. Mounting. The LFCP shall incorporate provisions for attachment to the vehicle by mechanical fasteners.

2.1.2.3. Fluid Connections. The LFCP inlet and outlet fluid connections shall be located on a single mounting surface attached to the LFCP.

2.1.2.4. Electrical Connections. Electrical connections shall be located on a single mounting surface attached to the LFCP.

2.2. Characteristics.

2.2.1. Performance.

2.2.1.1. Operating Life. The LFCP shall be designed for operation at the specified performance level for a minimum of 2500 hours of maintenance free operation.

2.2.1.2. Voltage and Power Output. The LFCP voltage output shall be 24.0 to 32.5 volts d.c. over a nominal power range of 0.5 to 2.0 kilowatts. For emergency operation, the LFCP shall be capable of supplying 3.5 kilowatts at a voltage of not less than 18 volts d.c. for a period not to exceed eight (8) hours. These conditions shall be met under all combined conditions of environment, service life, reactant purity, and other voltage output variation factors inherent in LFCP design or usage.

2.2.1.3. Short Circuit Capacity. The LFCP shall have sufficient capacity to operate a short circuit protection device without deterioration or damage to the LFCP.

2.2.1.4. Reactants. During operation, the LFCP shall be provided with a continuous supply of gaseous hydrogen and oxygen filtered through a 15 micron absolute filter.

2.2.1.4.1. Hydrogen. Hydrogen consumption of the LFCP, excluding venting, shall be in accordance with Figure 51 over the power range of 0.5 to 3.5 kW. The amount of hydrogen vented shall be minimized consistent with LFCP requirements for reactant purity.

The hydrogen shall be procured in accordance with the requirements of MIL-P-27201B, Type II, with a maximum degradation at the LFCP interface as follows:

Purity:	In accordance with Table XI and shall have a minimum purity of 99.695 percent of volume.
Temperature Range:	TBD to Plus 170°F (76.7°C)
Pressure Range:	16.8 to 21.4 psia (11.6 - 14.8 N/cm^2)

TABLE XI. MAXIMUM CHEMICAL IMPURITY CONTENT, HYDROGEN

Impurity	Max. Allowable Concentration (Parts per Million, Vol. Basis)
Helium	3000
Total Gaseous Impurities (excluding He)	11
N_2, H_2O and Volatile Hydrocarbons	9
O_2 Plus Argon	1
Carbon Bearing Gases (other than methane)	1

2.2.1.4.2. Oxygen. Oxygen consumption of the LFCP, excluding venting, shall be in accordance with Figure 52 over the power range of 0.5 to 3.5 kW. The amount of oxygen vented shall be minimized consistent with LFCP requirements for reactant purity.

The oxygen shall be procured in accordance with the requirements of MIL-P-25502E, Type II, Grade A, with a maximum degradation at the LFCP interface as follows:

Purity: In accordance with Table XII and shall have a minimum purity of 99.452 percent by volume.

Temperature Range: TBD to plus 170°F (76.7°C)

Pressure Range: 28.1 to 33.6 psia (19.4 - 23.2 N/cm²)

TABLE XII. MAXIMUM CHEMICAL IMPURITY CONTENT, OXYGEN

Impurity	Max. Allowable Concentration (Parts per Million, Vol. Basis)
Helium	480
Alkynes as Acetelene	0.62
Total Hydrocarbons	66.7 (as methane)
CO_2, CO	3.0
Moisture	26.3

2.2.1.5. Water Production. The water produced by the LFCP shall be delivered against a maximum vehicle collection system back pressure of 15 psia (10.3 N/cm^2) and a maximum vent system back pressure of 1 psia (.7 N/cm^2). The minimum vehicle collection system back pressure during operation will be 7.5 psia (5.2 N/cm^2). Back pressures are measured at the LFCP interface. The specified water production rate, under steady conditions, shall be in accordance with Figure 53. Minimum delivery temperature at LFCP interface shall be 40°F (4.4°C). Maximum delivery temperature at LFCP interface shall be 200°F (93.3°C).

2.2.1.6. Start/Stop Capabilities. The LFCP shall be capable of being started and stopped automatically. When supplied with an external load of no less than TBD watts, the LFCP shall reach maximum load capability within TBD minutes from prestart temperature of 40°F (4.4°C). The LFCP shall be capable of completing TBD starts during the 2500 hour operating life. The LFCP shall contain provisions for both ground and inflight startup and shutdown. The maximum time to achieve shutdown shall be one minute. Product water shall be vented overboard during startup.

2.2.1.6.1. False Starts. The LFCP shall be capable of being shutdown on reactants or inert gases and allowed to cool to ambient temperature two (2) consecutive times from any temperature in the start cycle without damage or detrimental effects.

2.2.1.6.2. FCP Inerting. The LFCP shall be capable of being inerted using either helium per MSFC-SPEC-364 or nitrogen per MSFC-SPEC-234. The LFCP shall contain provision for removal of inerts within the startup period.

2.2.1.7. Electrical Power Requirements. The electrical power input requirements of the LFCP shall be as listed below. All power, except for the end cell heater power, shall be supplied from the vehicle bus through interface connectors.

Function	Power Type	Max. Power
Coolant Pump	External inverter a.c.	TBD
Controls & Instrumentation	External d.c.	TBD
H_2 & O_2 Purge Valves	External d.c.	TBD
Product Water Control Valves	External d.c.	TBD
Endcell Heaters	Internal d.c.	TBD

2.2.1.8. Instrumentation and Controls. The LFCP shall incorporate instrumentation/ sensors and controls necessary for checkout, monitoring and operation.

2.2.1.8.1. Instrumentation Requirements. The LFCP instrumentation/ sensors shall have provisions for monitoring the variables listed in Table XIII.

2.2.1.8.2. Electrical Controls. The LFCP shall provide the following control functions for remote operation:

Start and Stop.

TABLE XIII. INSTRUMENTATION REQUIREMENTS

Parameter	Operating Range
Hydrogen Pressure	0 - 30 psia (0 - 20.7 N/cm^2)
Stack Coolant Inlet Temperature	-50 - 300°F (-45.6 - 148.9°C)
O_2 Flowmeter	0 - 5 pph (0 - 2.27 kg/hr)
H_2 Flowmeter	0 - 0.75 pph (0 - 340.5 g/hr)
Reactant Purge Valve Closure	Event
Coolant Pressure	0 - 30 psia (0 - 20.7 N/cm^2)
Stack Coolant Outlet Temperature	-50 - 300°F (-45.6 - 148.9°C)
Coolant Pump Status	Event
Product Water Vent Valve Status	Event

2.2.1.9. Reactant Purging. The LFCP shall utilize continuous purging to meet the performance requirements of this specification. The purge flow rates shall be as follows:

Load (Amps)	Max. H_2 Flow (LB/HR)	Max. O_2 Flow (LB/HR)
TBD	TBD	TBD
TBD	TBD	TBD

The LFCP purge system shall operate against a maximum back pressure of 7.5 psia (5.2 N/cm^2).

2.2.1.10. Heat Rejection Requirements. The maximum heat rate to be rejected from the LFCP to the vehicle coolant loop shall be as shown in Figure 54. The LFCP shall be capable of rejecting heat to a vehicle coolant loop with a minimum flow of 2500 pph (1135 kg/hr) of Freon-21 with a temperature of not more than TBD at the LFCP interface vehicle coolant loop inlet.

2.2.1.10.1. Coolant. The coolant used in the LFCP shall be FC-40, a product of the 3M Co. The composition, purity and fluid properties of the coolant shall be in accordance with "Technical Information Manual -Fluorinert Brand Electronic Liquid FC-40", Minnesota Mining and Manufacturing Co., 1968. The coolant shall be filtered through a 25 micron absolute filter.

2.2.1.10.2. Coolant Pressure. The LCP shall include an accumulator to accommodate coolant expansion and contraction with temperature changes and to establish system coolant pressure.

2.2.1.10.3. Coolant Pump. The LFCP shall include a coolant pump whose characteristics are shown in Figure 55.

2.2.1.10.4. Radiated and Conducted Heat. The LFCP waste heat rejection to the vehicle structure shall not exceed TBD BTU/HR at a vehicle temperature of 40°F (4.4°C).

2.2.1.11. Internal Operating Conditions.

2.2.1.11.1. Operating Temperature. The normal LFCP operating temperature shall be between 175°F (79.4°C) and 210°F (98.9°C). A temperature of 250°F (121.1°C) may be tolerated for TBD hours without detrimental effect.

2.2.1.11.2. Operating Pressure. The normal operating pressure shall be between 17 psia (11.7 N/cm^2) and 23 psia (15.9 N/cm^2). However, the LFCP shall be capable of withstanding, during operating or non-operating conditions, a loss of pressure without permament damage.

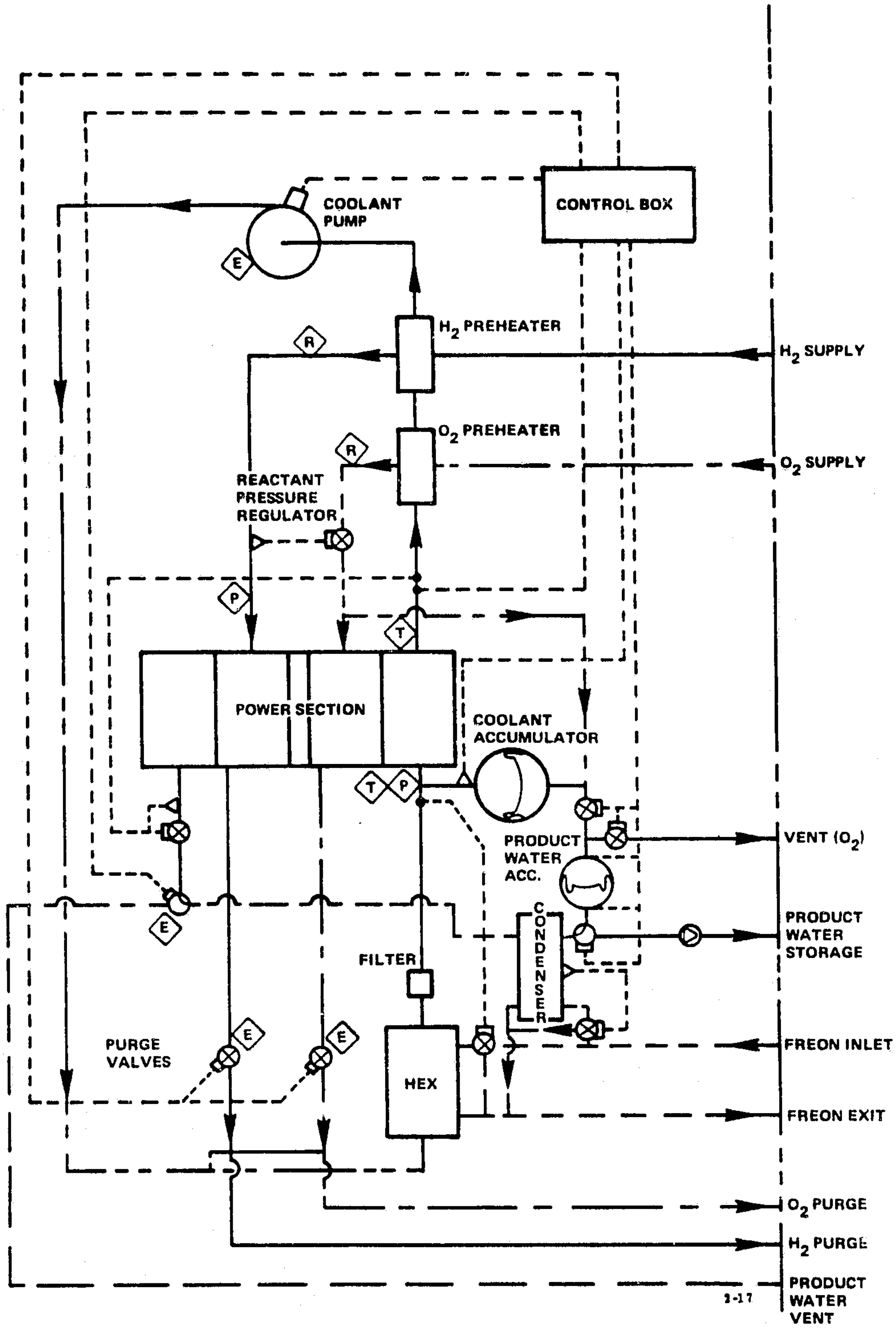


Figure 48. Fuel Cell Powerplant Flow and Instrumentation Schematic

(TBD)

Figure 49. FCP Electrical Wiring Diagram

(TBD)

