DEVELOPMENT OF AN ALKALINE FUEL CELL SUBSYSTEM

Final Program Summary Report

for the Period

April 10, 1986 – March 31, 1987

FCR-8590

CONTRACT NO. NAS 9-17613

Prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

Prepared by

International Fuel Cells
South Windsor, CT 06074
DEVELOPMENT OF AN ALKALINE FUEL CELL SUBSYSTEM

Final Program Summary Report

for the Period

April 10, 1986 – March 31, 1987

FCR-8590

CONTRACT NO. NAS 9-17613

Prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

Prepared by

International Fuel Cells
South Windsor, CT 06074
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td>Prototype Power Section Design</td>
<td>2</td>
</tr>
<tr>
<td>Cell Requirements and Area Selection</td>
<td>2</td>
</tr>
<tr>
<td>Repeating Unit Design</td>
<td>2</td>
</tr>
<tr>
<td>Prototype Power Section Design and PDR</td>
<td>5</td>
</tr>
<tr>
<td>Development of Fuel Cell Stack Components</td>
<td>5</td>
</tr>
<tr>
<td><strong>CONCLUSION</strong></td>
<td>7</td>
</tr>
<tr>
<td><strong>RECOMMENDATIONS</strong></td>
<td>8</td>
</tr>
<tr>
<td><strong>APPENDIX – Cell Stack Assembly Preliminary Design Review</strong></td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Repeating Unit Advanced Fuel Cell Power Section</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Fuel Cell Planform Comparison</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>1.0-Ft² Gold-Plated Photofabricated Nickel Foil Electrode Substrate</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>1.0-Ft² Matrix Electrode Vacuum Filtration Tooling</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>1.0-Ft² Polyphenylene Sulfide Cell Holder Plate</td>
<td>7</td>
</tr>
</tbody>
</table>
INTRODUCTION

The Space Station electrical power system will include an energy storage capability. The function of the energy storage system is to store electrical energy generated during the daylight portion of the orbit and to deliver electrical power during the night portion of the orbit. Several NASA and NASA-sponsored studies of energy storage systems for Space Station applications have shown that Regenerative Fuel Cell Systems offer significant benefit over current state-of-the-art energy storage devices. NASA–JSC plans to integrate an electrolyzer subsystem and fuel cell subsystem into a Space Station Prototype (SSP) regenerative fuel cell to demonstrate this energy storage function.

The fuel cell subsystem for the SSP will contain an advanced power section mated with a government-furnished Orbiter Powerplant accessory section modified with improved components to provide extended life and greater capacity. A microprocessor controller will be used to operate, control, and integrate the fuel cell power plant and the electrolyzer into a Space Station Prototype (SSP) regenerative fuel cell system.

The fuel cell subsystem for the SSP is to have the following features: a nominal output power of 10 kW, a minimum electrical efficiency of 55 percent, one-square foot active area cells and accessory section components with projected life times of 20,000-hours or greater.

Under Contract No. NAS9–17613, International Fuel Cells initiated a two task program to develop advanced fuel cell components which could be assembled into an alkaline power section for the SSP fuel cell subsystem. The first task was to establish a preliminary SSP power section design to be representative of the 200–cell Space Station power section design begun under NAS9–15990. The power section design was to incorporate technol-
ogy improvements for extended endurance and low weight identified under the NASA-Lewis fuel cell programs. The second task of the program was to conduct tooling and fabrication trials and fabrication of selected cell stack components.

All work associated with the development of an alkaline SSP fuel cell system was terminated following receipt of a stop work order issued by JSC on 24 July 1986.

Prototype Power Section Design

Cell Requirements and Area Selection - The prototype power section design requirements were established based upon the requirements of the Statement of Work and supplementary information from NASA and Space Station Phase B studies. Studies were conducted that evaluated alternative cell configurations. The results indicated that significant improvements in fuel cell system efficiency and reliability could be achieved by developing a one-square foot cell configuration. Specifically a ten percentage point improvement in power plant could be obtained by use of a one-square foot cell rather than the Orbiter-sized half-square foot cell configuration. This efficiency improvement could be accomplished by operating two 0.5-ft² Orbiter-type stacks electrically in parallel; however, the doubling of the number of cells results in a factor of two lower MTBF and nearly a 5 percent heavier cell stack when compared to the 1.0-ft² cell stack configuration. As a result of 1.0-ft² cell active area was selected for the prototype stack design.

Repeating Unit Design - The repeating unit of the power section is a group of individual fuel cells together with the cooler for removing waste heat from the group of cells. This unit repeats throughout the entire stack.

For the prototype power section the repeating unit design is comprised of five parts which are repeatedly "stacked." A cross-section of the repeating unit is shown in Figure 1. Starting at the top of figure the parts are a nickel cell-separator plate, a ribbed graphite electrolyte reservoir plate, a unitized cell assembly, and a silver-plated polyphenylene sulfide cell holder frame. This pattern repeats for three cells. Between the third and fourth
A silver-plated polyphenylene sulfide cooler plate is inserted to form a coolant flow cavity. This 3-cell unit with a cooler is the repeating unit. It repeats again and again to form the power section.

**Figure 1. Repeating Unit Advanced Fuel Cell Power Section**

The function of each part is as follows: The bipolar cell holder frame conducts electrical current through the silver plating to the adjacent cell. A 5-mil thick nickel separator plate isolates the oxygen and hydrogen cavities of adjacent cells. An identical separator isolates the cooler plate from the three-cell repeating element. A flow field in the cell holder frame and the ribbed carbon anode electrolyte reservoir plate (ERP) provide for the circulation of oxygen and hydrogen; a flow field in the cooler plate provides for the circulation of coolant. The advanced 1.0-ft² cell design incorporates internal reactant and coolant manifolds. Metering ports in the plastic plates ensure the uniform distribution of hydrogen, oxygen, and coolant in the respective flow fields. These plates contain molded seals that seal the spaces between plates, separators, and electrode assemblies to prevent mixing of hydrogen, oxygen or coolant and leakage of these fluids from the fuel cell power section.
The cell and repeating unit designs incorporate the advanced material and component technology developed under NASA-LeRC sponsored programs. This includes corrosion-resistant polyphenylene sulfide frames and coolant plates, stable butyl rubber bonded potassium titanate matrices, extended endurance platinum-on-carbon catalyst anodes, lightweight anode carbon electrolyte reservoir plates (ERP), low-weight perforated nickel foil electrode substrates, and thin nickel coolant separator plates.

The planform of the 1.0-ft² advanced fuel cell design is compared to the Orbiter production cell in Figure 2. The specific weight of the repeating unit based on this planform and the improved corrosion resistant materials is 2.3 lbs/ft². For the Orbiter repeating unit the weight is 2.9 lbs/ft². A six-cell stack of 1/2 ft² area cells incorporating all of the 1.0-ft² cell configuration technology improvements was endurance tested to a simulated Regenerative Fuel Cell load profile under the NASA-Lewis Long-Life, High Performance Fuel Cell Program, Contract No. NAS3-22234 and successfully completed over 6000 hours of operation with no loss in performance.

![Figure 2. Fuel Cell Planform Comparison](image-url)
Prototype Power Section Design and PDR

The prototype power section design was based on the 3 cells/1 cooler repeating unit. It consists of 66 repeating units for a total of 198 cells and 67 coolers. One additional cooler unit is added on one end of the power section to make the cooler arrangement symmetrical and the thermal profiles throughout all repeating units the same. The power section output is 25 kW at 180 to 200 volts. Its operating pressure is 60 psia and its nominal operating temperature is 180°F.

A Preliminary Design Review of the power section, repeating unit and cells was conducted with NASA-JSC. Design documentation, including drawings of the power section assembly and individual cell components, was prepared and provided to NASA. Fuel cell background information on endurance of the power section design were also provided at the PDR. The Design Review Data Package is attached in Appendix I.

