Fuel Cell Technology Program
Final Report
PWA-4756

(NASA-CR-134002)  FUEL CELL TECHNOLOGY          N73-30056
PROGRAM  Final Report (Pratt and Whitney
Aircraft) ~66~p HC ;              CSCL 10A
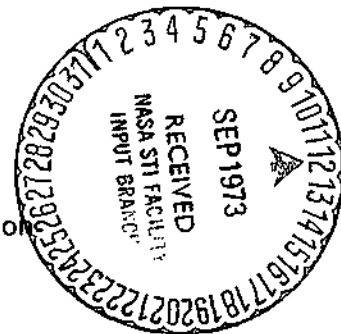    62

                                      Unclas
                              G3/03  12109

25 July 1973

Prepared For

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

Approved by: _____ Project Manager

# Pratt & Whitney Aircraft    DIVISION OF UNITED AIRCRAFT CORPORATION

EAST HARTFORD, CONNECTICUT

# FOREWORD

This Fuel Cell Technology Program Final Report was prepared by Pratt & Whitney Aircraft Division of United Aircraft Corporation, South Windsor Engineering Facility, South Windsor, Connecticut, in accordance with the requirements of Exhibit G, Data Requirements List, Line Item No. 8, NASA Contract No. NAS9-11034.

# CONTENTS

ILLUSTRATIONS

# ILLUSTRATIONS (CONT.)

## 1.0 SUMMARY

A fuel cell technology program was established 11 July 1970 under NASA Contract NAS9-11034 to advance the state-of-the-art of hydrogen-oxygen fuel cells using the Pratt & Whitney Aircraft low temperature, potassium hydroxide electrolyte technology as the base. The tasks of this program consisted of:

- fuel cell system studies and liaison with Space Shuttle Prime Contractors to define a Space Shuttle powerplant

- component and subsystem technology advancement

- demonstrator powerplant (DM-1) test to demonstrate the technology at the system level.

The DM-1 powerplant test was terminated at 750 hours because of a cell failure. Post-test analyses were conducted and corrective action was defined. A report, PWA-4364, dated 27 April 1972, covering contract effort through the corrective action definition was issued.

This report describes program tasks consisting of baseline cell design and stack testing, hydrogen pump design and testing, and DM-2 powerplant testing and technology extension efforts.

A baseline Scheme I cell configuration capable of a minimum of 2000 hours of life was defined. A 6-cell prototype stack, incorporating most of the Scheme I cell features, was tested for a total of 10,497 hours. A Scheme I 6-cell stack incorporating all of the design features was tested. At the end of the contract technical period of performance, 8600 hours were accumulated.

A drag-type hydrogen pump and water separator capable of a minimum of 2000 hours of life was designed. A breadboard unit incorporating the features of the flight-weight design was tested for a total of 10,000 hours with one bearing change at 6700 hours. At 10,000 hours, the test was voluntarily terminated.

The DM-2 powerplant with a 34 cell stack, an accessory section packaged in the basic configuration anticipated for the Space Shuttle powerplant and a powerplant control unit, was defined, assembled, and tested. Scheme I cells were used in the stack and a drag-type hydrogen pump was installed in the accessory section. A test program was established, in conjunction with NASA/JSC, based on the Space Shuttle Orbiter mission. A 2000-hour minimum endurance test and a 5000-hour goal were set and the test started on August 8, 1972. The 2000-hour milestone was completed on November 3, 1972. On 13 March 1973, at the end of the thirty-first simulated seven-day mission and 5072 load hours, the test was concluded, all goals having been met. At this time, the DM-2 was in excellent condition and capable of additional endurance.

A baseline technology extension task was conducted concurrently with the other program tasks. The specific goal of this task was to define design approaches and materials leading to a cell with a minimum 5000-hour life. Cost saving and weight reduction alternatives were also considered. An improved electrode catalyst and a design approach for spacing cell coolers were identified as prime candidates to be considered for incorporation into the baseline.

As a result of the testing on the two 6-cell stacks, the hydrogen drag pump and the DM-2 powerplant, it is concluded that the Pratt & Whitney Aircraft fuel cell technology readiness for the Space Shuttle has been demonstrated.