Figure 50. FCP Configuration Drawing

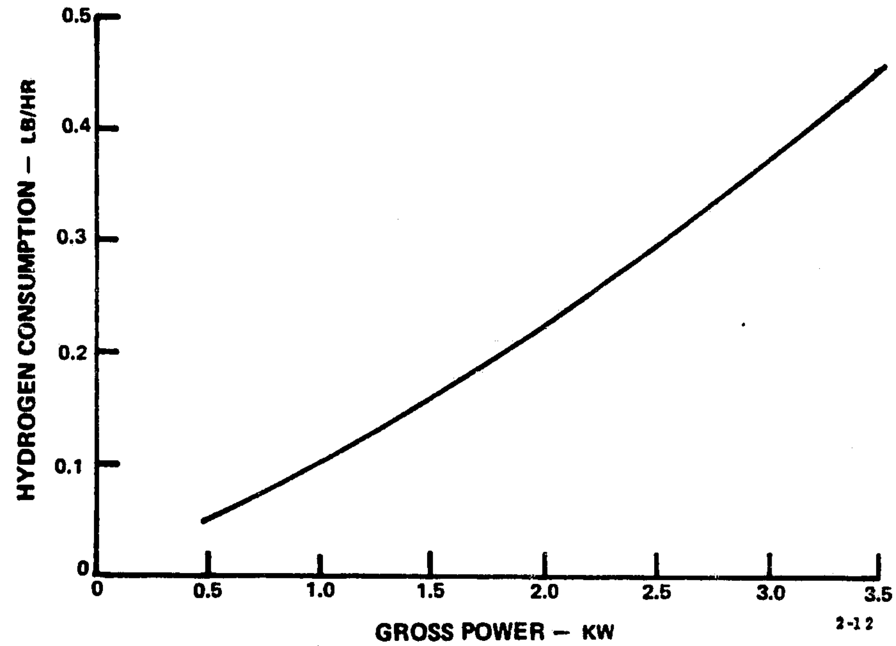


Figure 51. Maximum Hydrogen Consumption Rate

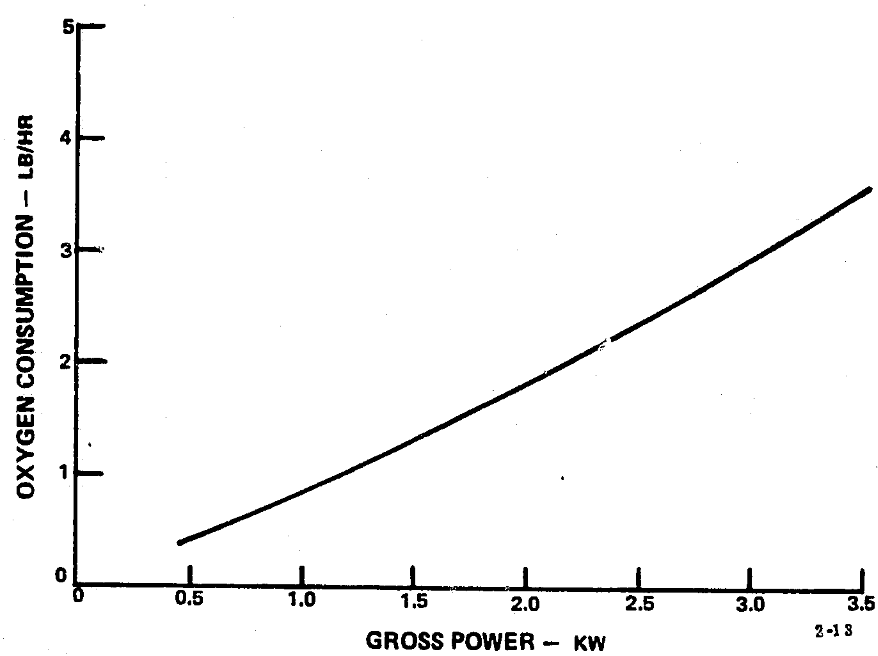


Figure 52. Maximum Oxygen Consumption Rate

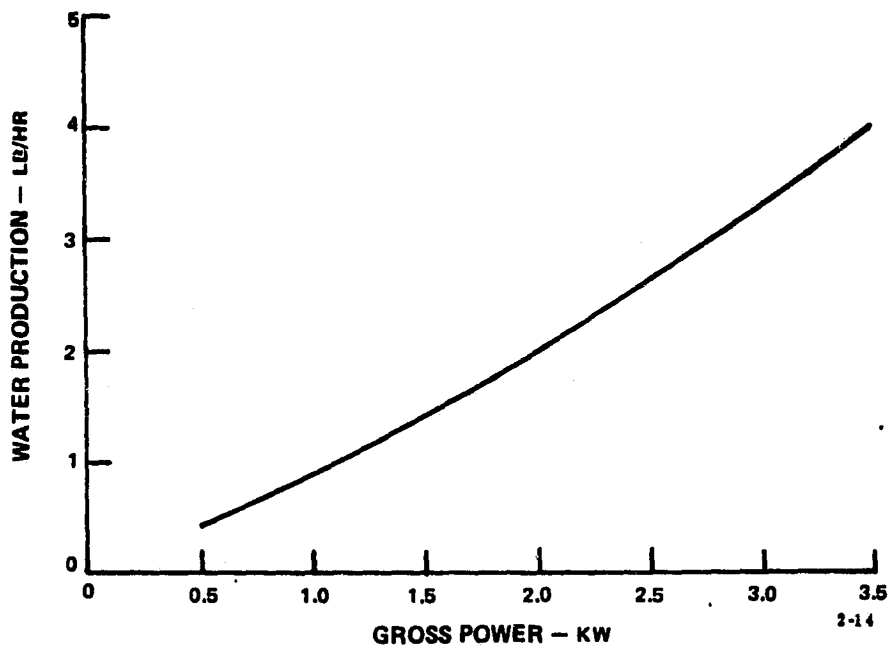


Figure 53. Maximum Water Generation Rate

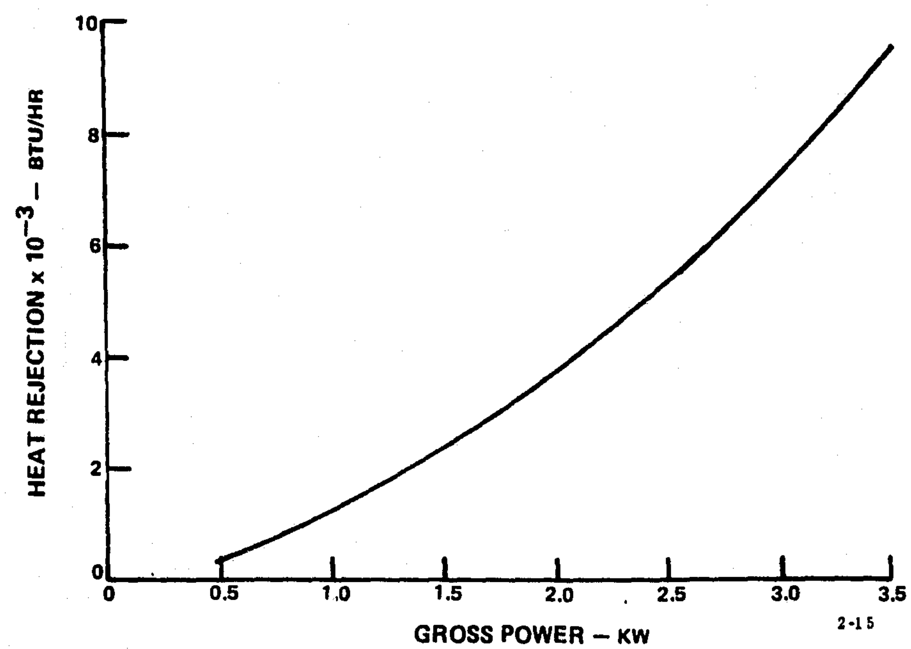


Figure 54. Maximum Heat Rejection Requirements

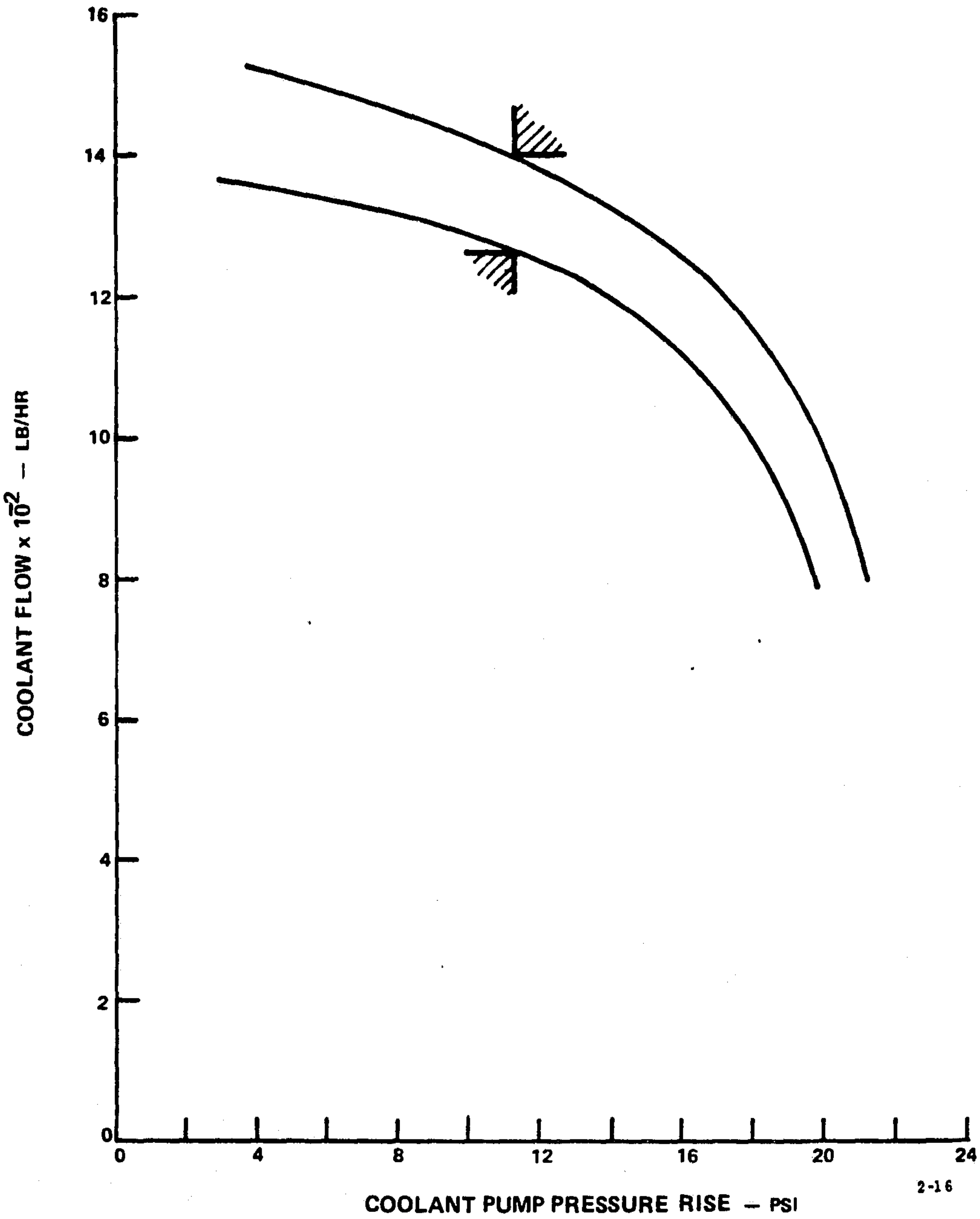


Figure 55. Coolant Pump Characteristic

APPENDIX B

LIGHTWEIGHT FUEL CELL POWERPLANT PRELIMINARY DESIGN TABLE

APPENDIX B. LFCP PRELIMINARY DESIGN TABLE

INTRODUCTION

This Design Table presents the preliminary operating characteristics of the Lightweight Fuel Cell Powerplant (LFCP). The Design Table includes the following:

- A preliminary fluid schematic.
- Coolant loop pressure drop allocations.
- Characteristics of those components that affect the system match.
- Nominal operating characteristics of the powerplant - both in curve form and computer printed heat and mass balance charts.

The operating characteristics presented herein reflect the most recent NASA requirements for the Lightweight Fuel Cell Powerplant.

OBJECTIVES OF THE DESIGN TABLE

- Define the component characteristics that will result in satisfactory powerplant operation.
- Present the estimated powerplant operating characteristics.

MATCHING CRITERIA

- Maintain electrolyte concentration within acceptable limits.
- Maintain voltage regulation over life of powerplant.
- Operate with passive water removal water vapor partial pressure at 4 psia (2.8 N/cm^2).
- Operate with continuous reactant purge through constant area orifice.
- Maintain powersection operating temperature within acceptable limits.

SUMMARY

- As presented, the Design Table satisfies all the matching criteria defined above.

AREAS FOR REFINEMENT

Several areas exist which deserve refinement in subsequent revisions of this Design Table. They are as follows:

- Reflect powerplant insulation by appropriate heat loss values.
- Reflect component operating tolerances and determine associated operating limitations.
- Include impact of operating tolerances of condenser, heat exchanger and their associated control system on powerplant operation.