Development of Fuel Cell Stack Components

Fabrication trials were conducted to define manufacturing procedures for the platinum–carbon anode, cathode and potassium titanate matrix of the 1.0-ft2 cell. Special tooling was designed and constructed for the manufacture of these components. Supported platinum catalyst anodes and gold-platinum catalyst cathodes were successfully fabricated from the defined procedures. A photograph of the gold-plated photo fabricated nickel, foil electrode substrate is shown on Figure 3. Performance evaluation of electrode test samples satisfied IFC specifications for production cells with cathode exceeding the 850 mV @ 800 mA/cm² established for Orbiter-gold-platinum cathodes. Employing the established manufacturing procedures, large 15-inch by 15-inch "mat-type" butyl-rubber bonded potassium-titanate matrices were fabricated. The cross-pressure tolerance of these matrices was determined to be in excess of 20 psid. The matrix and electrode fabrication tooling is shown in Figure 4. This tool is used for vacuum filtration of matrix raw material into a "mat" or to deposit catalyst layers on finished matrices.
Figure 3. 1.0-ft² Gold-Plated Photofabricated Nickel Foil Electrode Substrate

Figure 4. 1.0-ft² Matrix-Electrode Vacuum Filtration Tooling
Cell holder and cooler plates molded from corrosion-resistant polyphenylene sulfide (PPS) have the benefits of reduced cost and extended endurance. Initially, the plan was to machine the plates from molded PPS blanks, eventually completely molding the parts in a one-step operation. Full-size PPS blanks were molded for machining trials. A cell holder produced in an initial machining trial is shown in Figure 5. The part is a full-size 1.0-ft² PPS cell holder. The completed plate had oxygen flow fields, edge seal grooves, reactant and coolant manifolding and full exterior contouring.

CONCLUSIONS

- A lightweight, reliable cell stack design suitable for the space station prototype regenerative fuel cell power plant has been completed. The design meets NASA's preliminary requirements for future multi-kilowatt Space Station missions.

- Cell stack component fabrication and tooling trials demonstrated cell components of the SSP stack design of the 1.0-ft² area can be manufactured using techniques and methods evaluated and developed under this and previous technology development programs sponsored by NASA.
RECOMMENDATIONS

- Development of the 1.0-ft$^2$ cell stack components should be completed to permit single cell and substack testing of the components to demonstrate that they meet SSP power plant design requirements and specifications.
APPENDIX

CELL STACK ASSEMBLY

PRELIMINARY DESIGN REVIEW
DEVELOPMENT OF AN ALKALINE FUEL CELL SUBSYSTEM

NASA-JSC CONTRACT NAS 9-17613

CELL STACK ASSEMBLY

PRELIMINARY DESIGN REVIEW

R. E. MARTIN

JUNE 1986
AGENDA

- INTRODUCTION
- SUMMARY
- ASSUMED DESIGN GUIDELINES AND GOALS
- CELL STACK ASSEMBLY/COMPONENT DESIGN REQUIREMENT
- ALKALINE FUEL CELL AREA COMPARISON
- DESIGN STATUS AND FEATURES
- TECHNOLOGY DEVELOPMENT STATUS
- SUPPLEMENTARY TASKS
INTRODUCTION

- THIS IS A PRELIMINARY DESIGN REVIEW.

- FLIGHT WEIGHT END PLATES AND INSULATORS ARE NOT INCLUDED.

- THE POWER SECTION CONFIGURATION THAT WE RECOMMEND IS PRESENTED

- THE RECOMMENDED CONFIGURATION CONTAINS ADVANCED FEATURES EVALUATED UNDER THE NASA LEWIS PROGRAM.
SUMMARY

- PREDICTED WEIGHT OF REPEATING PARTS IS 2.3 LBS/FT³

- THE POWER SECTION HAS 1 FT²/CELL ACTIVE AREA AND 199 CELLS.

- MAGNESIUM SEPARATOR PLATES REPLACED WITH PPS FRAME AND MONEL COVER SHEET FOR IMPROVED RELIABILITY, LIFE, AND POTENTIALLY LOWER COSTS.

- ADVANCED DETAILS INCLUDE:
  - ASBESTOS MATRIX REPLACED WITH PKT
  - Pt/Pd ANODE CATALYST REPLACED WITH SUPPORTED Pt CATALYST.
  - POROUS Ni ERP REPLACED WITH CARBON
  - Ni FOIL SUBSTRATE REPLACES FINE WIRE SCREEN ELECTRODE SUBSTRATE
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DESIGN POWER, KW</strong></td>
<td></td>
</tr>
<tr>
<td>• NET</td>
<td>25</td>
</tr>
<tr>
<td>• GROSS</td>
<td>25.4</td>
</tr>
<tr>
<td><strong>DESIGN VOLTAGE, VOLTS</strong></td>
<td></td>
</tr>
<tr>
<td>• MAXIMUM</td>
<td>200</td>
</tr>
<tr>
<td>• MINIMUM</td>
<td>180</td>
</tr>
<tr>
<td><strong>NUMBER OF CELLS</strong></td>
<td>200</td>
</tr>
<tr>
<td><strong>DESIGN CURRENT DENSITY, ASF</strong></td>
<td></td>
</tr>
<tr>
<td>• INITIAL</td>
<td>133</td>
</tr>
<tr>
<td>• 40,000-HOURS</td>
<td>140</td>
</tr>
<tr>
<td><strong>NASA REGENERATIVE FUEL CELL EFFICIENCY</strong></td>
<td></td>
</tr>
<tr>
<td>• FUEL CELL SUBSYSTEM EFFICIENCY</td>
<td>67.8%</td>
</tr>
<tr>
<td>• EQUIVALENT FUEL CELL PERFORMANCE</td>
<td>0.863 @ 412 ASF</td>
</tr>
<tr>
<td>(TWO-CELL RIG 39728-1)</td>
<td></td>
</tr>
<tr>
<td><strong>PEAK GROSS POWER, KW</strong></td>
<td>33.5</td>
</tr>
<tr>
<td><strong>CELL ACTIVE AREA, FT²</strong></td>
<td>1.0</td>
</tr>
<tr>
<td><strong>NOMINAL COOLANT INLET TEMPERATURE</strong></td>
<td>180 F</td>
</tr>
<tr>
<td><strong>NOMINAL REACTANT PRESSURE</strong></td>
<td>60 PSIA</td>
</tr>
<tr>
<td>• (HIGHER REACTANT PRESSURE - IMPROVED PERFORMANCE 120 PSIA)</td>
<td></td>
</tr>
<tr>
<td><strong>REPEATING UNIT SPECIFIC WEIGHT</strong></td>
<td>2.2 LBS/FT²</td>
</tr>
<tr>
<td><strong>LIFE GOAL</strong></td>
<td>40,000 HOURS</td>
</tr>
</tbody>
</table>
CELL STACK ASSEMBLY

COMPONENT DESIGN REQUIREMENTS
To:  Mr. R. E. Martin

From:  Jay Garow  Ext. 2372

Subject:  X708 Fuel Cell Power Plant Improvement Program – Cell Stack Assembly Requirements

The attached Component Requirements Document presents the preliminary performance requirements for the Advanced Technology Powersection Design. It is based on nominal Space Station Power Plant requirements of 25 kw, 180 to 200 volts.

cc.  Name

Clausi, J. V.
Davis, G. H.
Fanciullo, S.
Morganthaler, G. F.
Suljak, G. T.
Sawyer, R. D.

Jay Garow
COMPONENT REQUIREMENTS

CELL STACK ASSEMBLY

<table>
<thead>
<tr>
<th>DATE</th>
<th>REVISION</th>
<th>LETTER</th>
<th>SYMBOL</th>
<th>PREPARED</th>
<th>FUNCTIONAL GROUP</th>
<th>APPROVAL</th>
<th>PC24A PROJECT</th>
<th>APPROVAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/9/85</td>
<td>Preliminary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CELL STACK ASSEMBLY

Basis of Requirements

Figure 1 - 25 kW

Purge Rates

- H₂ Purge Rate = 4 pph
- O₂ Purge Rate = 8 pph

Scope

The cell stack assembly consists of, but is not limited to, the following:

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Assembly (EA)</td>
<td>200</td>
</tr>
<tr>
<td>Includes: - Fine-Pore Carbon Anode Electrode Reservoir Plate (ERP) - Pt/C Catalyst Anode - Gold-Plated Perforated Nickel Anode Substrate - Butyl Rubber Bonded Potassium Titanate Matrix - Au/Pt Catalyst Cathode - Gold-Plated Perforated Nickel Cathode Substrate</td>
<td></td>
</tr>
<tr>
<td>Glass-Filled Polyphenylene Sulfide Edge Frames</td>
<td></td>
</tr>
<tr>
<td>Metal Cover Sheet</td>
<td>300</td>
</tr>
<tr>
<td>Glass-Filled Polyphenylene Sulfide Seal Frame or Equivalent</td>
<td>100</td>
</tr>
<tr>
<td>Carbon Coolant Field Insert or Equivalent</td>
<td>100</td>
</tr>
<tr>
<td>Negative-end (H₂) Load Tab Plate</td>
<td>1</td>
</tr>
<tr>
<td>Positive-end (O₂) Load Tab Plate</td>
<td>1</td>
</tr>
<tr>
<td>Positive-end Insulator Plate</td>
<td>1</td>
</tr>
<tr>
<td>Negative-end Insulator Plate</td>
<td>1</td>
</tr>
<tr>
<td>Positive-end Pressure Plate</td>
<td>1</td>
</tr>
<tr>
<td>Negative-end Pressure Plate</td>
<td>1</td>
</tr>
<tr>
<td>Tie Rods, Washers, Nuts</td>
<td>As Req'd</td>
</tr>
<tr>
<td>Component</td>
<td>Parameter</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Hydrogen</strong></td>
<td>Flow (cfm)</td>
</tr>
<tr>
<td></td>
<td>Humidity Ratio (lbs H2O):(lbs dry H2)</td>
</tr>
<tr>
<td></td>
<td>Inlet Temperature (deg F)</td>
</tr>
<tr>
<td></td>
<td>Inlet Pressure (psia)</td>
</tr>
<tr>
<td><strong>Oxygen</strong></td>
<td>Flow (pph)</td>
</tr>
<tr>
<td></td>
<td>Dual Feed Mode</td>
</tr>
<tr>
<td></td>
<td>Single Feed Mode (with purge)</td>
</tr>
<tr>
<td></td>
<td>Inlet Temperature (deg F)</td>
</tr>
<tr>
<td></td>
<td>Inlet Pressure (psia)</td>
</tr>
<tr>
<td><strong>Coolant</strong></td>
<td>Flow (pph FC40)</td>
</tr>
<tr>
<td></td>
<td>Inlet Temperature (deg F)</td>
</tr>
<tr>
<td></td>
<td>Inlet Pressure (psia)</td>
</tr>
</tbody>
</table>

**Note:** The coolant system will be subjected to a vacuum (TBD) in order to facilitate a complete coolant fill.

**Allocated Pressure Drop:**
- Hydrogen (in. H2O), max. | 1.5
- Coolant (psi), max. | 1.5

**Allocated Heat Loss:** (Btu/hr), max. | TBD

**Abort Start Capability**
The CSA should be capable of being able to start-up and go to zero net power after having aborted two starts just prior to start complete.
**Applicable Documents**

TBD

**Operating Environment**

<table>
<thead>
<tr>
<th>Environment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>Space Vacuum or Air</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Up to 100 %</td>
</tr>
<tr>
<td>Temperature (deg F)</td>
<td>40 to 200 (TBD)</td>
</tr>
<tr>
<td>Pressure (psia)</td>
<td>0 to 20 (TBD)</td>
</tr>
<tr>
<td>Attitude</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**Vibration**

TBD

**Transportation and Handling**

TBD

**Start/Stop Cycles**

TBD
ALKALINE FUEL CELL AREA COMPARISON

• SUMMARY

• TYPICAL CONSTRAINTS - SPACE STATION APPLICATION
  • HIGH EFFICIENCY REQUIREMENT
  • VOLTAGE LEVEL REQUIREMENT
  • NO PACKAGING CONSTRAINTS
  • LOOSE VOLTAGE REGULATION BAND CONSTRAINTS

• CONCLUSIONS

• ANY CELL AREA CAN MEET VOLTAGE AND EFFICIENCY REQUIREMENTS.
• ORBITER-TYPE 0.5 FT² CAN BE PARALLELLED FOR EQUAL AREA AND SAFETY REQUIREMENTS.
• ADVANCED 1.0 FT² CELL RESULTS IN A DOUBLING OF THE MTBF FOR THE STACK (ASSUMES CELL MTBF INDEPENDENT OF SIZE).
• THERE IS A SMALL WEIGHT SAVINGS FOR THE 1.0 FT² CELL OVER THE .5 FT² CELL OF ABOUT 10%.
• A FUEL CELL POWER PLANT INCORPORATING THE ADVANCED 1.0 FT² CELL HAS FEWER PARTS, PARTICULARLY AS POWER REQUIREMENTS INCREASE.
DESIGN STATUS AND FEATURES
SUMMARY

- MATERIAL AND TECHNOLOGY IMPROVEMENTS IDENTIFIED UNDER THE NASA-LEWIS PROGRAM HAVE BEEN INCORPORATED INTO AN ADVANCED CELL DESIGN.
  - POTASSIUM TITANATE MATRIX
  - PLATINUM-ON-CARBON CATALYST ANODE
  - PERFORATED Ni-FOIL ELECTRODE SUBSTRATES
  - CARBON ELECTROLYTE RESERVOIR PLATE
  - POLYPHENYLENE SULFIDE CELL EDGE FRAMES (PPS ALSO USED FOR O₂ FIELD AND COOLER CONFIGURATION)

- CAPABILITIES OF THE ADVANCED 1.0 FT² POWER SECTION WERE IDENTIFIED

<table>
<thead>
<tr>
<th></th>
<th>DESIGN</th>
<th>ESTIMATED MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER - KW</td>
<td>25</td>
<td>62</td>
</tr>
<tr>
<td>CURRENT DENSITY - ASF</td>
<td>140</td>
<td>355</td>
</tr>
<tr>
<td>VOLTAGE - VOLTS</td>
<td>180</td>
<td>175</td>
</tr>
</tbody>
</table>

- THE ADVANCED 1.0 FT² CELL DESIGN WAS COMPLETED
  - STRUCTURAL ANALYSIS OF THE REPEATING ELEMENT
  - REACTANT AND COOLANT DISTRIBUTION ANALYSIS
  - THERMAL AND ELECTRICAL RESISTANCE ANALYSIS
  - END CELL HEAT LOSS ANALYSIS

- DETAIL DESIGN PRINTS OF THE ADVANCED 1.0 FT² CELL CONFIGURATION COMPONENTS HAVE BEEN PREPARED

- IDENTIFIED REMAINING CELL STACK DESIGN TASKS
SPECIFIC WEIGHT 2.3 LBS/FT²
## ESTIMATED WEIGHT OF REPEATING ELEMENTS

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>WEIGHT PER FT^2 ACTIVE AREA</th>
<th>% CONTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELECTRODES AND MATRIX</td>
<td>0.31</td>
<td>13</td>
</tr>
<tr>
<td>O_2 FIELD AND FRAME</td>
<td>0.78</td>
<td>34</td>
</tr>
<tr>
<td>SEPARATOR</td>
<td>0.44</td>
<td>19</td>
</tr>
<tr>
<td>COOLER</td>
<td>0.24</td>
<td>11</td>
</tr>
<tr>
<td>ELECTROLYTE</td>
<td>0.30</td>
<td>13</td>
</tr>
<tr>
<td>ANODE ERP</td>
<td>0.23</td>
<td>10</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2.3 LBS</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
1.0 ft² ADVANCED TECHNOLOGY CELL

12.1 in

11.5 in

0.97 ft²

1.58 ft²

ORBITER CELL

CELL PLANFORM AREA

HYDROGEN MANIFOLDS

COOLANT

OXYGEN
ADVANCED TECHNOLOGY 1.0 FT CELL FEATURES

- CORROSION-RESISTANT MATERIALS FOR LONG-LIFE
  - POTASSIUM TITANATE (PKT) MATRIX
  - POLYPHENYLENE SULFIDE (PPS) CELL, COOLER, AND INSULATOR PLATES
  - CARBON ELECTROLYTE RESERVOIR PLATE (ERP) - 10 MICRON FOR ELECTROLYTE RETENTION
  - SUPPORTED PLATINUM-ON-CARBON ANODE CATALYST