## 2.0 DM-2 ENDURANCE TEST

A summary of the DM-2 program is presented here. PWA-4721, DM-2 Power System 5000 Hour Test Report, dated 15 May 1973, contains a detailed description of the test program.

## 2.1 OBJECTIVE

The primary objective of the DM-2 powerplant test was to demonstrate, at the system level, the readiness of the alkaline fuel cell technology developed under NASA Contract NAS9-11034 for the Space Shuttle. The objective was to be accomplished by operating the powerplant a minimum of 2000 hours at current densities representative of Space Shuttle requirements. Additional design evaluation testing, with a goal of 5000-hours total operating time, was planned.

## 2.2 DESCRIPTION OF TEST ARTICLE

The DM-2 is a complete fuel cell electrical power source with a 34-cell stack, an accessory section packaged in the basic configuration anticipated for the Space Shuttle powerplant and a powerplant control unit. The cells include design improvements which result from the NASA/JSC Fuel Cell Technology Program. A drag-type hydrogen pump and water separator assembly with improved life characteristics is used in place of the vane-type pump used in the previous DM-1 demonstrator powerplant. A miniaturized coupled reactant regulator is used in place of the breadboard regulator used in the DM-1. All other components are from the DM-1. A flow schematic of the powerplant is shown in Figure 1. Figure 2 shows the powerplant and control unit mounted for test.