LFCP PRELIMINARY DESIGN TABLE

System Configuration	Figure 56
Component Characteristics	
Powersection	
Cell area	0.25 ft^2 (232.3 cm^2)
No. cells	34
Cells/cooler	2
Operating pressure (nominal)	19 psia (13.1 N/cm^2)
Cell performance level	Figure 57
Reactant Pressure Regulator	
Control Band	16-23 psia (11 - 15.9 N/cm^2)
Electrical Resistance to Interface	TBD
Condenser	TBD
Thermal Control Heat Exchanger	TBD
Coolant Pump	
Maximum flow rate	1333 lb/hr. (605.2 kg/hr)
Minimum flow rate	1333 lb/hr. (605.2 kg/hr)
Pressure	Table XIV
Reactant Preheaters	
Performance level	Orbiter PC17C Preheaters

Powerplant Operating Characteristics (Nominal Match)

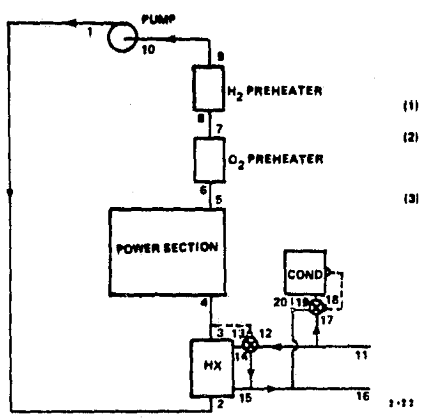
Sea Level Operation

80°F (26.7°C) reactants	Figures 58-72

Specification Parameters

Specific hydrogen consumption	Figure 73
Specific oxygen consumption	Figure 74
Water Production Rate	Figure 75
Maximum heat rejection	Figure 76

TABLE XIV. LIGHTWEIGHT FUEL CELL POWERPLANT PRESSURE DROP SUMMARY



NOTES
(1) FC-40 COOLANT FLOW IS 1333PPH
(2) PLUMBING ΔP'S ARE ALLOCATED ON A TOTAL BASIS UNTIL THE PLUMBING CONFIGURATION IS DEFINED
(3) FREON COOLANT LOOP FLOW IS 2500PPH

COMPONENT	LOCATION	ΔP ~ PSI			
		Allocated	Calculated	Measured	Revisions
FC-40 Coolant Loop					
Plumbing	1-2	0.6 (2)			
Heat Exchanger	2-3	4.0			
Plumbing	3-4	(2)			
Power Section	4-5	5.5			
Plumbing	5-6	(2)			
O_2 Preheater	6-7	0.7			
Plumbing	7-8	(2)			
H_2 Preheater	8-9	0.6			
Plumbing	9-10	(2)			
Total Pump Head Rise	10-1	11.4			
Freon Coolant Loop					
Plumbing	11-12, 11-17	0.5			
Thermal Control Valve	12-13	} 20			
Condenser Control Valve	17-18				
Plumbing	13-14, 18-19	(2)			
Heat Exchanger	14-15	} 0.5			
Condenser	19-20				
Plumbing	15-16, 20-16	(2)			
Total	11-16	3.0			