- ADVANCED CONFIGURATION FOR LOWER COST
  - ONE-PIECE MOLDED PPS FRAME
  - MOLDED PPS CELL PLATE
  - MOLDED PPS COOLER PLATE
  - PERFORATED Ni-FOIL ELECTRODE SUBSTRATES
  - THIN (5-MIL) NICKEL FOIL SEPARATOR
  - SIMPLE CELL EDGE SEAL

- ADVANCED CONFIGURATION FOR LOWER WEIGHT
  - CARBON ERP
  - PERFORATED Ni-FOIL SEPARATOR
  - THIN NICKEL FOIL SEPARATOR
  - MOLDED PPS CELL, COOLER, AND INSULATOR PLATES

- ADVANCED CONFIGURATION FOR IMPROVED RELIABILITY
  - FEWER CELL COMPONENT PARTS
  - PERFORATED Ni-FOIL ELECTRODE SUBSTRATE
  - CORROSION-RESISTANT CELL COMPONENT MATERIALS
  - IMPROVED CELL EDGE SEAL
1.0 ft² CELL ELECTRODE ASSEMBLY

- **CATHODE**
  - CATALYST - - - - - - - - - - - - - - - - - - - - - - - - 90% GOLD-10% PLATINUM
  - LOADING - - - - - - - - - - - - - - - - - - - - - - - - - 20 mg/cm²
  - SUBSTRATE * - - - - - - - - - - - - - - - - - - - - - - - - - GOLD-PLATED, PHOTOETCHED NICKEL FOIL

- **MATRIX**
  - MATERIAL * - - - - - - - - - - - - - - - - - - - - - - - - 96% POTASSIUM TITANATE - 4% BUTYL RUBBER
  - THICKNESS - - - - - - - - - - - - - - - - - - - - - - - - - 20-MILS

- **ANODE**
  - CATALYST * - - - - - - - - - - - - - - - - - - - - - - - - - 10% PLATINUM-ON-CARBON
  - LOADING * - - - - - - - - - - - - - - - - - - - - - - - - - - 0.5 mg cm²
  - SUBSTRATE * - - - - - - - - - - - - - - - - - - - - - - - - - - GOLD-PLATED, PHOTOETCHED NICKEL FOIL

- **ELECTROLYTE RESERVOIR PLATE/HYDROGEN FLOW FIELD**
  - MATERIAL * - - - - - - - - - - - - - - - - - - - - - - - - - POROUS CARBON

* ADVANCED TECHNOLOGY CELL COMPONENT*
<table>
<thead>
<tr>
<th>RIG NO.</th>
<th>NO. CELLS</th>
<th>ADVANCED TECHNOLOGY CELL COMPONENT</th>
<th>TEST HOURS</th>
</tr>
</thead>
<tbody>
<tr>
<td>39461-1</td>
<td>4</td>
<td>SUPPORTED Pt/C CATALYST ANODE</td>
<td>5,000</td>
</tr>
<tr>
<td>39578-1</td>
<td>6</td>
<td>SUPPORTED Pt/C CATALYST ANODE</td>
<td>18,000</td>
</tr>
<tr>
<td>39493-1</td>
<td>4</td>
<td>SUPPORTED Pt/C CATALYST ANODE CARBON ELECTROLYTE RESERVOIR PLATE HYBRID POLYSULFONE EDGE FRAME</td>
<td>3,500</td>
</tr>
<tr>
<td>39673-1</td>
<td>4</td>
<td>SUPPORTED Pt/C CATALYST ANODE CARBON ELECTROLYTE RESERVOIR PLATE BUTYL BONDED PKT MATRICES</td>
<td>4,500</td>
</tr>
<tr>
<td>39678-1</td>
<td>4</td>
<td>MOLDED PPS CELL EDGE FRAMES BUTYL BONDED PKT MATRICES PERFORATED NICKEL FOIL SUBSTRATES NICKEL SEPARATOR PLATES</td>
<td>6,000</td>
</tr>
<tr>
<td>39714-1</td>
<td>6</td>
<td>SUPPORTED Pt/C CATALYST ANODE MOLDED PPS CELL EDGE FRAMES BUTYL BONDED PKT MATRICES PERFORATED NICKEL FOIL SUBSTRATES CARBON ELECTROLYTE RESERVOIR PLATE NICKEL SEPARATOR PLATE CATHODE NICKEL ELECTROLYTE RESERVOIR PLATE</td>
<td>4,000*</td>
</tr>
<tr>
<td>39728-1</td>
<td>2</td>
<td>SUPPORTED Pt/C CATALYST ANODEーズ MOLDED PPS CELL EDGE FRAMES BUTYL BONDED PKT MATRICES PERFORATED NICKEL FOIL SUBSTRATE CARBON ELECTROLYTE RESERVOIR PLATE NICKEL SEPARATOR PLATE NICKEL OXYGEN FLOW FIELD</td>
<td>1,500</td>
</tr>
</tbody>
</table>

* TEST CONTINUING
REGENERATIVE FUEL CELL ENDURANCE TEST

- 6 cell stack
- \( A_{\text{cell}} = 0.5 \text{ ft}^2 \)

**At open cycle**

**At 200 ASF**

Average cell voltage

Test time - Hours
WASA LEWIS SIX-CELL STACK LONG-TERM ENDURANCE TEST:
FIS 501111 PERFORMANCE HISTOR Y

- OPEN CIRCUIT
- CURRENT DENSITY
- CELL VOLTAGE - LOAD

[Graph showing current density and cell voltage changes over time]

- ONE CYCLE
THERMAL ANALYSIS RESULTS

- THREE CELLS PER COOLER
- DESIGN TEMPERATURE GRADIENT 4.2°F (ORBITER 3.1°F)

ELECTRICAL RESISTANCE ANALYSIS RESULTS

- ONE-MIL SILVER PLATE ON MOLDED PPS
- DESIGN PLATE INTERNAL RESISTANCE (IR) 1.5 MV/CELL (140 AMPS)
  (MAXIMUM PLATE IR 3.7 MV/CELL 355 AMPS)

POWER SECTION THERMAL AND ELECTRICAL RESISTANCE ANALYSIS
VERIFIED BY DESIGN ANALYSIS
CELL/COOLER HEAT TRANSFER

* THERMAL RESISTANCE CALCULATED USING SIMPLIFIED MODEL
  
  * CONDUCTION THROUGH PPS FLOW FIELD
    - PPS SOLID
    - SILVER PLATE
  
  * CONDUCTION THROUGH MONEL SEPARATOR
  
  * CONDUCTION THROUGH ERP
  
  * CONDUCTION THROUGH CELL PACKAGE - ELECTRODES - MATRIX
  
  * CONVECTION TO COOLANT (FC40)

* THREE CELLS/COOLER

  \[ T(\text{HOT CELL}) - T(\text{FC40}) = 4.2 \text{ DEG F} \]
Resistance Calculation

\[ R_{\text{tot}} = R_1 + R_2 + R_3 \]

\[ \frac{1}{R_{\text{tot}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \]

\[ \frac{1}{R_{\text{web}}} = \frac{1}{R_{\text{pp5}}} + \frac{1}{R_{\text{a3holes}}} + \frac{1}{R_{\text{a8holes,inplane}}} \]

\[ R_3 = R_1 \]
\[ AT = 0.5\left( R_{\text{Mat}} + R_0 + R_{\text{Monel}} + R_0 + R_{\text{Monel}}\right) + 1.5\left( R_{\text{Mat}} + R_0 + R_{\text{Monel}} + R_{\text{film}}\right) = 4.0^\circ F \]

### Thermal Resistance - hr °F/ft

<table>
<thead>
<tr>
<th>Piece</th>
<th>Material</th>
<th>( k )</th>
<th>( R_{\text{Matrix}} )</th>
<th>( R_{\text{Cu}} )</th>
<th>( R_{\text{Nb}} )</th>
<th>( R_{\text{film}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td></td>
<td>0.18075 Btu/hr °F</td>
<td>9.817 \times 10^{-3}</td>
<td>2.270 \times 10^{-3}</td>
<td>3.063 \times 10^{-3}</td>
<td>3.247 \times 10^{-3}</td>
</tr>
<tr>
<td>O2 Rate</td>
<td>PPS</td>
<td>2.0 Btu/hr °F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver Plating</td>
<td></td>
<td>0.900 Btu/hr °F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monel</td>
<td>Monel</td>
<td>0.08 Btu/hr °F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>Monel</td>
<td>1.0 Btu/hr °F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Film</td>
<td>FC40</td>
<td>187.33 Btu/hr °F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- This drawing is only conditionally issued, and neither receipt nor possession thereof conveys or transfers any right in, or license to use, the subject matter of the drawing or any design or technical information shown therein, nor any right to reproduce this drawing or any part thereof, except for manufacture by vendors for United Technologies Corporation and for manufacture under the corporation's written license. No right to reproduce this drawing is granted unless by written agreement with or written permission from the corporation. Notwithstanding the foregoing, nothing contained in this notice shall prevent this drawing from being reproduced or used to the extent contemplated by any applicable contract between United Technologies Corporation and the Government of the United States.
CELL IR