## 2.3 DESCRIPTION OF TEST PROGRAM

The DM-2 powerplant test program was described in PWA-4510, System Test Plan, dated 10 July 1972. The test program, established in conjunction with NASA/JSC, consisted of a series of simulated Space Shuttle Orbiter Missions of one week (168 hours) duration shown in Figure 3. A four-mission cycle was operated with a scheduled eight-hour shutdown between each mission. This was followed by a four-mission cycle with the shutdown eliminated to simulate a 30-day Shuttle mission shown in Figure 4. This process was repeated for the duration of the test. The current density levels of the mission cycle were based on anticipated Space Shuttle electrical load requirements. In addition to steady-state operation at the representative current density levels and the shutdowns and restarts, the load profile included up-and-down power transients and a spike overload. Samples of the product water were taken periodically for analysis. The operating temperature level of the powerplant was set to be compatible with estimated vehicle heat rejection capabilities and fuel cell life requirements.
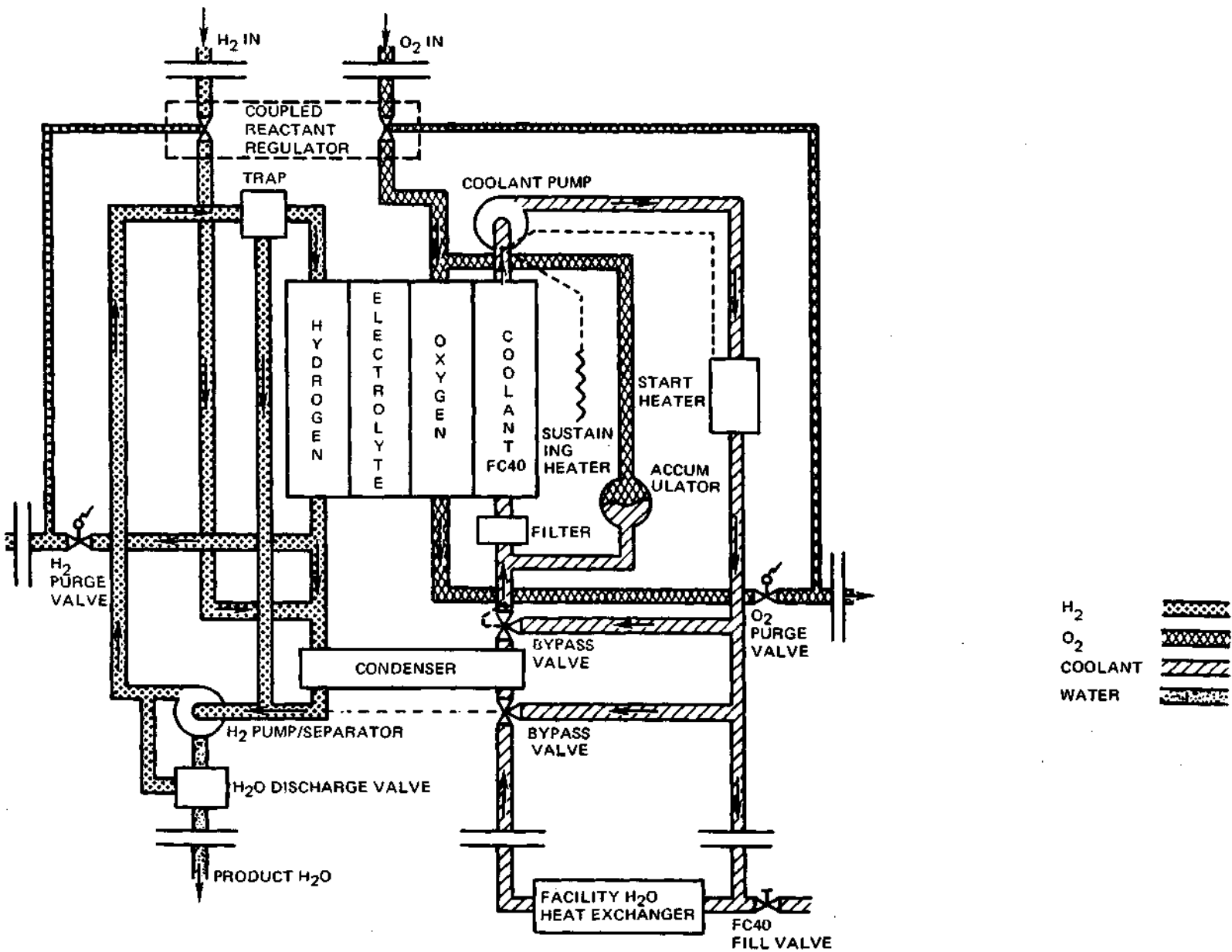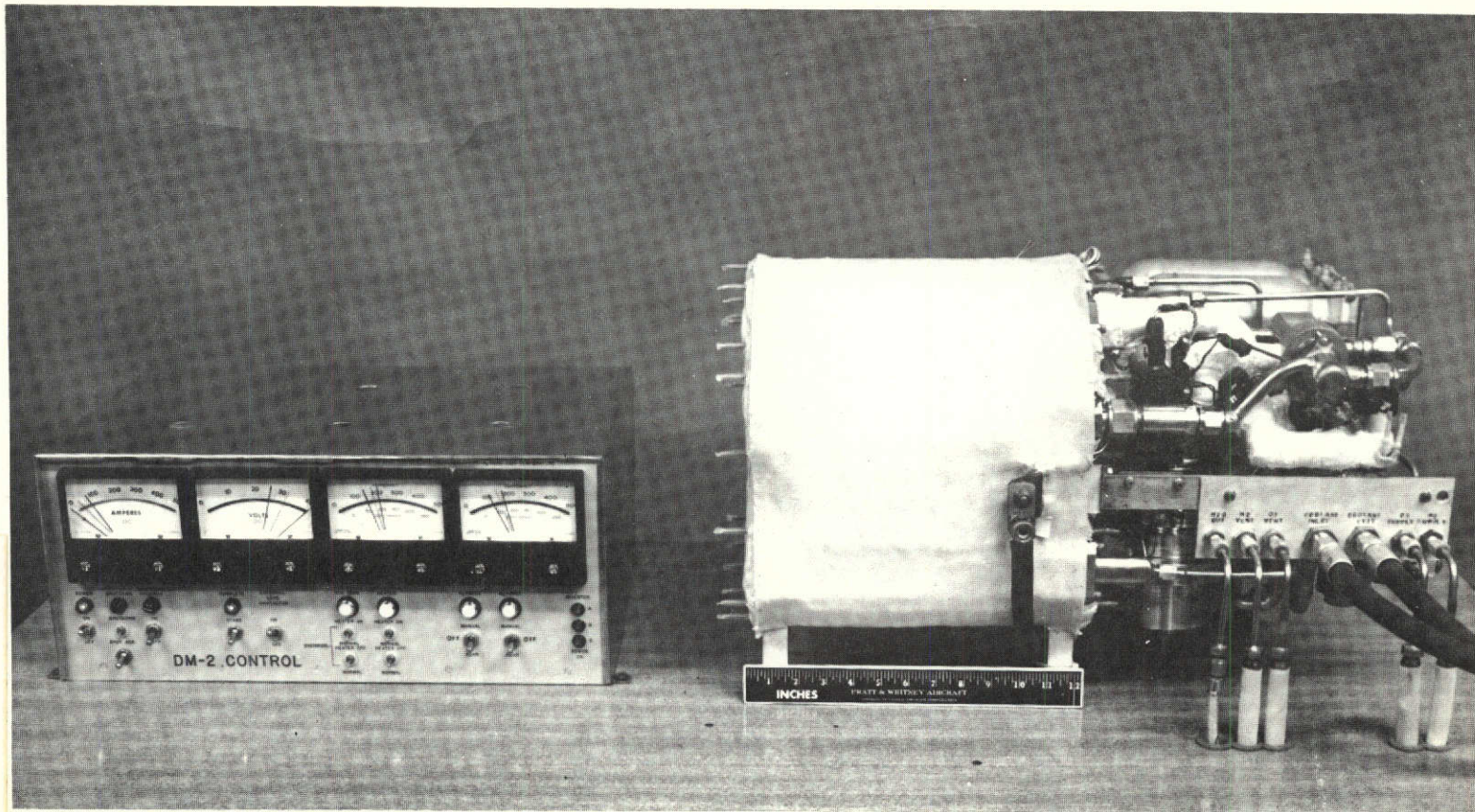
Figure 1 - DM-2 Powerplant Schematic