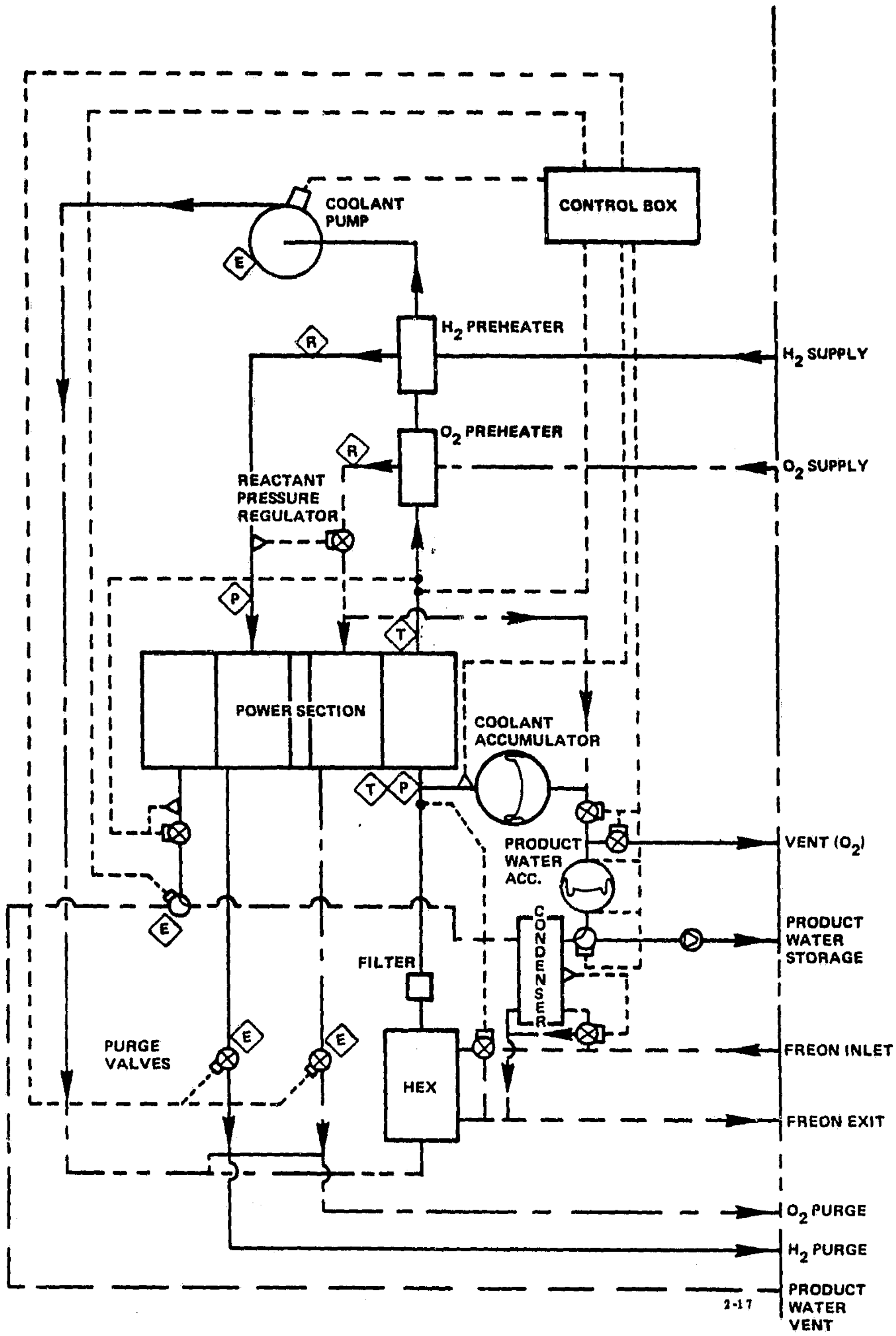


Figure 56. Preliminary Lightweight Fuel Cell Powerplant Fluid Schematic

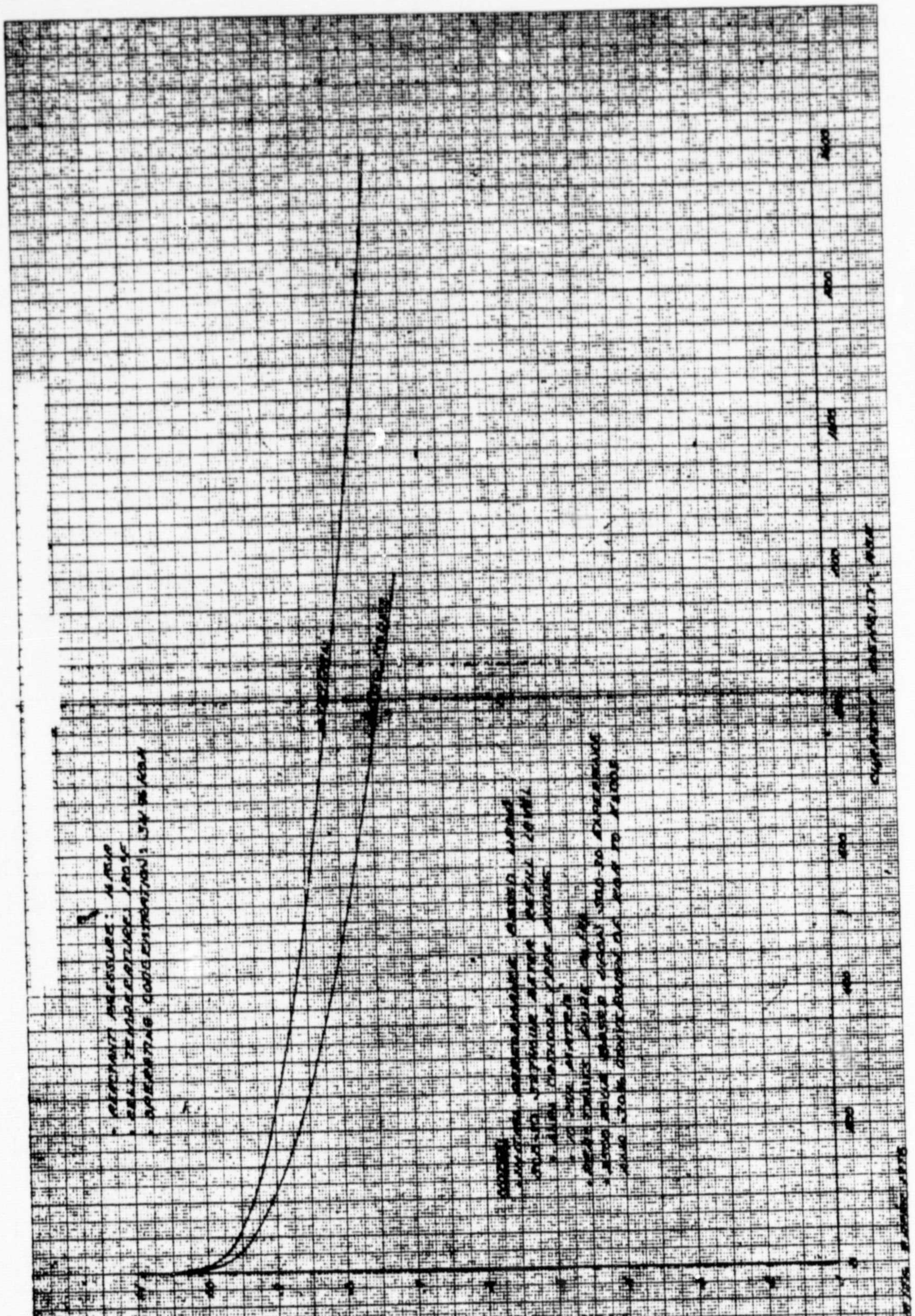


Figure 57. Estimated Lightweight Fuel Cell Powerplant Performance

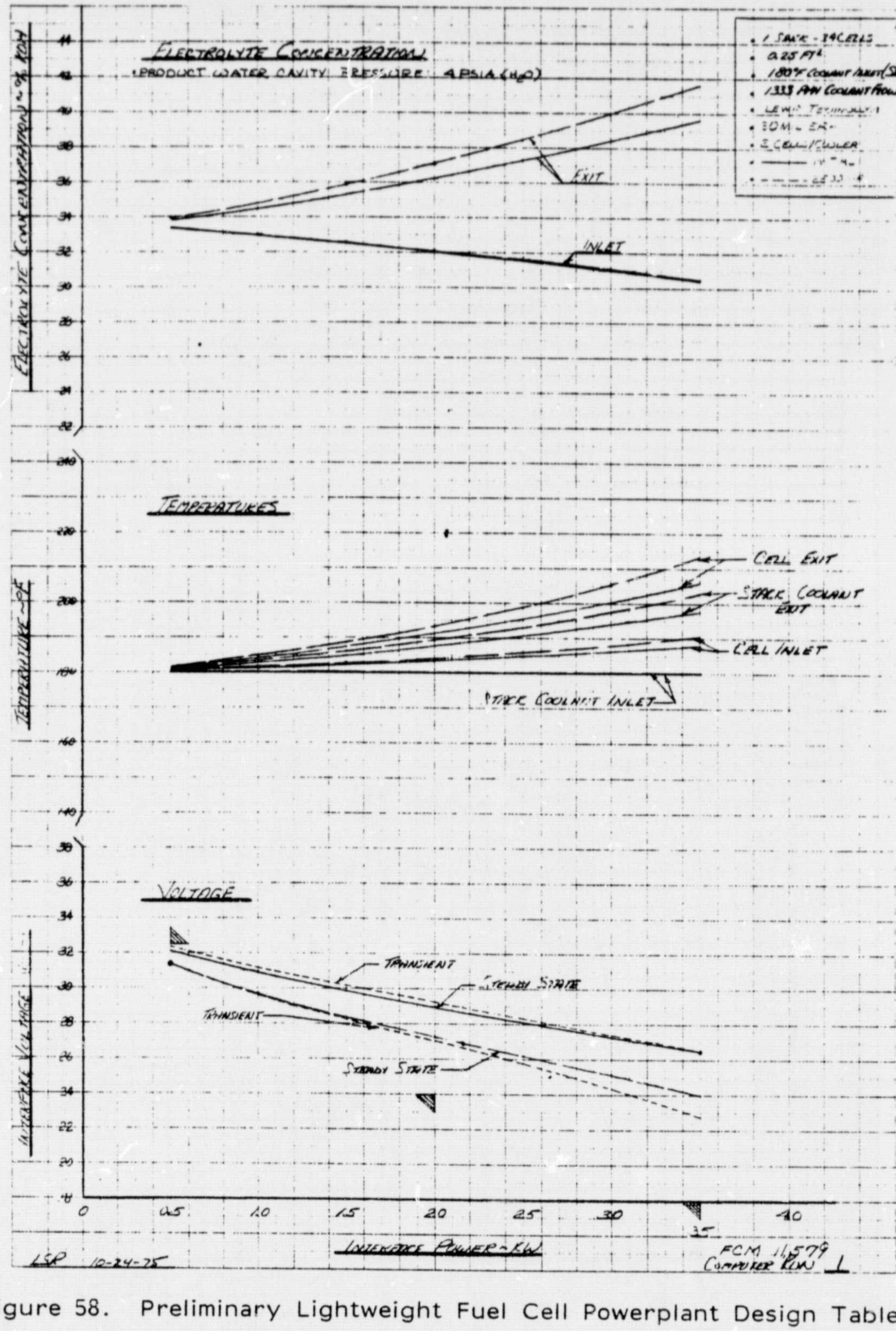


Figure 58. Preliminary Lightweight Fuel Cell Powerplant Design Table

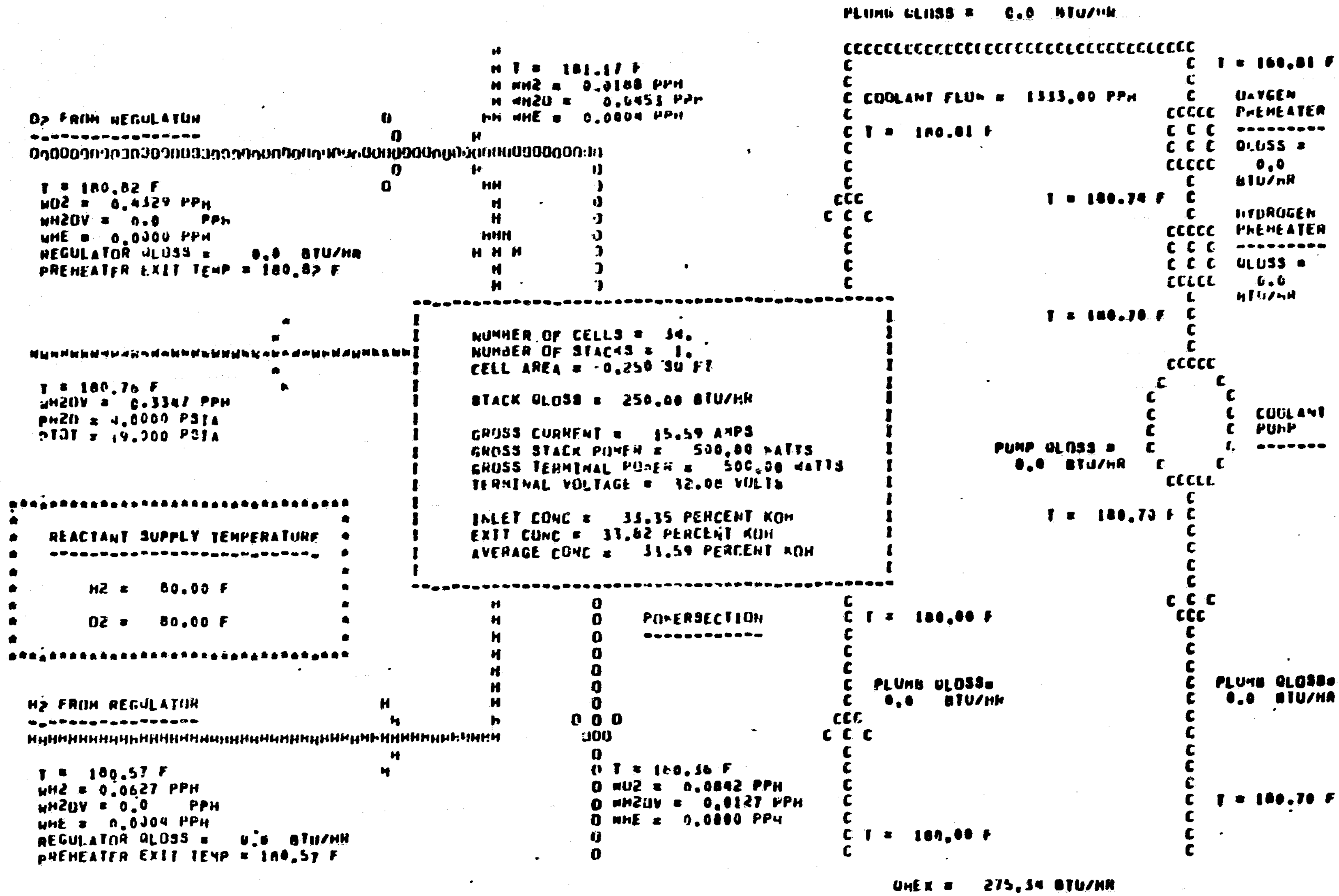