* PPS USED IN O2 AND COOLER FLOW FIELDS IS AN INSULATOR

* PROVIDE ELECTRICAL CONTINUITY BY SILVER PLATING
  - HOLES THROUGH WEB

* APPROXIMATE VOLTAGE DROP CALCULATED
  - SAME MODEL AS THERMAL RESISTANCE CALCULATION
  - COOLER IR AMORTIZED OVER 3 CELLS

* CONTACT RESISTANCE IGNORED

* CALCULATIONS BASED ON 1 MIL SILVER PLATE

* 1.5 MV/CELL AT 140 AMPS, DUE TO PLATES
IR DUE TO SEPARATOK PLATES AND FLOW FIELD COMPONENTS

Through Plane Resistance = \( \frac{1}{R_{\text{COOLER}}} + \frac{1}{R_{\text{MATERIAL}}} + R_{\text{IN}} + R_{\text{OUT}} \)

In Plane Resistance = \( \frac{1}{R_{\text{COOLER, IN PLANE}}} + \frac{1}{R_{\text{MATERIAL, IN PLANE}}} \)

Total IR = \((R_{\text{MATERIAL}} + R_{\text{IN}}) I = 139.104 \text{ amps} (1.045 \times 10^{-2} + 4.122 \times 10^{-2}) = 1.49 \text{ mV} \)

<table>
<thead>
<tr>
<th>PIECE</th>
<th>MATERIAL</th>
<th>ELECTRIC RESISTIVITY</th>
<th>IR ( \text{mV} / 100 \text{ ASF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>COOLER</td>
<td>PPS</td>
<td>9.8 ohm-cm/mil 44</td>
<td>5.54 \times 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>SILVER PLATING</td>
<td>9.8 ohm-cm/mil 44</td>
<td>8.33 \times 10^{-3}</td>
</tr>
<tr>
<td>MONEL</td>
<td>MONEL 400</td>
<td>301 ohm-cm/mil 48</td>
<td>6.975 \times 10^{-8}</td>
</tr>
<tr>
<td>H2 PLATE</td>
<td>CARBON</td>
<td>( \frac{9.8}{0.31} \times 10^{-2} \text{ mV} ) at 100 ASF</td>
<td>6.232 \times 10^{-2}</td>
</tr>
<tr>
<td>O2 PLATE</td>
<td>PPS</td>
<td>9.8 ohm-cm/mil 44</td>
<td>3.33 \times 10^{-3}</td>
</tr>
</tbody>
</table>

FOR REPRODUCTION USE, CONTACT UNITED TECHNOLOGIES CORPORATION

NOTICE TO ALL PERSONS RECEIVING THIS DRAWING

THIS DRAWING IS ONLY CONDITIONALLY ISSUED, AND NEITHER RECEIPT NOR POSSESSION THEREOF CONFER ANY RIGHT TO REPRODUCE THE DRAWING OR ANY PORTION THEREOF, NOR ANY RIGHT TO REPRODUCE THIS DRAWING OR ANY PART THEREOF, EXCEPT FOR MANUFACTURE BY VENDORS FOR UNITED TECHNOLOGIES CORPORATION AND FOR MANUFACTURE UNDER THE CORPORATION'S WRITTEN AGREEMENT WITH OR WRITTEN PERMISISON FROM THE CORPORATION, NOTWITHSTANDING THE FOREGOING, NOTHING CONTAINED IN THIS NOTICE SHALL PREVENT THIS DRAWING FROM BEING REPRODUCED OR USED TO THE EXTENT CONTAINED BY ANY APPLICABLE CONTRACT BETWEEN UNITED TECHNOLOGIES CORPORATION AND THE GOVERNMENT OF THE UNITED STATES.

NAME | APPROVED | TITLE
DATE | MATERIAL | SPEC. | SKETCH NO. | CLASS

SHEET NO. | NO. OF SHEETS

UNITED TECHNOLOGIES
POWER SYSTEMS DIVISION
## STRUCTURAL DESIGN

### POWER SECTION REPEATING ELEMENTS

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
<th>DESIGN</th>
<th>ALLOWABLE</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEPARATOR PLATE</td>
<td>MONEL ALLOY 400</td>
<td>17.9 KSI</td>
<td>25.0 KSI</td>
<td>4</td>
</tr>
<tr>
<td>CELL HOLDER PLATE</td>
<td>MOLDED A-100 (PPS/FG)</td>
<td>1400 PSI</td>
<td>1500 PSI</td>
<td>4</td>
</tr>
<tr>
<td>CELL COOLER PLATE</td>
<td>MOLDED A-100 (PPS/FG)</td>
<td>1400 PSI</td>
<td>1500 PSI</td>
<td>4</td>
</tr>
<tr>
<td>END COOLER PLATE</td>
<td>MOLDED A-100 (PPS/FG)</td>
<td>1220 PSI</td>
<td>1500 PSI</td>
<td>4</td>
</tr>
<tr>
<td>HYDROGEN MANIFOLD</td>
<td>MOLDED A-100 (PPS/FG)</td>
<td>1300 PSI</td>
<td>3000 PSI</td>
<td>4</td>
</tr>
<tr>
<td>ANODE ERP</td>
<td>PARTICULATE CARBON ERP (FINE-PORE 10 MICRON)</td>
<td>226 PSI</td>
<td>400 PSI</td>
<td>4</td>
</tr>
</tbody>
</table>

*POWER SECTION REPEATING ELEMENT DESIGN VERIFIED BY DESIGN ANALYSIS*
## DESIGN MATERIAL PROPERTIES

### SEPARATOR PLATE

**MATERIAL: MONEL ALLOY 400**

<table>
<thead>
<tr>
<th></th>
<th>Y.S.</th>
<th>U.T.S.</th>
<th>MODULUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.T.:</td>
<td>20.0 KSI</td>
<td>70.0 KSI</td>
<td>26,000,000 PSI</td>
</tr>
<tr>
<td>250 F:</td>
<td>25.0 KSI</td>
<td>63.6 KSI</td>
<td>26,000,000 PSI</td>
</tr>
</tbody>
</table>

**COEFFICIENT OF THERMAL EXPANSION = 7.8 E-6 IN/IN/F**

### CATHODE ELECTRODE PLATE, CELL COOLER PLATE, AND END COOLER PLATE

**MATERIAL: INJECTION MOLDED RYTON R-9 PPS/FG**

<table>
<thead>
<tr>
<th></th>
<th>FLEXURE</th>
<th>TENSILE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STRENGTH MODULUS</td>
<td>STRENGTH MODULUS</td>
</tr>
<tr>
<td>R.T.:</td>
<td>22.5 KSI 1,590,000 PSI</td>
<td>15.3 KSI 1,000,000 PSI</td>
</tr>
<tr>
<td>250 F:</td>
<td>12.0 KSI 600,000 PSI</td>
<td>6.0 KSI 400,000 PSI</td>
</tr>
</tbody>
</table>

**COEFFICIENT OF THERMAL EXPANSION = 11.0 E-6 IN/IN/F (IN-PLANE) 20.0 E-6 IN/IN/F (THRU-PLANE)**

### ANODE ERP

**MATERIAL: PARTICULATE CARBON SUBSTRATE**

**DENSITY = .036 LB./CU.IN.**
**SEPARATOR PLATES**

- **MATERIAL:** MONEL ALLOY 400
  
  R.T.: Y.S. = 20.0 KSI  U.T.S. = 70.0 KSI  E = 26,000,000 PSI
  
  250 F: Y.S. = 25.0 KSI  U.T.S. = 63.6 KSI  E = 26,000,000 PSI

- **COEFFICIENT OF THERMAL EXPANSION:** 7.8E-6 IN/IN/°F

- **THICKNESS:** t = .005"

- **WORST CASE ASSUMPTION:** EDGE SEAL BONDS SEPARATOR PLATE TO PPS/FG PLATES

  - **IN-PLANE PRESSURE STRESS:**
    
    ![Diagram of in-plane pressure stress]
    
    DESIGN ALLOWABLE: (250 F)
    
    TENSILE STRESS < .67xY.S.
    