Figure 2 - DM-2 Powerplant and Control Unit Mounted for Test
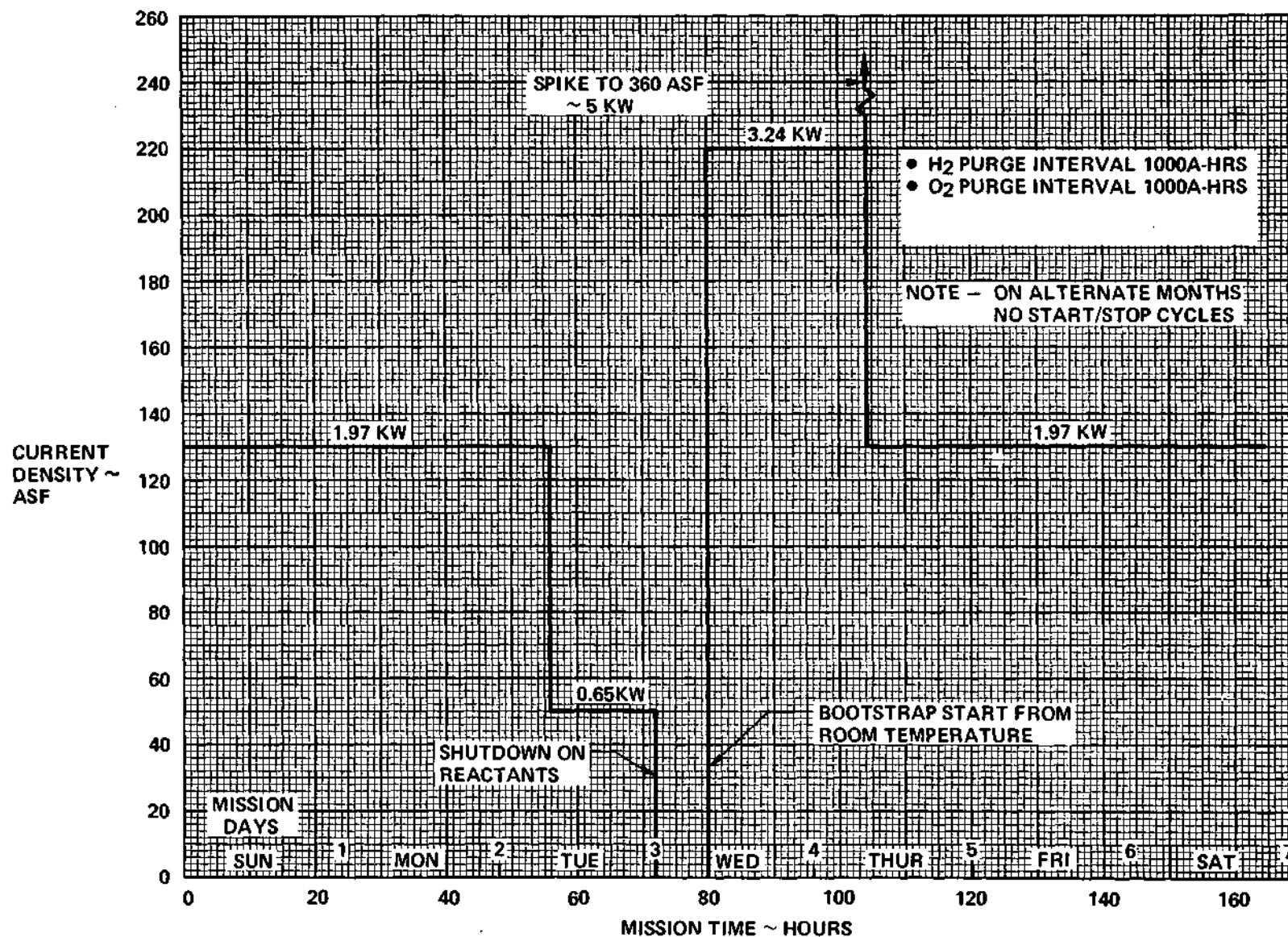
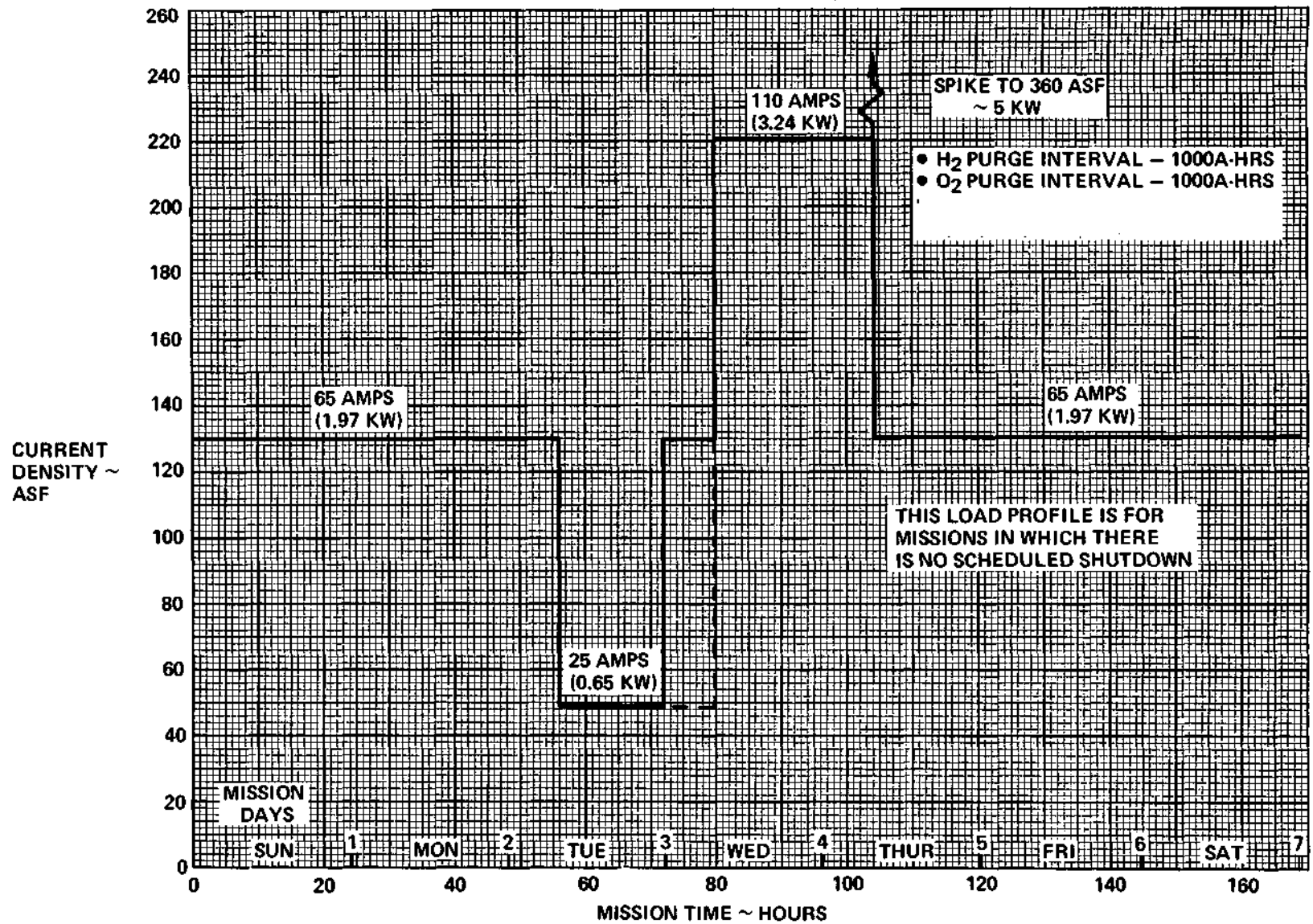WCN-1818