Figure 59. Beginning of Life Powerplant Characteristics, 0.5kW

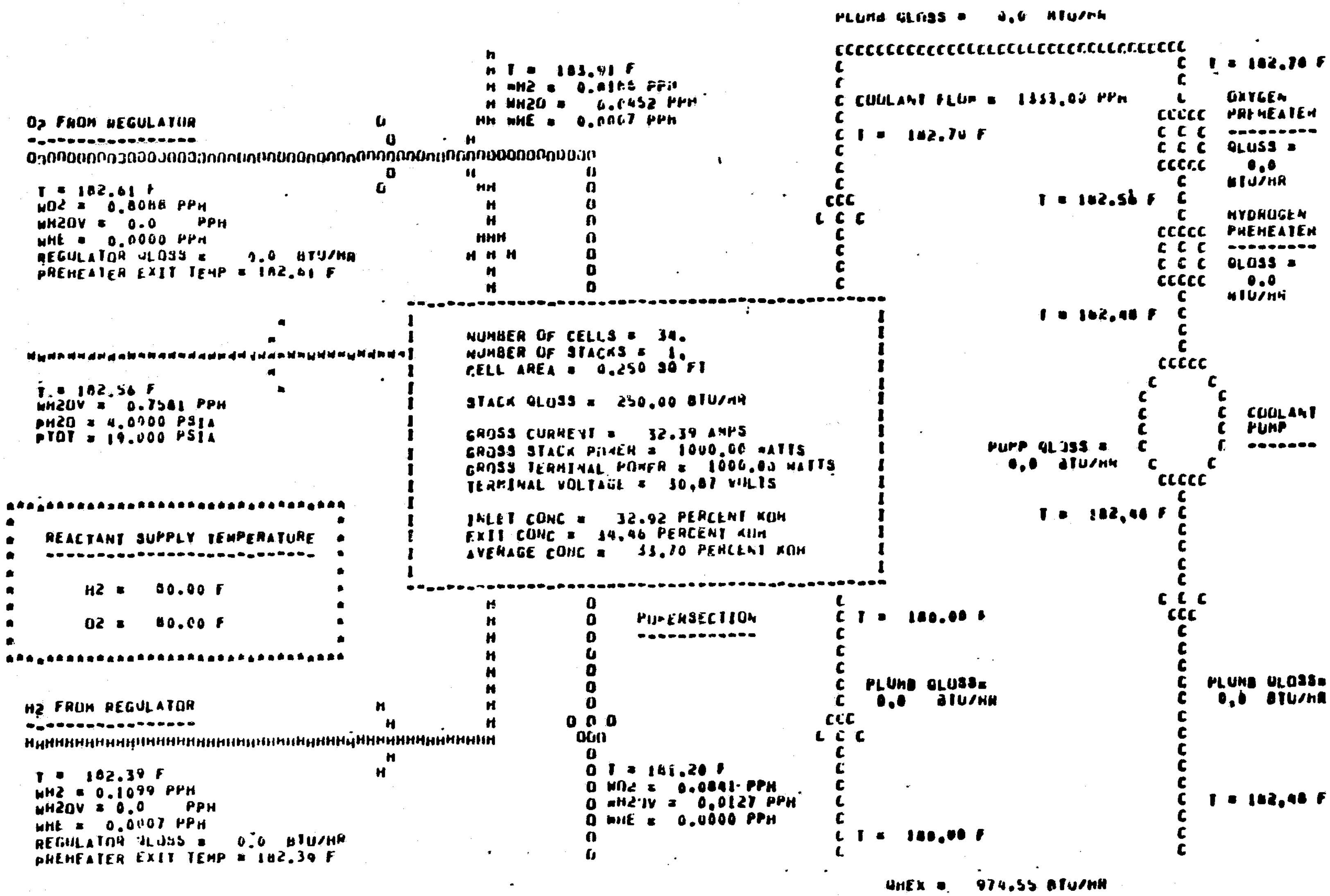


Figure 60. Beginning of Life Powerplant Characteristics, 1.0kW

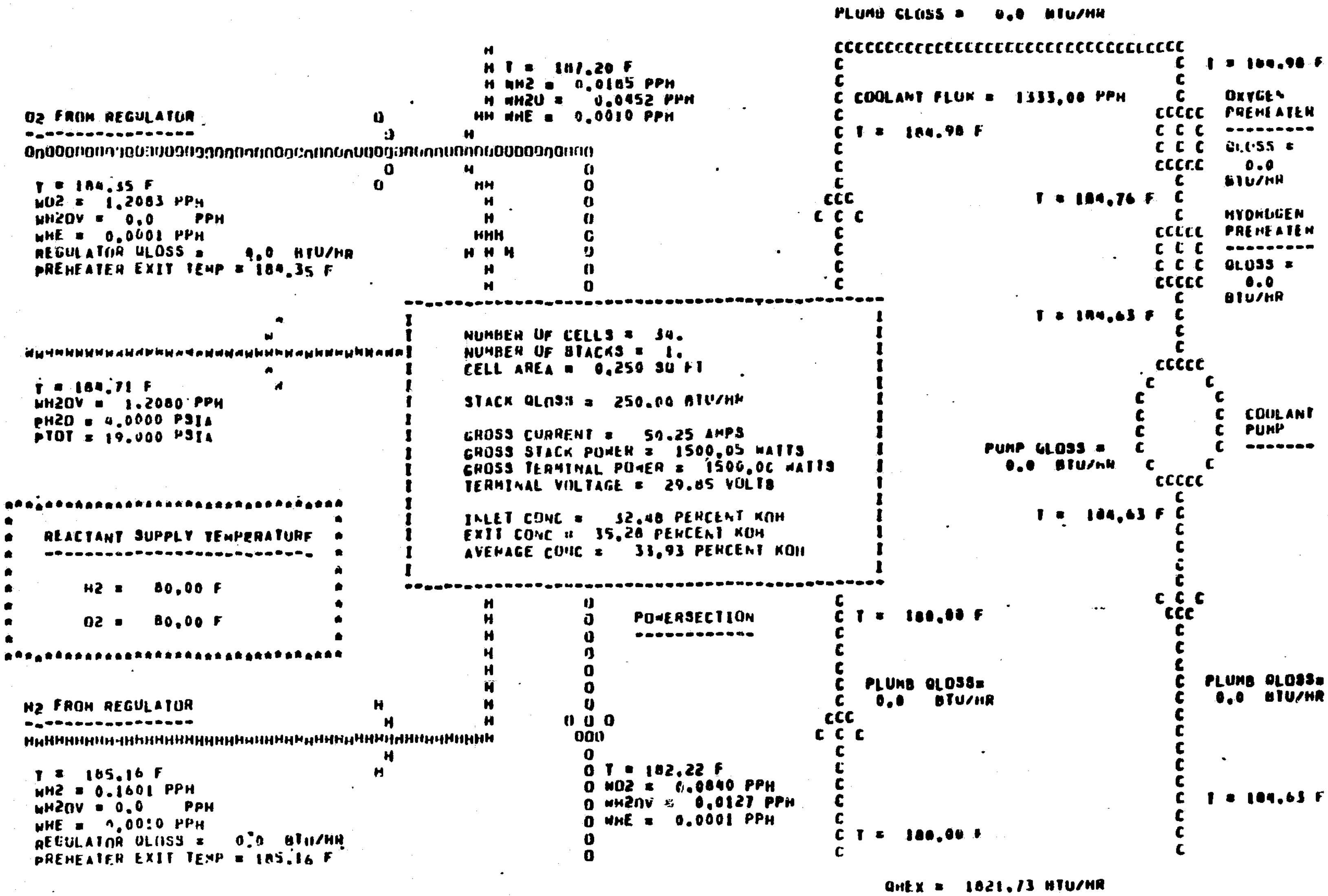


Figure 61. Beginning of Life Powerplant Characteristics, 1.5kW

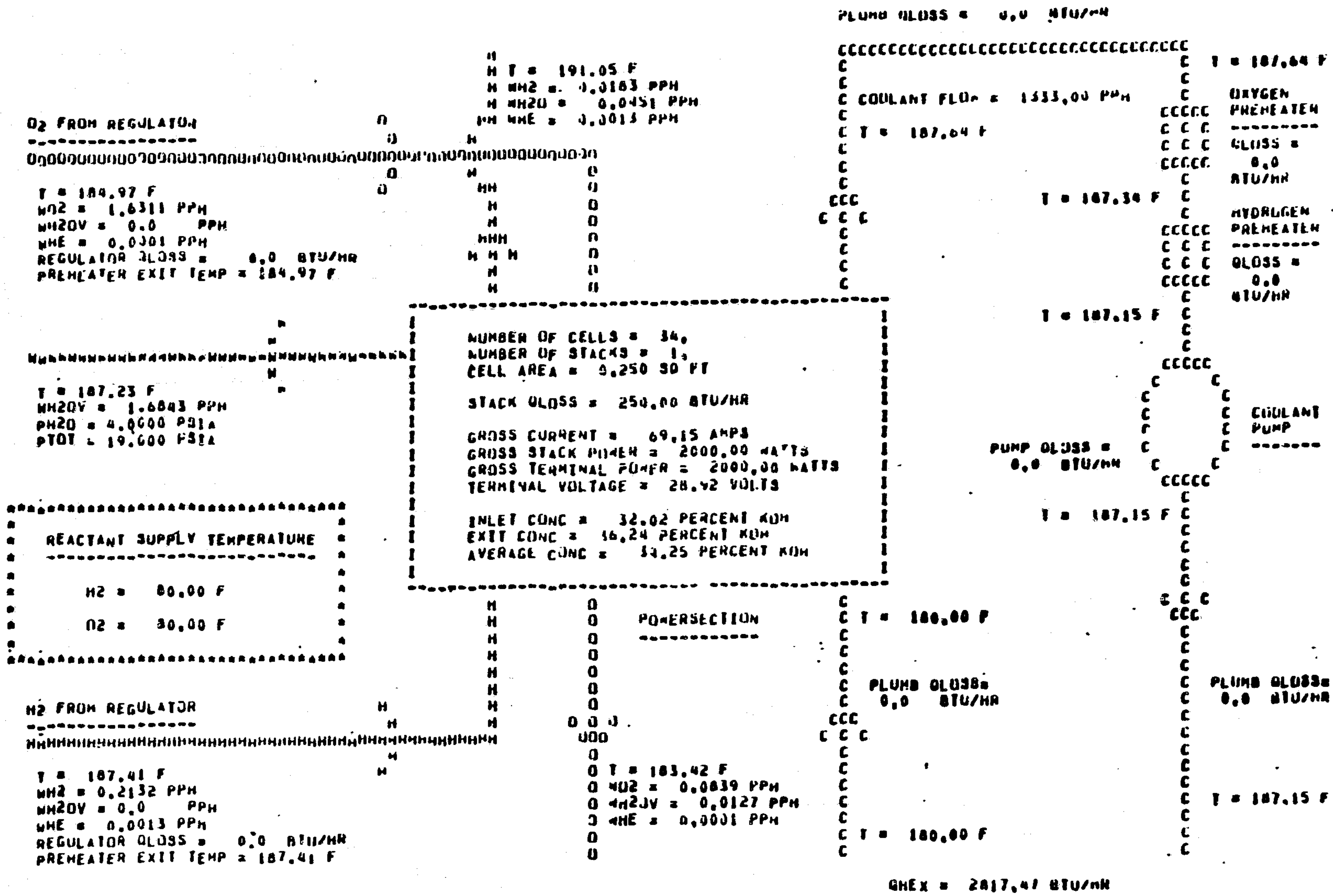


Figure 62. Beginning of Life Powerplant Characteristics, 2.0kW

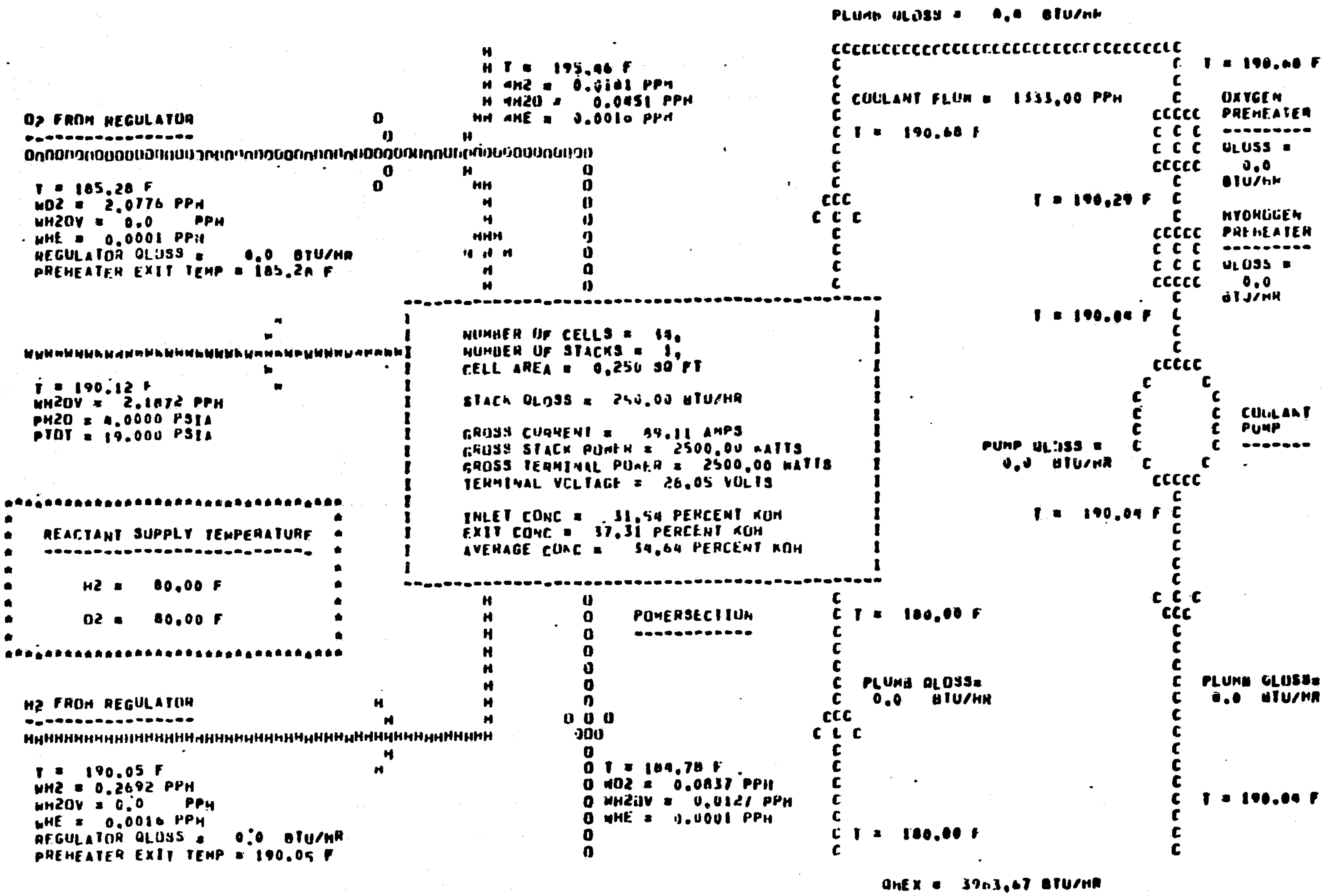