    (16.7 KSI)

  - **THRU-PLANE PRESSURE STRESS:**
    
    ![Diagram of thru-plane pressure stress]
    
    DESIGN ALLOWABLE: (250 F)
    
    BENDING STRESS < 1.0xY.S.
    
    (25.0 KSI)

  - **THERMAL STRESS:**
    
    ![Diagram of thermal stress]
    
    DESIGN ALLOWABLE: (250 F)
    
    TENSILE STRESS < .67xY.S.
    
    (16.7 KSI)

- **TOTAL STRESS:**
  
  17.9 KSI < 25.0 KSI ALLOWABLE
- **Cathode Electrode Plate**

  - **Material:** Injection molded Rytan R-9 PPS/FG

  - **Flexure**
    - **Strength**
      - R.T.: 22.5 KSI
      - 250°F: 12.0 KSI
    - **Modulus**
      - 1,530,000 PSI
      - 600,000 PSI

  - **Tensile**
    - **Strength**
      - 15.3 KSI
      - 6.0 KSI
    - **Modulus**
      - 1,000,000 PSI
      - 400,000 PSI

  - **Compressive Strength:**
    - 20.7 KSI
    - 12.7 KSI

  - **Coefficient of Thermal Expansion:**
    - 11.0 E-6 in/in/F (in-plane)
    - 20.0 E-6 in/in/F (thru-plane)

  - **Thickness:** t = .020" (web) & t = .155" (frame)

  - **Worst Case Assumption:** Edge seal does not bond cathode plate to separator plate

  - **In-plane Pressure Stress:** (No thermal stress)

  - **Design Allowable:** (250°F)

  - Tensile stress < .25xStrength (1500 PSI)

  - **Stress Concentration:**

    - **Kt = 3.0** (bi-axial stress field with .075" dia. holes and .135" hole spacing)

    - \( \sigma_{\text{avg}} = 465 \text{ PSI} \)

    - \( \sigma_{\text{max}} = K_t \sigma_{\text{avg}} \)

  - **Maximum Average Stress:** 465 PSI

  - **Maximum Stress = 1400 PSI < Design Allowable**
**CELL COOLER PLATE**

- **MATERIAL:** INJECTION MOLED RYTON R-3 PPS/F6

<table>
<thead>
<tr>
<th></th>
<th>FLEXURE STRENGTH</th>
<th>TENSILE STRENGTH</th>
<th>COMPRESSIVE STRENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MODULUS</td>
<td>MODULUS</td>
<td></td>
</tr>
<tr>
<td>R.T.:</td>
<td>22.5 KSI</td>
<td>15.3 KSI</td>
<td>20.7 KSI</td>
</tr>
<tr>
<td></td>
<td>1,530,000 PSI</td>
<td>1,000,000 PSI</td>
<td></td>
</tr>
<tr>
<td>250 F:</td>
<td>12.0 KSI</td>
<td>6.0 KSI</td>
<td>12.7 KSI</td>
</tr>
<tr>
<td></td>
<td>600,000 PSI</td>
<td>400,000 PSI</td>
<td></td>
</tr>
</tbody>
</table>

COEFFICIENT OF THERMAL EXPANSION = 11.0 E-6 IN/IN/F (IN-PLANE)  
28.0 E-6 IN/IN/F (THRU-PLANE)

- **THICKNESS:** t = .020" (WEB) & t = .104" (FRAME)

- **WORST CASE ASSUMPTION:** EDGE SEAL DOES NOT BOND COOLER PLATE TO SEPARATOR PLATE

- **IN-PLANE PRESSURE STRESS:** (NO THERMAL STRESS)

  DESIGN ALLOWABLE: (250 F)

  TENSILE STRESS < .25xSTRENGTH (1500 PSI)

- **STRESS CONCENTRATION:**

  - Kt = 4.5 (BI-AXIAL STRESS FIELD WITH .100" DIA. HOLES AND .135" HOLE SPACING)

  \[
  \sigma_{\text{avg}} = 312 \text{ PSI} \\
  \sigma_{\text{max}} = K_t \sigma_{\text{avg}}
  \]

  - MAXIMUM AVERAGE STRESS: 312 PSI

  - MAXIMUM STRESS = 1400 PSI < DESIGN ALLOWABLE
**END COOLER PLATE**

**MATERIAL:** INJECTION MOLDED RYTON R-3 PPS/FG

<table>
<thead>
<tr>
<th></th>
<th>FLEXURE</th>
<th>TENSILE</th>
<th>COMpressive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STRENGTH</td>
<td>MODULUS</td>
<td>STRENGTH</td>
</tr>
<tr>
<td>R.T.</td>
<td>22.6 KSI</td>
<td>1,530,000 PSI</td>
<td>15.3 KSI</td>
</tr>
<tr>
<td>250 F</td>
<td>12.0 KSI</td>
<td>600,000 PSI</td>
<td>6.0 KSI</td>
</tr>
</tbody>
</table>

**COEFFICIENT OF THERMAL EXPANSION:**

- 11.0 E-6 IN/IN/F (IN-PLANE)
- 28.0 E-6 IN/IN/F (THRU-PLANE)

**THICKNESS:** t = .020" (WEB) & t = .120" (FRAME)

**WORST CASE ASSUMPTION:** EDGE SEAL DOES NOT BOND CATHODE PLATE TO SEPARATOR PLATE

**IN-PLANE PRESSURE STRESS:** (NO THERMAL STRESS)

**DESIGN ALLOWABLE:** (250 F)

**TENSILE STRESS < .25*STRENGTH** (1500 PSI)

**STRESS CONCENTRATION:**

- Kt = 3.4 (BI-AXIAL STRESS FIELD WITH .085" DIA. HOLES AND .135" HOLE SPACING)

\[
\sigma_{max} = K_t \sigma_{avg}
\]

**MAXIMUM AVERAGE STRESS:** 360 PSI

**MAXIMUM STRESS = 1220 PSI < DESIGN ALLOWABLE**
HYDROGEN MANIFOLD INTERNAL PRESSURE

- PPS/FB PLATES (CATHODE ELECTRODE, CELL COOLER, & END COOLER)
- FLEXURE STRESS OF MANIFOLD WALL FROM 60 PSIG INTERNAL PRESSURE
- FLEXURE DESIGN ALLOWABLE = 0.25x(FLEXURE STRENGTH) = 3000 PSI

MAXIMUM STRESS = 1300 PSI < DESIGN ALLOWABLE
ANODE ERP

- MATERIAL: PARTICULATE CARBON SUBSTRATE
- DENSITY: .036 LB./CU. IN.
- CRUSH STRENGTH: 400 PSI

- ANODE LOAD: $P = 80.6$ PSI (AVG.) (CELL PINCH TOTAL LOAD = 12,000 #)
- RIB LOADING: $P = 226$ PSI (2.81x(AVG. PRESSURE))
- NUBBIN LOADING: $P = 218$ PSI (2.71x(AVG. PRESSURE))

- MAXIMUM COMPRESSION STRESS = 226 PSI (CRUSH STRENGTH S.F. = 1.77)
STRUCTURAL DESIGN

POWER SECTION NON-REPEATING ELEMENTS

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
<th>PARAMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRESSURE PLATES</td>
<td>300 SERIES STAINLESS STEEL</td>
<td>1.0&quot; THICKNESS</td>
</tr>
<tr>
<td>INSULATOR PLATES</td>
<td>A-100 (PPS/FG)</td>
<td>0.625&quot; &amp; 0.360&quot; (ORBITER)</td>
</tr>
<tr>
<td>TIE-RODS</td>
<td>AMS 4971 TITANIUM</td>
<td>.250&quot; DIAMETER</td>
</tr>
</tbody>
</table>