Figure 3 - DM-2 Load Profile

Figure 4 - DM-2 Load Profile Used for Non-Shutdown Operation

## 2.4    DESCRIPTION OF TEST FACILITY

An existing sea level test stand is used for the endurance test. This test stand provides reactant gases to the powerplant interface, contains a heat exchanger for rejection of powerplant waste heat, and provides variable electrical loads. The facility Automatic Data Acquisition and Recording (ADAR) system records data and monitors selected DM-2 operating parameters and has the capability to automatically send a shutdown signal to the powerplant control unit if any of these parameters exceed predetermined limits. Figure 5 shows a block diagram of the test installation.

## 2.5   TEST RESULTS

The DM-2 powerplant test started on 8 August 1972 and successfully completed its 2000-hour milestone on 3 November 1972. On 10 March 1973, the DM-2 completed 5000 hours.

A total of 21 self-energized starts, including the acceptance test start, were completed. Eighteen of these starts followed shutdowns in which the powerplant was left pressurized on reactants. On the other three starts, the powerplant had been previously inerted with nitrogen. All starts were completed in approximately ten minutes. The acceptance test bootstrap start characteristics shown in Figure 6 are typical of all the starts. Throughout the test, all powerplant controls, thermal switches, and components functioned as designed. The powerplant performance and operating characteristics are presented in Figure 7. The powerplant was operated for one-mission cycle (168 hours) with the hydrogen purge eliminated for the purpose of determining the effect on powerplant operation. Powerplant performance remained nominal throughout the mission cycle. The powerplant was also operated satisfactorily for 100 hours with both the hydrogen and oxygen purge eliminated. Periodic calibrations showed the performance of the power section and all components was nominal throughout the test. Analysis of product water samples performed by NASA/JSC and an independent laboratory shows the water to be of high purity.