Figure 63. Beginning of Life Powerplant Characteristics, 2.5kW

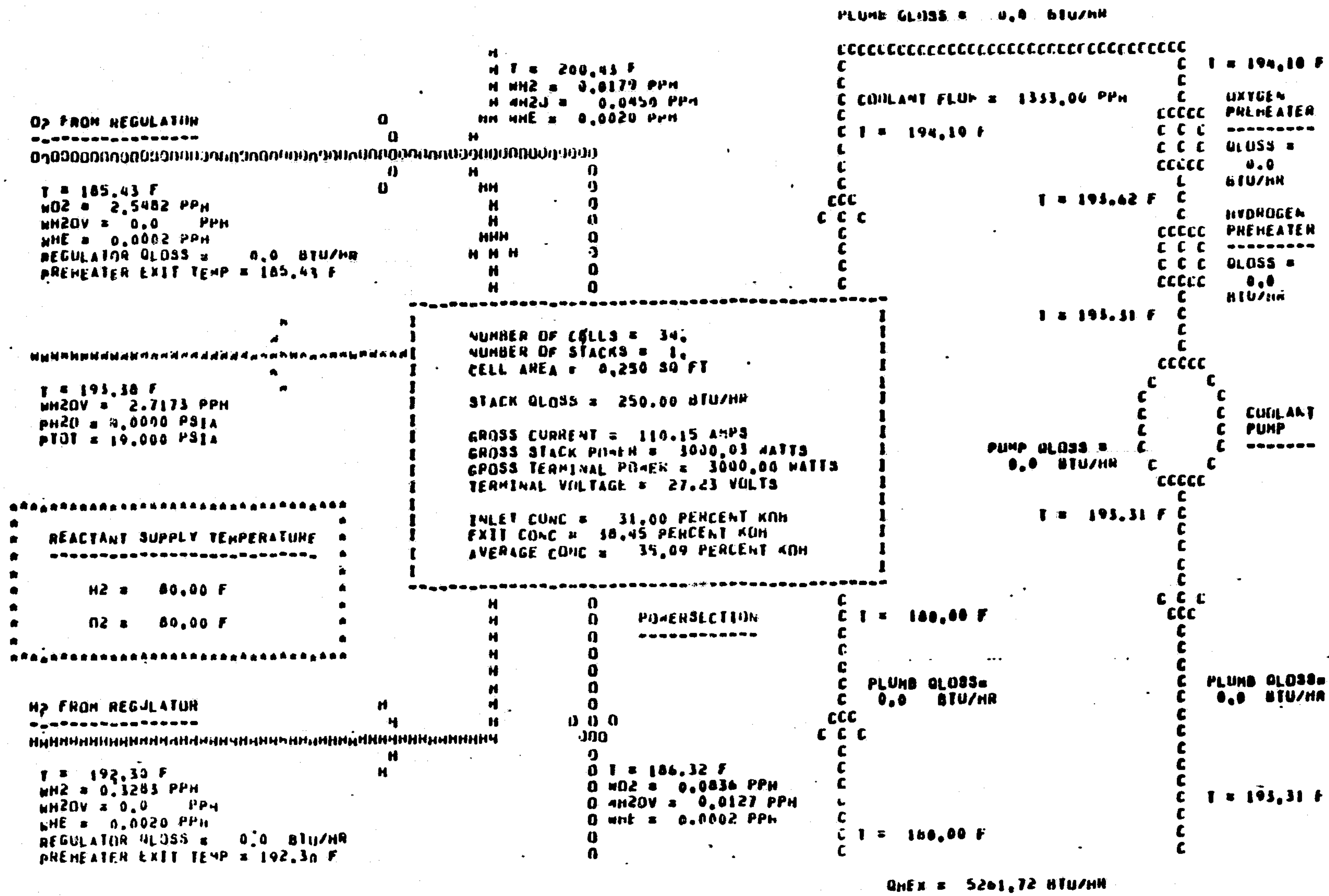


Figure 64. Beginning of Life Powerplant Characteristics, 3.0kW

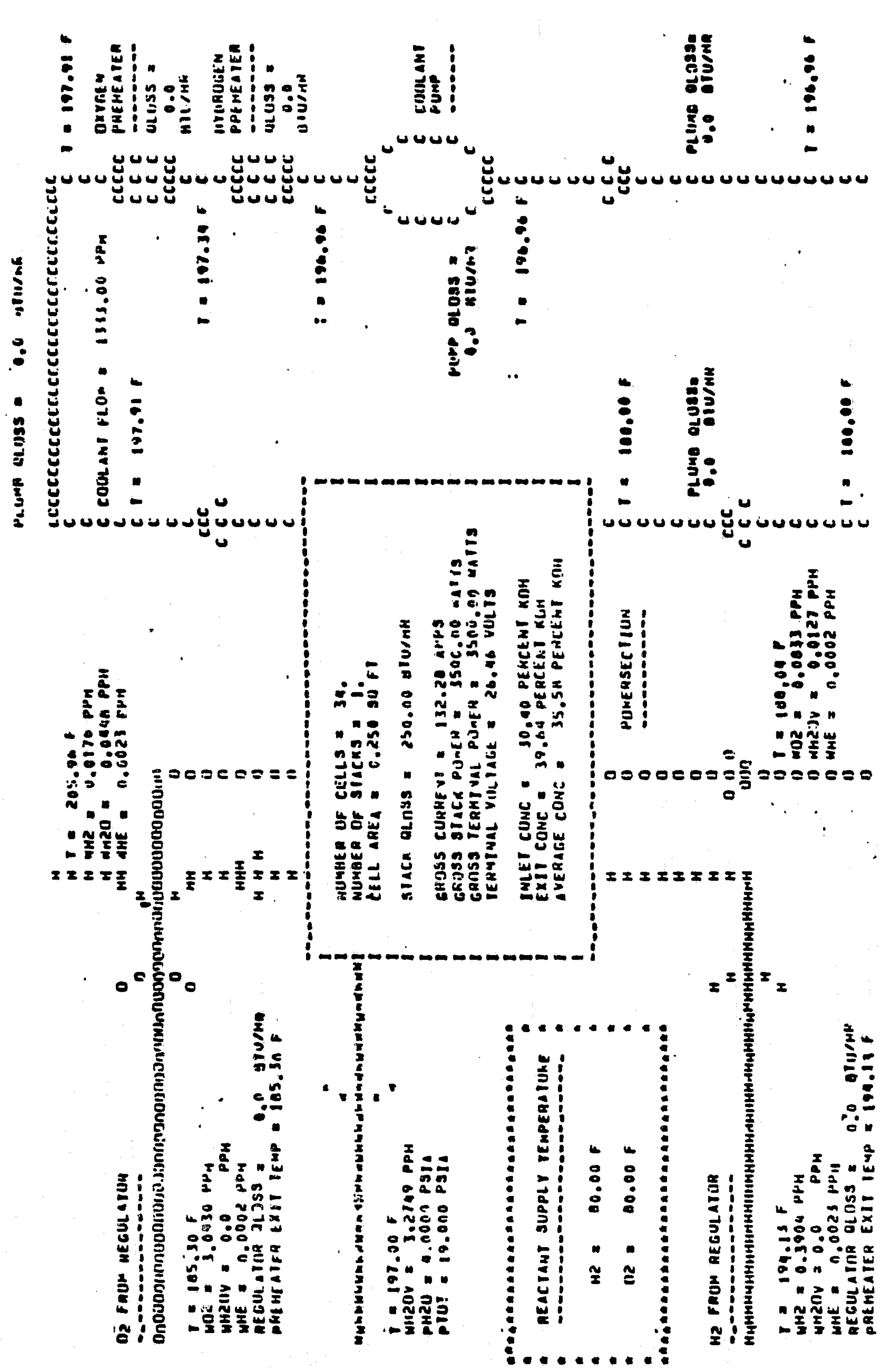


Figure 65. Beginning of Life Powerplant Characteristics, 3.5kW

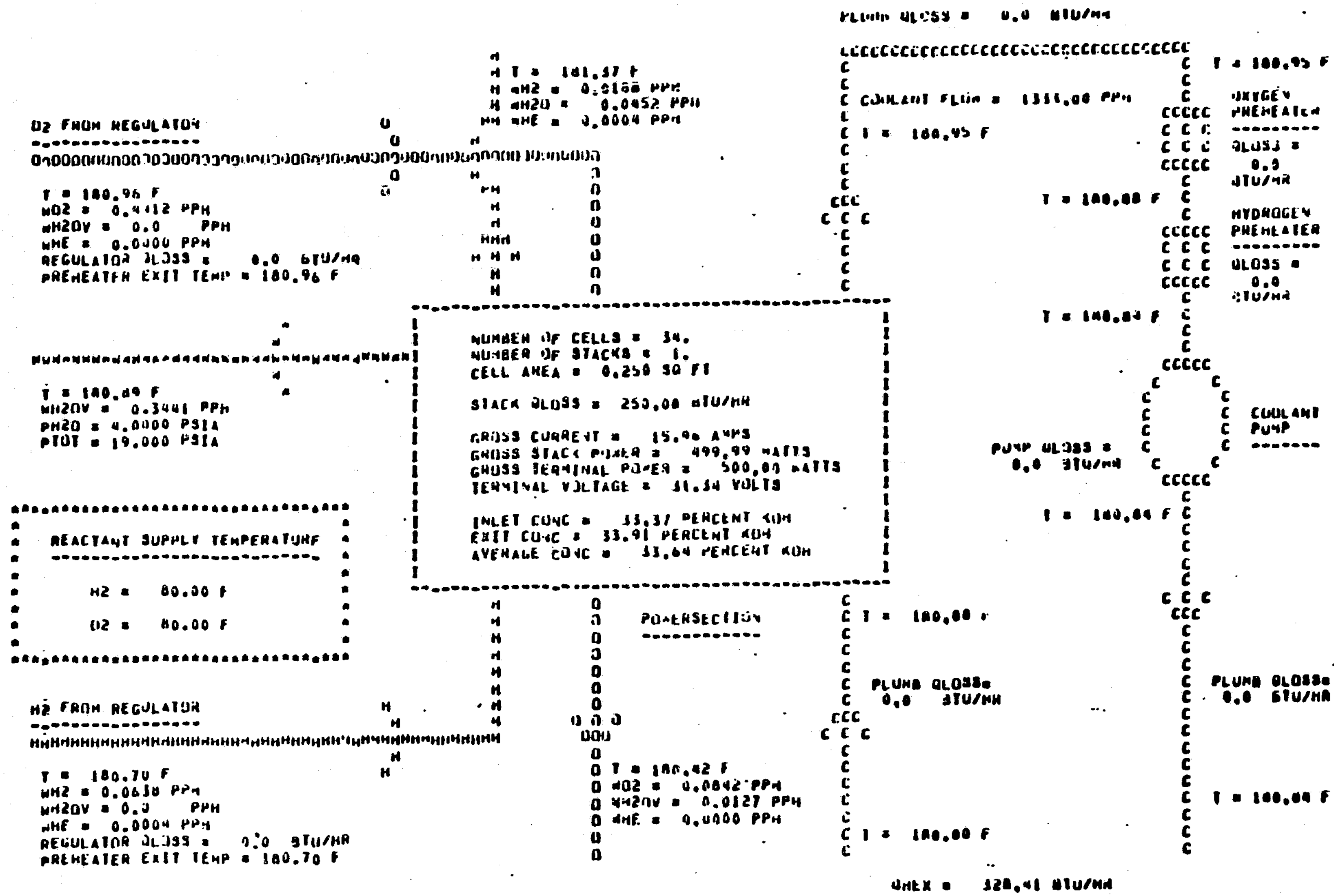


Figure 66. Powerplant Characteristics at 2500-hours, 0.5kW