POWER SECTION AXIAL LOAD ANALYSIS

- MAXIMUM STRESS   124.5 KSI
- DESIGN STRESS    125.0 KSI

POWER SECTION NON-REPEATING ELEMENT DESIGN VERIFIED BY DESIGN ANALYSIS
CELL STACK CONFIGURATION:

PRESSURE PLATES
- MATERIAL: 300 SERIES STAINLESS STEEL
- THICKNESS: \( t = 1.00" \)

INSULATOR PLATES
- MATERIAL: RYTON R-3 PPS/F6
- THICKNESS: \( t = .625" \) & \( .360" \) (ORBITER FCP THICKNESSES)

SEPARATOR PLATES
- MATERIAL: MONEL 400
- THICKNESS: \( t = .005" \)

ELECTRODE PLATES
- MATERIAL: INJECTION MOLDED RYTON R-3 PPS/F6
- THICKNESS: \( t = .155" \) (CATHODE ELECTRODE PLATE FRAME)

COOLER PLATES
- MATERIAL: INJECTION MOLDED RYTON R-3 PPS/F6
- THICKNESS: \( t = .104" \) (CELL COOLER PLATE FRAME) & \( t = .120" \) (END COOLER PLATES)

TIE-RODS
- MATERIAL: AMS 4971 TITANIUM
- DIAMETER: .250"-28 THREAD WITH REDUCED SHANK DIAMETER (.215") OR FULLY THREADED ROD TO GIVE CONSTANT AREA AND MAXIMUM FLEXIBILITY
CELL STACK AXIAL LOAD

AXIAL LOAD MODEL

- PRESSURE PLATES: \( L = 2.00'' \) (TWO PLATES)
- INSULATORS: \( L = 0.985'' \) (BOTH PLATES)
- SEPARATOR PLATES: \( L = 1.340'' \) (260 PLATES)
- ELECTRODES: \( L = 37.949'' \) (199 CATHODES, 66 CELL COOLERS, & 2 END COOLERS)
- TIE-RODS: \( A = 0.0362 \) SQ. IN. (CONSTANT AREA - 21 TIE-RODS)
  \( L = 38.000'' \) (SHANK)

AXIAL LOAD ANALYSIS

CELL STACK LOADING

- INTERNAL PRESSURE: 60 PSIG
- CELL MATRIX PINCH: 12,000 # (TOTAL)
- SEAL LOADING: 4800 # (TOTAL FOR 50 PLI)

TIE-ROD LOADING

- INITIAL COLD LOAD: 3760 # (STRETCH = .279")
- PRESSURIZED COLD: 3850 # (STRETCH = .286")
- PRESSURIZED HOT: 4510 # (MAXIMUM LOAD)

MAXIMUM STRESS: 124.5 KSI < 125 KSI DESIGN STRESS
  (S.F. = 1.40 - 175 KSI U.T.S.)
X708 CELL STACK AXIAL LOAD

Tie-Rod Load Cycle - Load vs. Stretch

Material: AMS 4571 Titanium (UTS = 175 ksi)

\[ A = 0.0362 \text{ in}^2 \text{ } (0.250-28 \text{ thou}) \]

\[ E = 16 \times 10^6 \text{ psi} \]

Original page is of poor quality.
<table>
<thead>
<tr>
<th></th>
<th>FIELD DEPTH MILS</th>
<th>PORT DEPTH MILS</th>
<th>PORT WIDTH MILS</th>
<th>NO PORTS IN/OUT</th>
<th>PRESSURE LOSS - CALCULATED/ALLOCATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYDROGEN</td>
<td>50</td>
<td>38</td>
<td>35</td>
<td>4/4</td>
<td>3.4/3.5</td>
</tr>
<tr>
<td>OXYGEN</td>
<td>30</td>
<td>19</td>
<td>21</td>
<td>3/3</td>
<td>2.5/ -</td>
</tr>
<tr>
<td>CELL COOLER</td>
<td>40</td>
<td>40</td>
<td>30</td>
<td>4/4</td>
<td>.5/1.5</td>
</tr>
<tr>
<td>END COOLER</td>
<td>50</td>
<td>50</td>
<td>39</td>
<td>4/4</td>
<td>.5/1.5</td>
</tr>
</tbody>
</table>

* POWER SECTION REACTANT AND COOLANT DISTRIBUTION VERIFIED BY DESIGN ANALYSIS.
REACTANT FLOW FIELD DESIGN

* BASIC CELL DESIGN IS FLOW FIELDS AND PORTS
  * NUBBINS FOR MINIMUM WEIGHT
  * PORTS CONTROL CELL TO CELL FLOW DISTRIBUTION

* MANIFOLDS SIZED FOR NEGLIGIBLE CONTRIBUTION TO FLOW MALDISTRIBUTION

* SILVER PLATING ON PPS FLOW FIELDS TO ENHANCE HEAT TRANSFER AND PROVIDE ELECTRICAL CONTINUITY
FLOW DISTRIBUTION
- SETS MANIFOLD SIZE
- NOT A DETERMINING FACTOR IN PORT AND FIELD SIZING
- ~ 12% AT DESIGN FLOW

CLEARING KOH DROPS FROM PORTS
- 4 INLET PORTS, 4 EXIT PORTS
- INLET PORT WORST CASE
- CAN CLEAR ANY PLUGGED PORT IN STACK AT NOMINAL FUEL FLOW
  - .038 x .035 PORTS
  - 4 INLET:4 EXIT PORTS

PRESSURE DROP ~ 3.5 IWC
OXYGEN FIELDS

* FLOW DISTRIBUTION
  - SETS A MINIMUM MANIFOLD SIZE
  - NOT A DETERMINING FACTOR IN SIZING FIELDS OR PORTS
  - 26% AT DESIGN POINT

* CLEARING KOH DROPS FROM PORTS
  * NOT POSSIBLE TO CLEAR DROPS FROM AT REASONABLE PURGE RATES WITH PORTS > .020 MIL DEPTH AND WIDTH
  * DESIGN TO ENSURE CLEARING OF AT LEAST ONE PORT IN EACH CELL INLET AND OUTLET
  * 4 PORTS DESIRABLE FOR BEST SWEEPING OF FLOW FIELDS
    - NEED MORE PURGE FLOW TO BLOW OUT DROPS
  * 3 PORTS WILL ALLOW PORT CLEARING AT CDG PURGE FLOW
    - .020 PORTS - NO MARGIN
  * 50% INCREASE IN PURGE FLOW ALLOWS LARGER PORTS
    - LESS SENSITIVE TO TOLERANCES

* PRESSURE DROP ~ 2.5 IWC
POWER SECTION END CELL HEAT LOSS

• ASSUMPTIONS
  • NO ELECTRICAL HEATERS ON END CELLS
  • END CELL HEAT SUPPLIED BY COOLER ON STACK ENDS

• SPECIAL COOLER PLATE DESIGN
  • INCREASED COOLANT FIELD DEPTH - 10 MILS
  • INCREASED COOLANT PORT DIMENSIONS - 10 MILS
  • CALCULATED COOLANT PRESSURE - 0.5 PSI (ALLOCATED 1.5 PSI)
  • POWER PLANT STARTUP ANALYSIS REQUIRED

• COOLER DESIGN VERIFIED BY DESIGN ANALYSIS
<table>
<thead>
<tr>
<th>END COOLERS PORT</th>
<th>END COOLER CAPACITY</th>
<th>BEGIN COOLER CAPACITY</th>
<th>DESIGNED FLOW IN END COOLERS</th>
<th>END COOLER SQUARE PORT WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FLOW IN END COOLER (PPM)

POOR QUALITY
REMAINING CELL STACK DESIGN TASKS

• IDENTIFY MAXIMUM POWER CAPABILITY OF THE 1.0 FT² POWER SECTION

• REVIEW COMPATIBILITY OF MATERIALS IN THE CELL STACK ASSEMBLY WITH OXYGEN
REFERENCE: NASA PUBLICATION 1113
TECHNOLOGY DEVELOPMENT STATUS

SUMMARY

- Orders for material and cell components required for both NASA programs has been placed.
  - Gold-plated perforated nickel foil electrode substrates
  - Cathode catalyst
  - Stack non-repeating parts

- Cell component fabrication trials initiated

- Endurance testing of the NASA-Lewis six-cell 1.0 ft² pilot stack planned to begin - September 1986