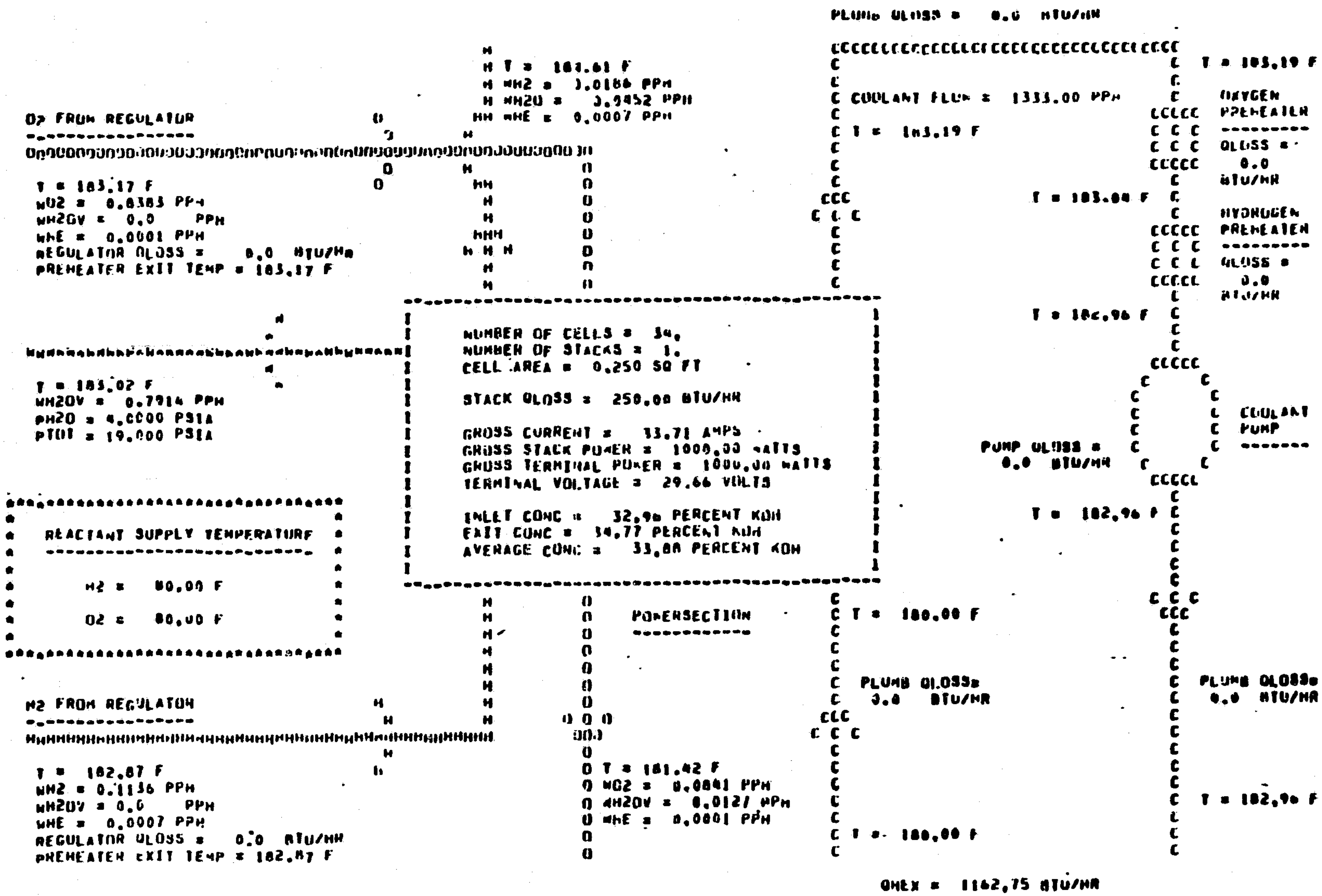


Figure 67. Powerplant Characteristics at 2500-hours, 1.0kW

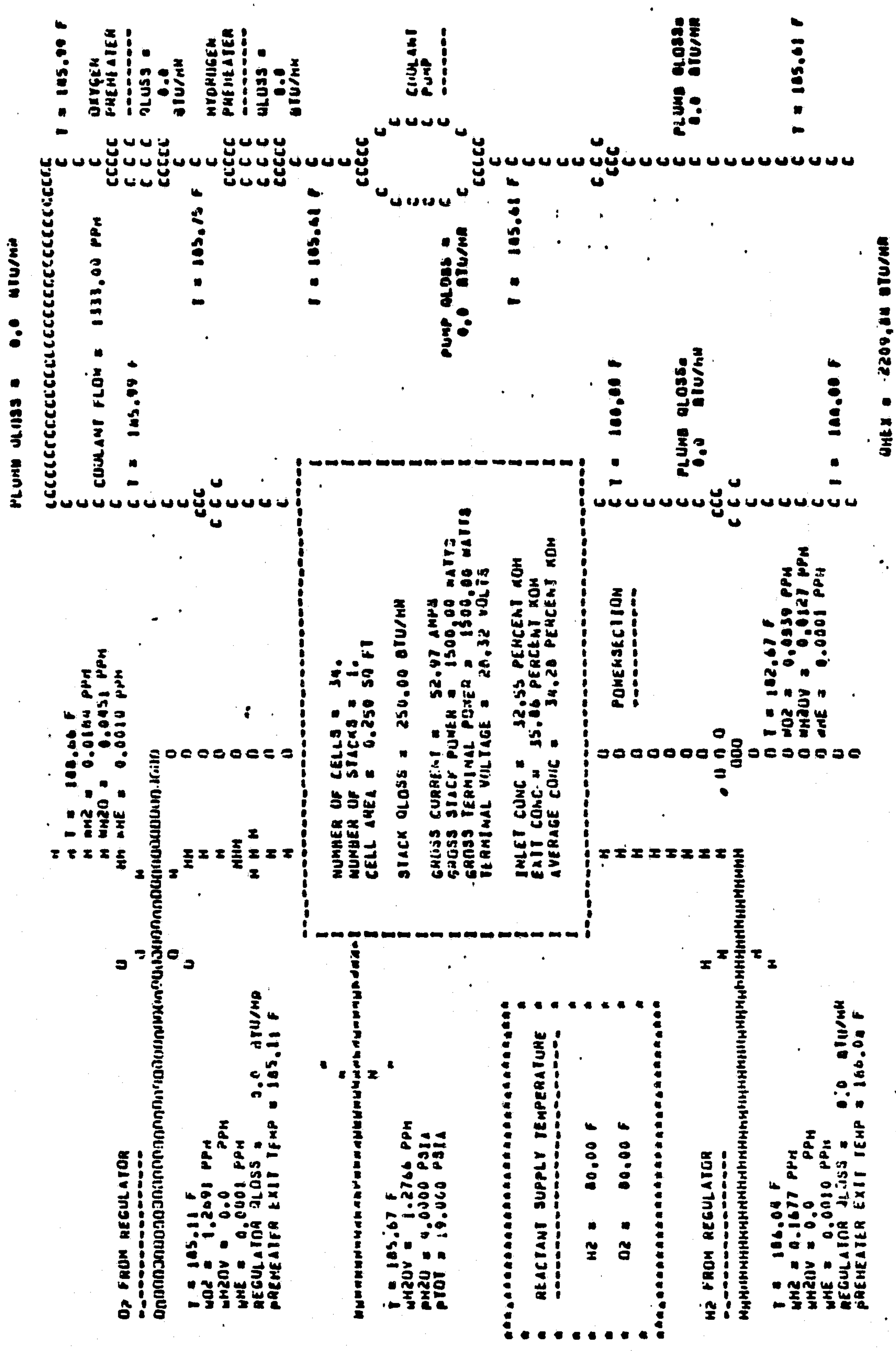


Figure 68. Powerplant Characteristics at 2500-hours, 1.5kW

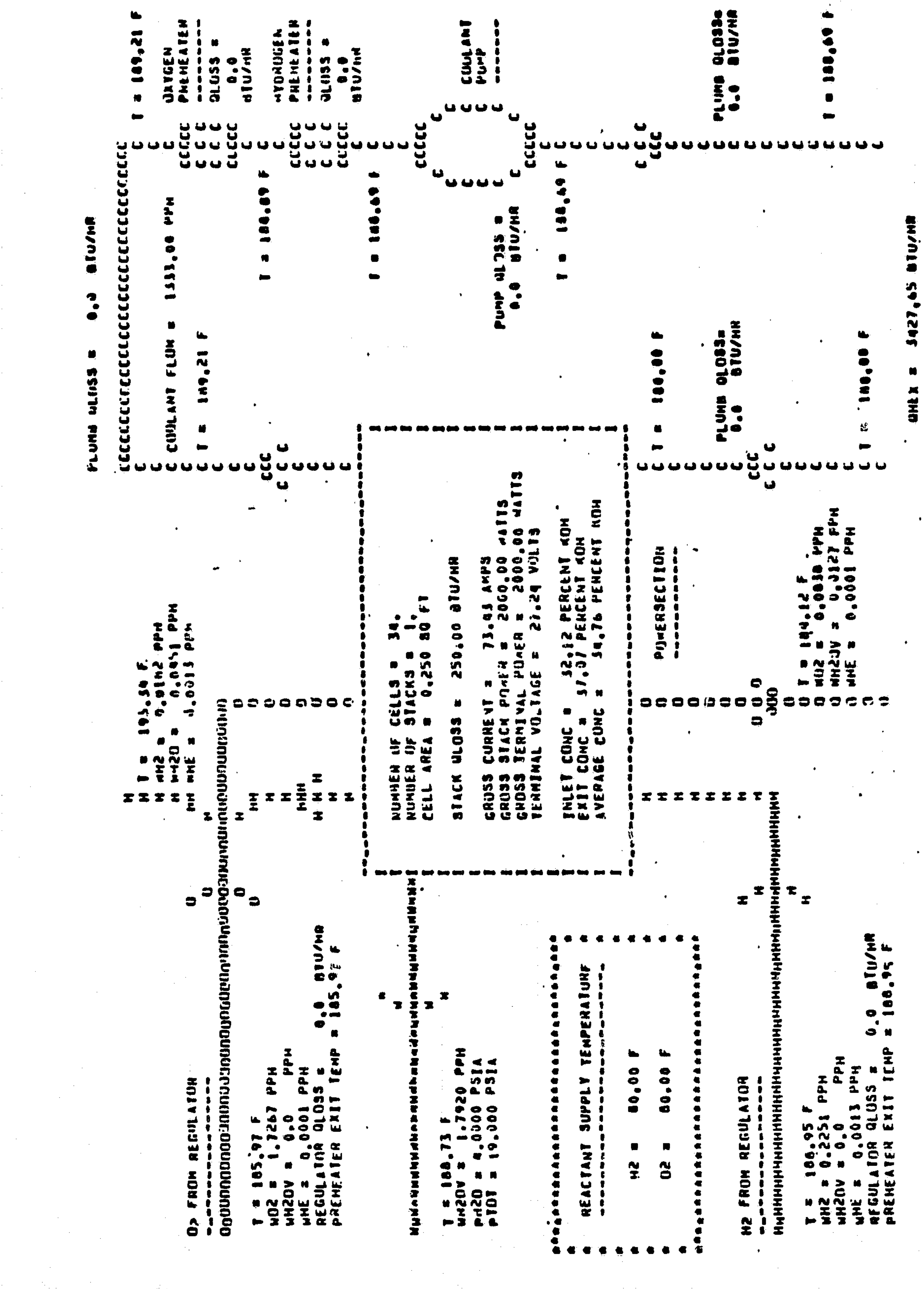


Figure 69. Powerplant Characteristics at 2500-hours, 2.0kW

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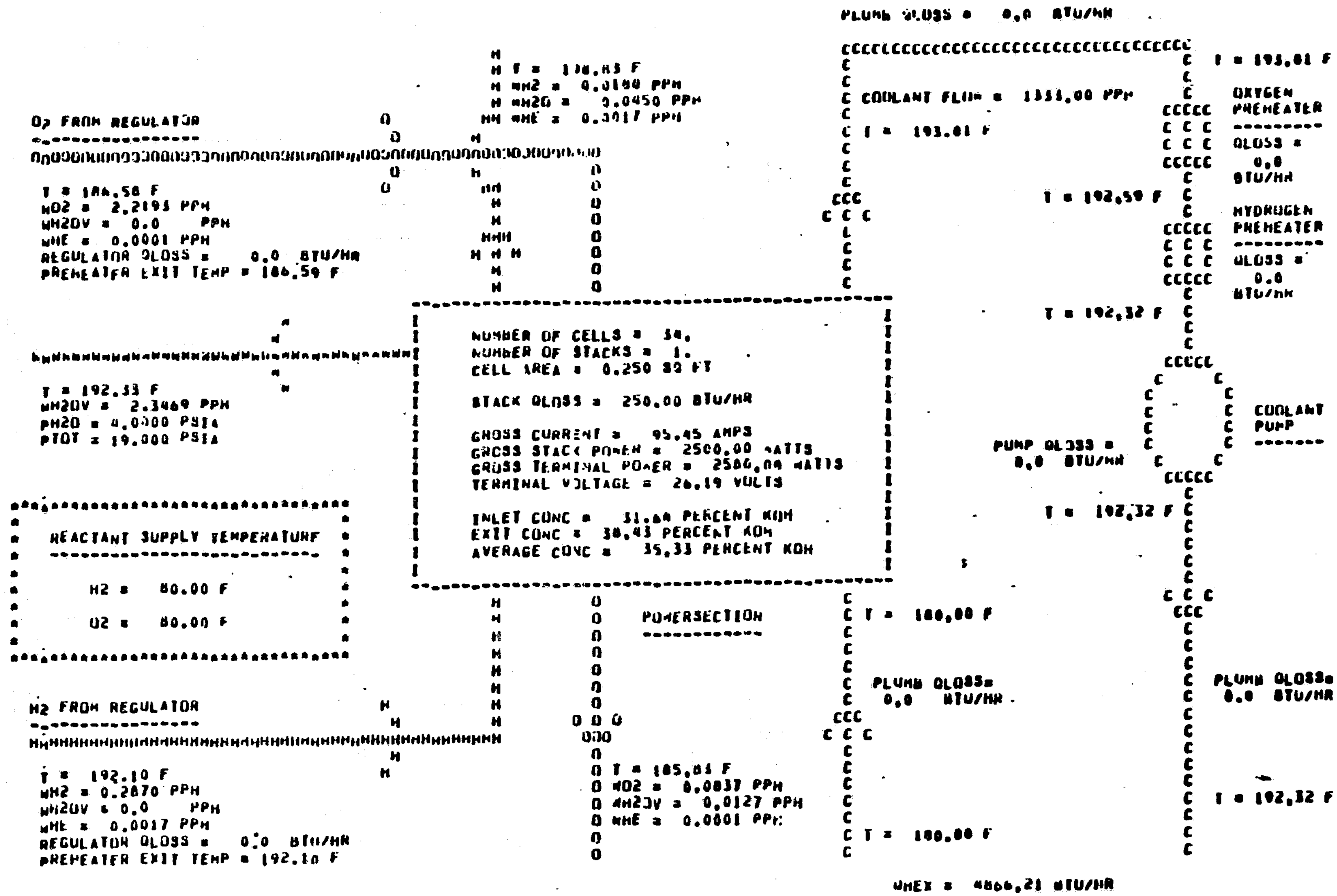

Figure 70. Powerplant Characteristics at 2500-hours, 2.5kW

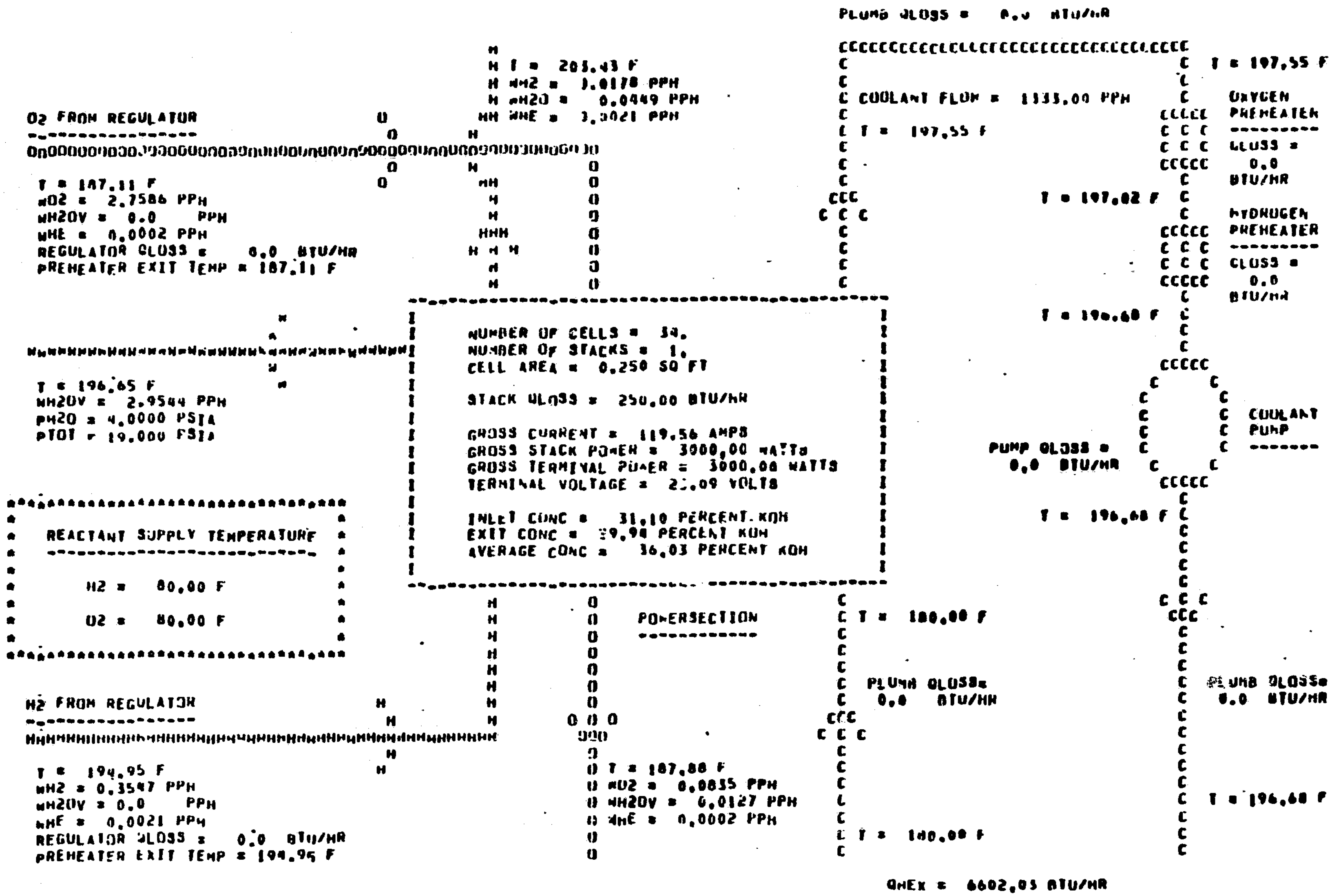

Figure 71. Powerplant Characteristics at 2500-hours, 3.0kW

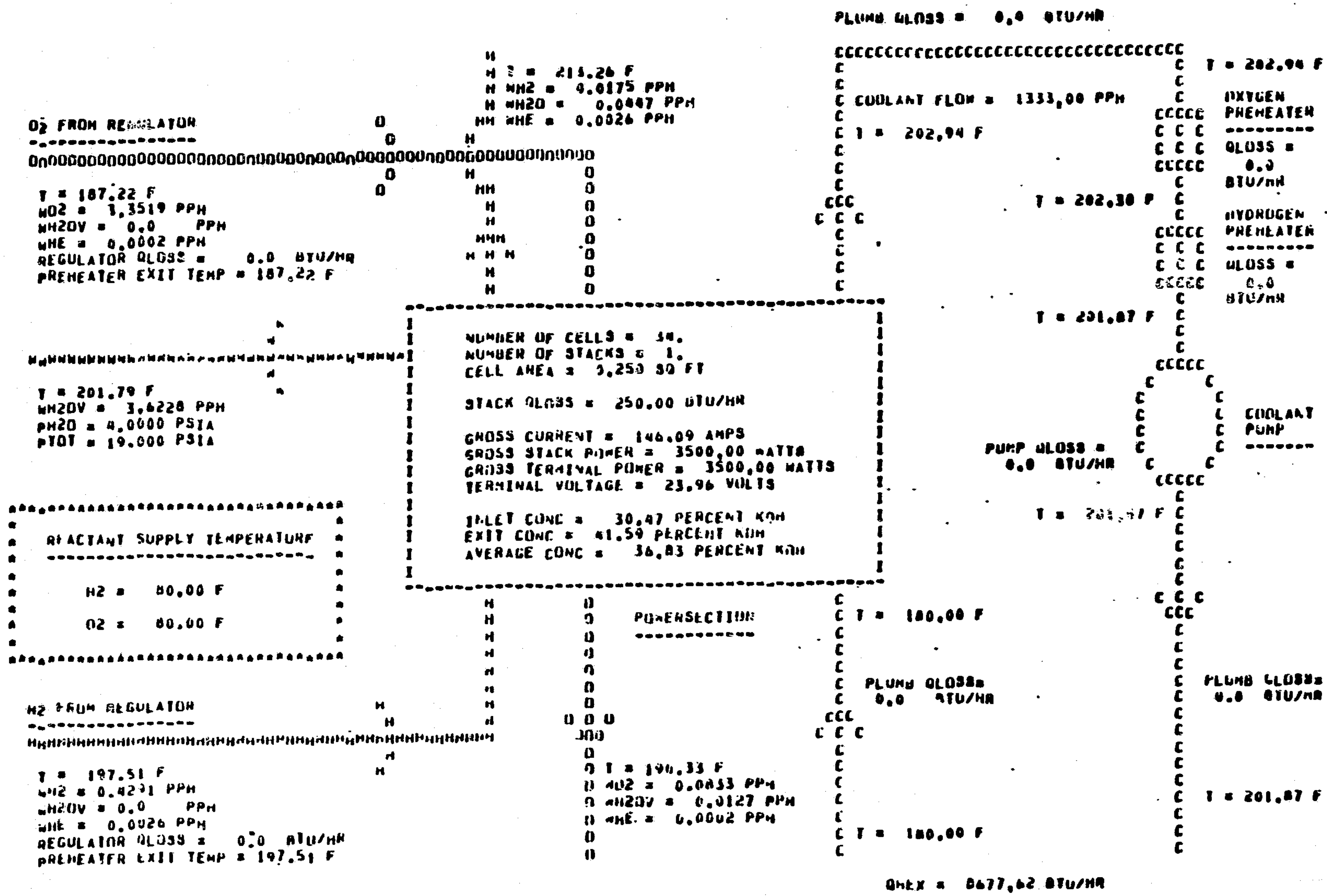

Figure 72. Powerplant Characteristics at 2500-hours, 3.5kW

C-2

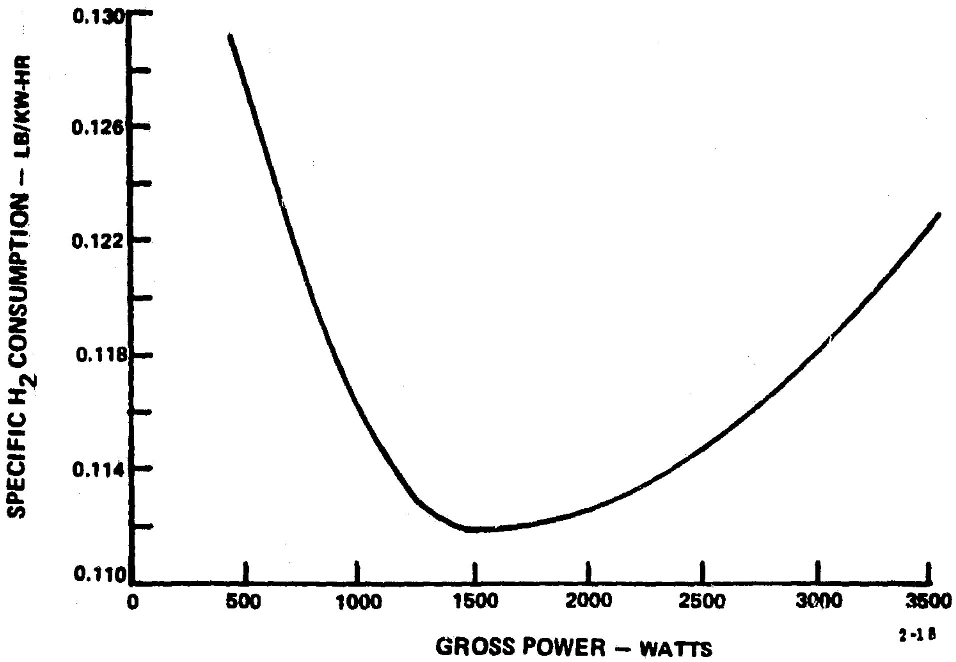

Figure 73. Specific Hydrogen Consumption

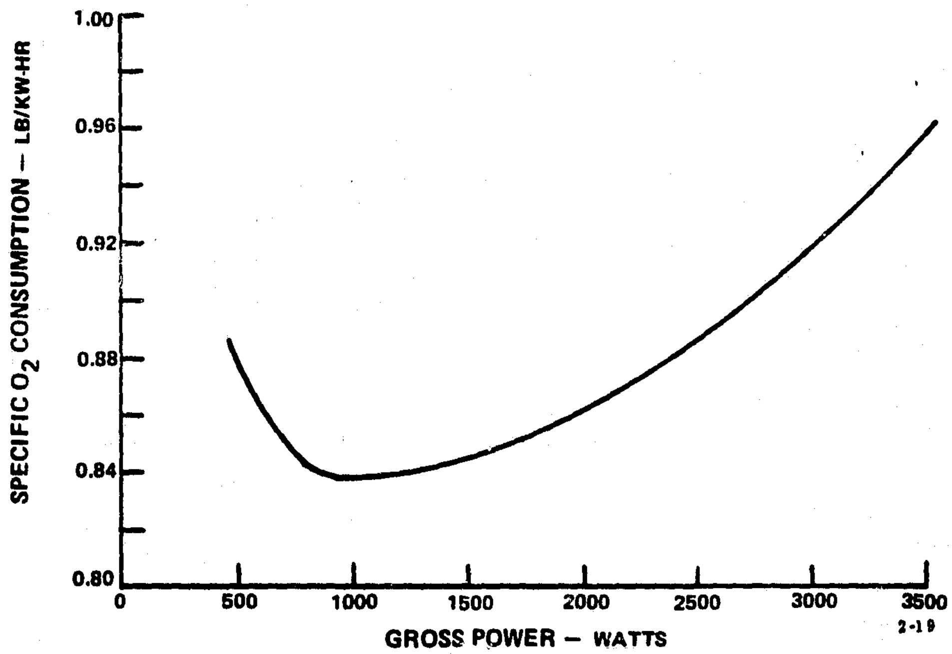

Figure 74. Specific Oxygen Consumption

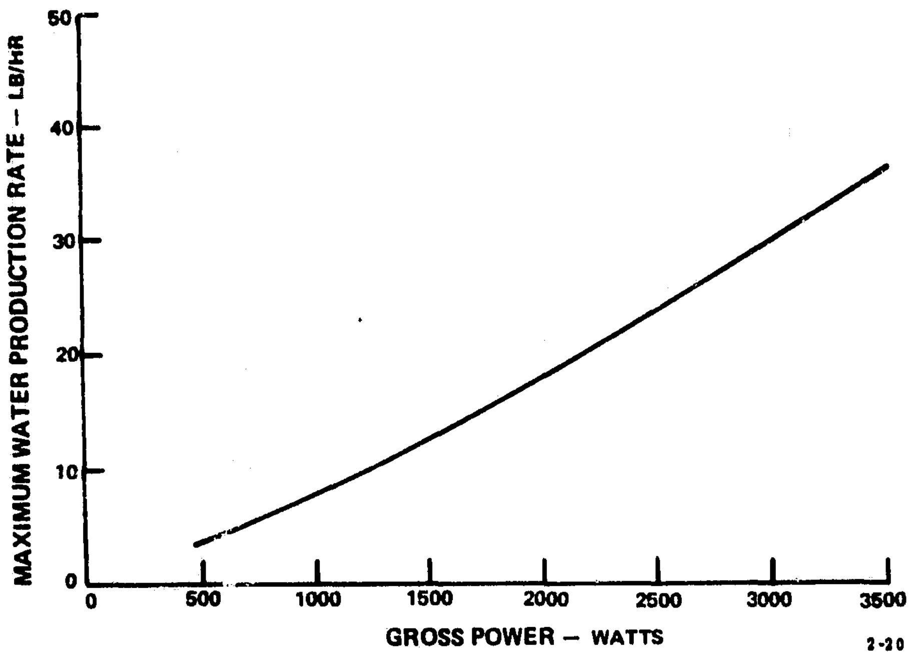

Figure 75. Powerplant Water Production

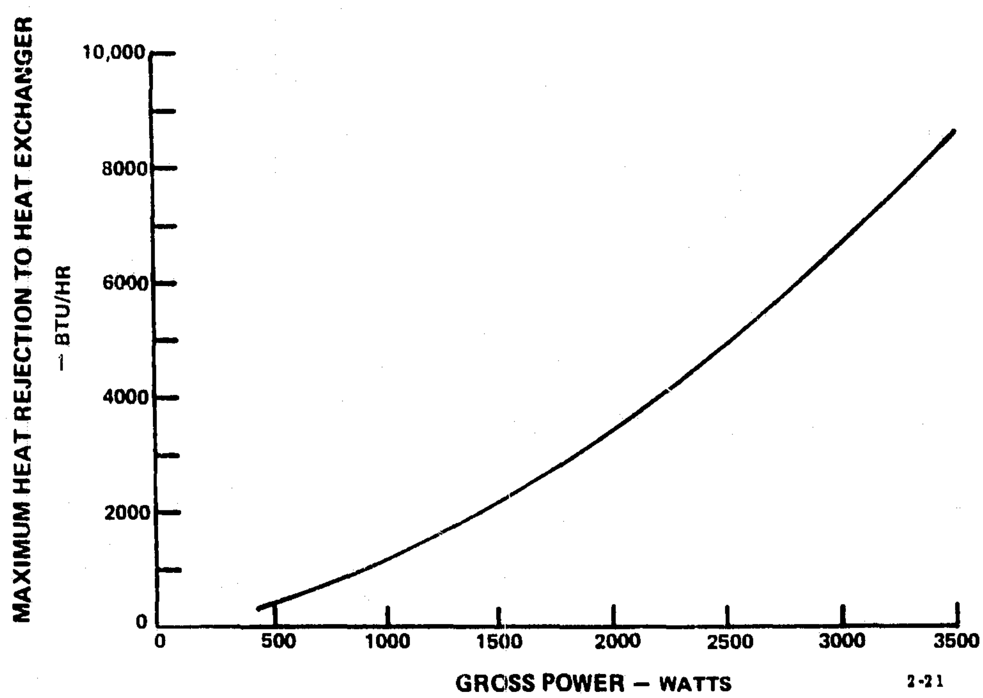

Figure 76. Powerplant Maximum Heat Rejection to Heat Exchanger

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