- NASA-JSC 15-cell 1.0 ft² technology ready module performance checkout test planned for February 1987

- Identified remaining development tasks
CELL ELECTRODE ASSEMBLY

SEALS

• STATUS
  - CELL EDGE SEAL
    - SUBSCALE (4" X 4") ONE-PIECE EDGE SEAL ASSEMBLY TRIAL COMPLETED.
    - EDGE SEAL CONCEPT CROSSPRESSURE GOAL > 20 PSID ATTAINED
  - FRAME SEALS
    - PARKER SEAL SCHEDULED TO MOLD STANDARD GASK-O-SEAL IN PPS PLATE
    - FABRICATION TRIALS AT PARKER FOR IMPROVED CONTOUR SEALS ON HOLD
    - DOWTY LTD. CONTINUES TO DEVELOP PRINTED SEALS
      - SCREEN PRINTED EPR SEALS DEVELOPED FROM BUTYL RUBBER EXPERIENCE
      - SCREEN PRINTED EPR SEALS 4-MILS HIGH-ADVANCED CELL DESIGN REQUIRES 8-MIL HIGH SEALS
      - DOWTY CONTINUES TO DEVELOP SEALS AT NO COST TO IFC

• CONCERNS - 1.0 FT² CELL ASSEMBLY
  - MANUFACTURING TOLERANCES - REACTANT CROSS LEAKAGE
  - CELL ASSEMBLY THERMAL GROWTH
CELL ELECTRODE ASSEMBLY

CATHODE

• STATUS
  • GOLD-PLATED PERFORATED Ni-FOIL ELECTRODE SUBSTRATES
    • SUBSTRATES AVAILABLE FOR NASA-LEWIS 6-CELL STACK
    • SUBSTRATES FOR NASA-JSC PROGRAM ORDERED
  • Au Pt CATALYST
    • CATALYST AVAILABLE FOR NASA-LEWIS 6-CELL STACK
    • CATALYST FOR NASA-JSC PROGRAM ORDERED
  • ELECTRODES
    • MANUFACTURING TRIALS ON ONE - 1.0 FT² ELECTRODE COMPLETED
    • HALF-CELL PERFORMANCE OF TRIAL SAMPLE EXCEEDS ORBITER SPECIFICATION
    • SHOP READY TO FABRICATE ELECTRODES
    • ELECTRODES FOR NASA-LEWIS 6-CELL STACK COMPLETED
  • CONCERNS
    • NONE
CELL ELECTRODE ASSEMBLY

ANODE

STATUS

- Au-PLATED Ni-FOIL ELECTRODE SUBSTRATES
  - SUBSTRATES AVAILABLE FOR NASA-LEWIS 6-CELL STACK
  - SUBSTRATES FOR NASA-JSC PROGRAM ORDERED

- SUPPORTED Pt-on-CARBON CATALYST - AVAILABLE

PLAN

- ELECTRODES FOR NASA-LEWIS TO BE CATALYZED EARLY IN JUNE

CONCERNS

- ELECTROLYTE FILL METHOD
CELL ELECTRODE ASSEMBLY

BUTYL BONDED POTASSIUM TITANATE MATRIX

- STATUS
  - POTASSIUM TITANATE AND BUTYL RUBBER MATERIAL FOR BOTH PROGRAMS AVAILABLE
  - PRELIMINARY 1.0 FT² FABRICATION TRIALS COMPLETED - CROSS PRESSURE
    GOAL ≥ 20 PSID ATTAINED

- PLAN
  - MATRICES FOR NASA-JSC AND NASA-LEWIS PROGRAMS TO BE FABRICATED
    IN LATE JUNE

- CONCERNS
  - CONSISTENT CROSS PRESSURE CAPABILITY
  - HANDLEABILITY
CELL ELECTRODE ASSEMBLY

CARBON ELECTROLYTE RESERVOIR PLATE (ERP)

- STATUS
  - FINE-PORE (~10 MICRONS) CARBON ERP BLANKS FOR BOTH PROGRAMS AVAILABLE
  - MACHINING TRIALS SUCCESSFULLY COMPLETED
  - PLACED ORDER FOR MACHINING CARBON ERP'S FOR BOTH PROGRAMS IN SHOP

- CONCERNS
  - NONE
POLYPHENYLENE SULFIDE (PPS) CELL AND COOLER PLATES

• STATUS
  • FIFTY MOLDED PPS BLANKS FOR BOTH PROGRAMS AVAILABLE (25 BLANKS AT TWO MOLD TEMPERATURES)
  • VENDOR MACHINING TRIALS IN PROGRESS
  • REQUEST FOR QUOTATION ISSUED TO THREE MACHINING VENDORS - QUOTES OVERDUE
  • SILVER PLATING OF PPS (4 IN X 4 IN) BLANKS SUCCESSFULLY COMPLETED

• PLANS
  • MOLDED EDGE SEAL TRIALS (0.5 FT² CELL)

• CONCERNS
  • PLATE DISTORTION FROM MOLDING AND MANUFACTURING OPERATIONS
    • EFFECTS OF THERMAL CYCLING
    • EFFECTS OF SEAL MOLDING
  • PLATED PLATE ELECTRICAL CONDUCTIVITY
  • MANUFACTURED COST
RIG NON-REPEAT HARDWARE STATUS

• DRAWINGS FOR RIG NON-REPEAT PARTS COMPLETED

• ORDER ISSUED FOR NON-REPEAT PARTS FOR BOTH PROGRAMS
  • LOAD COLLECTOR PLATES
  • INSULATOR PLATES
  • END PLATES

• DESIGN ANALYSIS REVIEWING TIEROD REQUIREMENTS FOR 6-CELL AND 15-CELL MODULE

• CONCERNS
  • NONE
REMAINING DEVELOPMENT TASKS

- CONDUCT CELL COMPONENT FABRICATION TRIALS

- MANUFACTURE AND ASSEMBLE 1.0 FT² CELL ELECTRODE ASSEMBLY

- IDENTIFY AND CONSTRUCT MODULE TEST STAND FIXTURES

- ASSEMBLE MULTI-CELL 1.0 FT² MODULES

- CONDUCT MODULE PERFORMANCE EVALUATION TEST
CRITICAL ISSUES AND RISK ASSESSMENT

- Polyphenylene sulfide cell and cooler plate manufacturing and cost
  - Assessment: H

- Electrical conduction of plated polyphenylene sulfide plates
  - Assessment: M

- Cell electrode assembly edge seal
  - Assessment: M

- Consistent potassium titanate matrix crosspressure capability
  - Assessment: L
ADDITIONAL PROGRAMS NEEDED

SUPPLEMENTARY TASKS

- COMPLETE POWER SECTION DETAIL DESIGN
  - LIGHTWEIGHT CURRENT TAKEOFF PLATES
  - LIGHTWEIGHT END PLATES
  - LIGHTWEIGHT INSULATOR PLATES
  - END CELL COOLER DRAWINGS
- IDENTIFY IMPACT OF INCREASED SYSTEM PRESSURE (120 PSIA) ON SPECIFIC WEIGHT
- EVALUATE EDGE SEAL APPROACHES WITH THE POTENTIAL FOR "ZERO" REACTANT LEAKAGE TO AMBIENT
- CONDUCT A PRODUCTION DEVELOPMENT PROGRAM
  - DEVELOP CELL COMPONENT AND CELL ASSEMBLY PRODUCTION CAPABILITY
  - DEVELOP A PRODUCTION POWER SECTION
- ASSEMBLE AND TEST FULL SIZE (200 CELLS) POWER SECTION
- DEFINE AN ADVANCED TECHNOLOGY ALKALINE FUEL CELL POWER PLANT SYSTEM
- IDENTIFY ALKALINE FUEL CELL POWER PLANT OPTIMUM ORBITAL REPLACEMENT UNITS (ORU)
- IDENTIFY COMPONENT SECTION REQUIREMENTS
- DEVELOP COMPONENT SECTION (ACCESSORY SECTION)
- PROCUREMENT, ASSEMBLE AND CHECKOUT TEST COMPONENT SECTION
- ASSEMBLE POWER PLANT
- CONDUCT A SYSTEM DEMONSTRATION TEST OF THE ADVANCED TECHNOLOGY ALKALINE FUEL CELL POWER PLANT