Early in the test program, data indicated that the coolant flow through the condenser was lower than desired. This was corrected by increasing the bleed-orifice size in the primary coolant control valve bypass line during a scheduled between-mission shutdown on 23 August 1972. During a scheduled shutdown on 18 October 1972, the coolant system was "topped off" to replace coolant lost because of weeping at the stack coolant inlet fitting. On 8 November 1972 at 2116 load hours during the scheduled shutdown between missions thirteen and fourteen, this fitting was tightened. No further coolant loss was experienced for the remainder of the test. The need for and the effectiveness of these maintenance actions were indicated by the normal powerplant instrumentation.
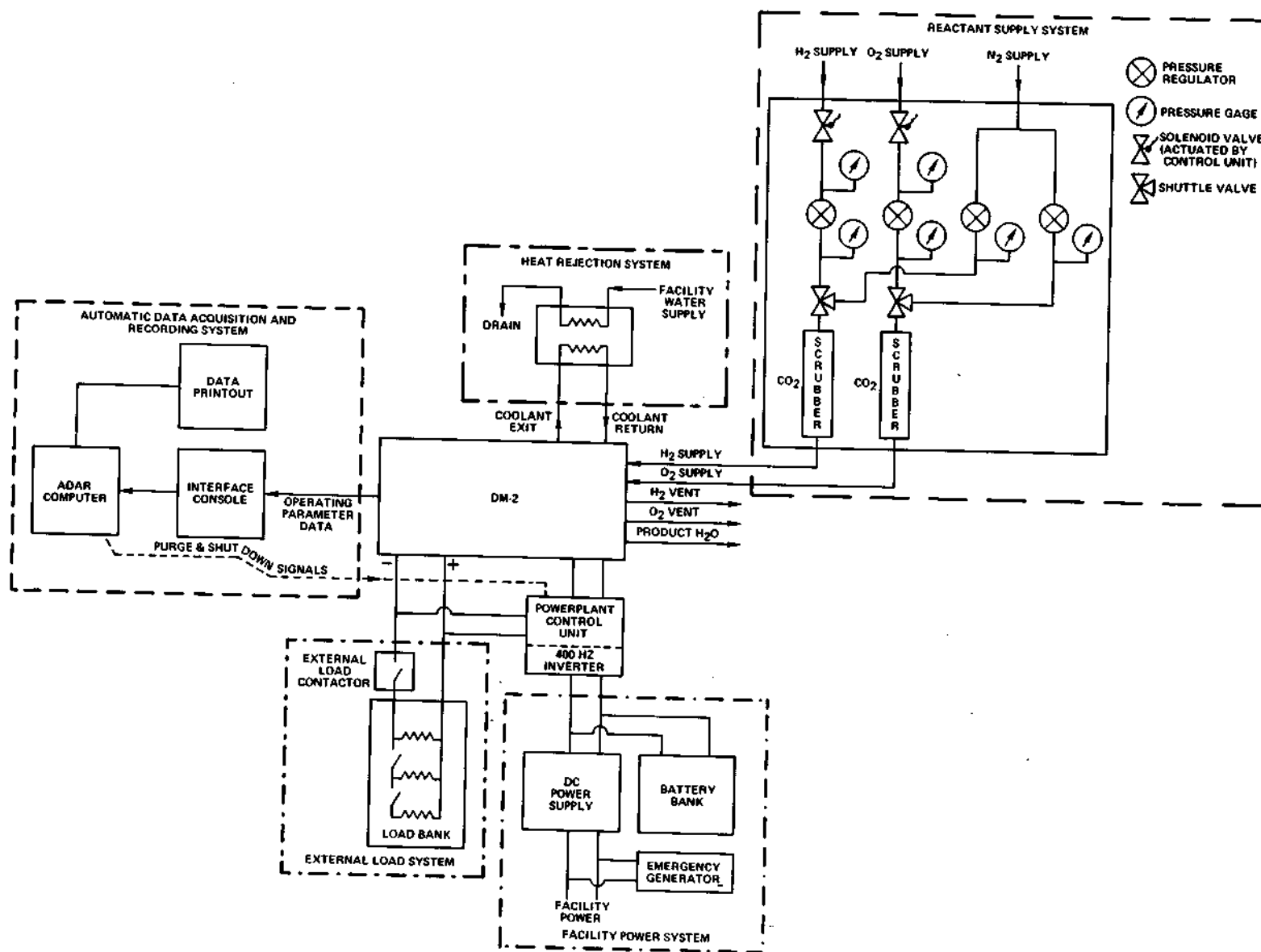
Figure 5 - DM-2 Test Facility Block Diagram
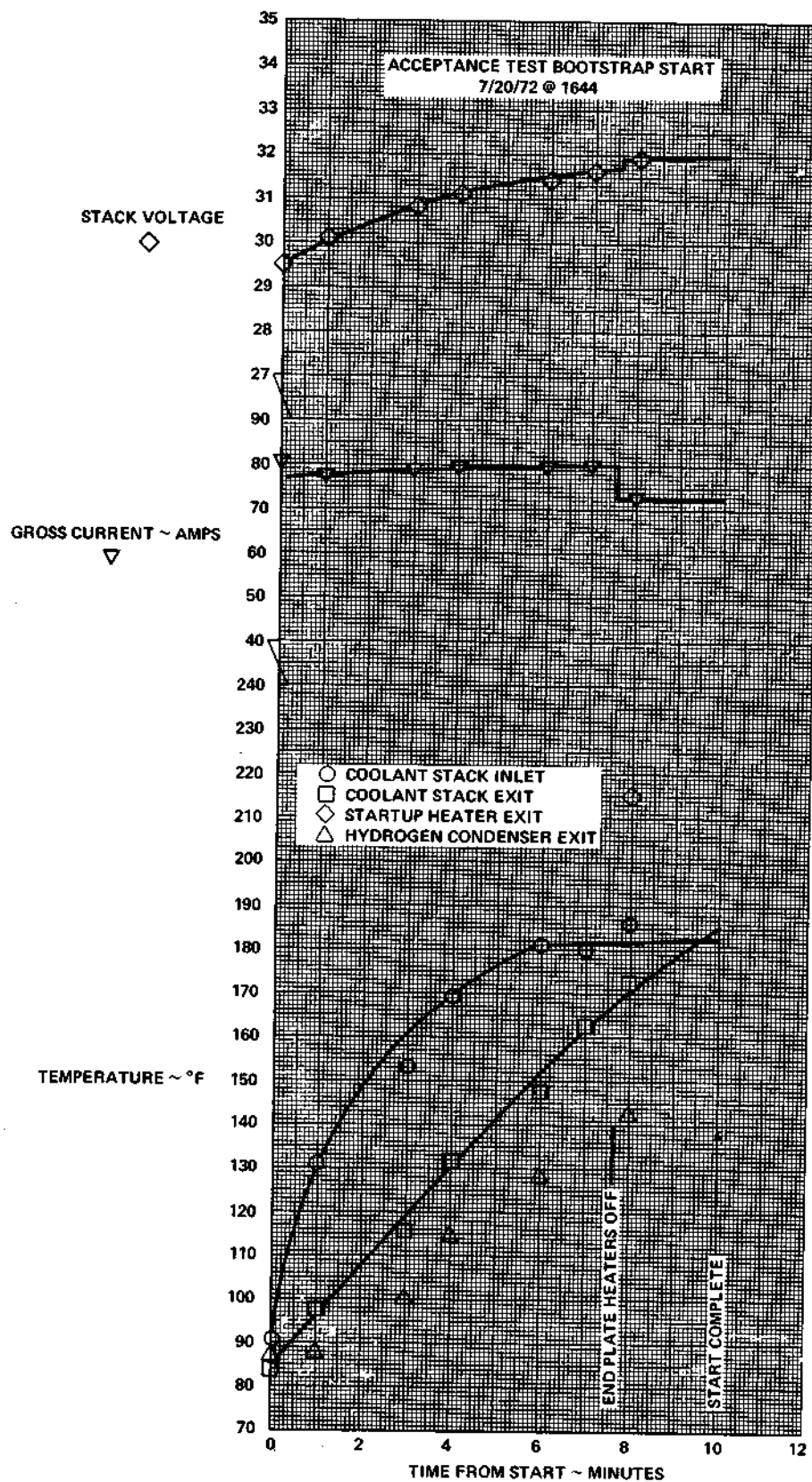
Figure 6 - DM-2 Powerplant Bootstrap Start Operating Characteristics
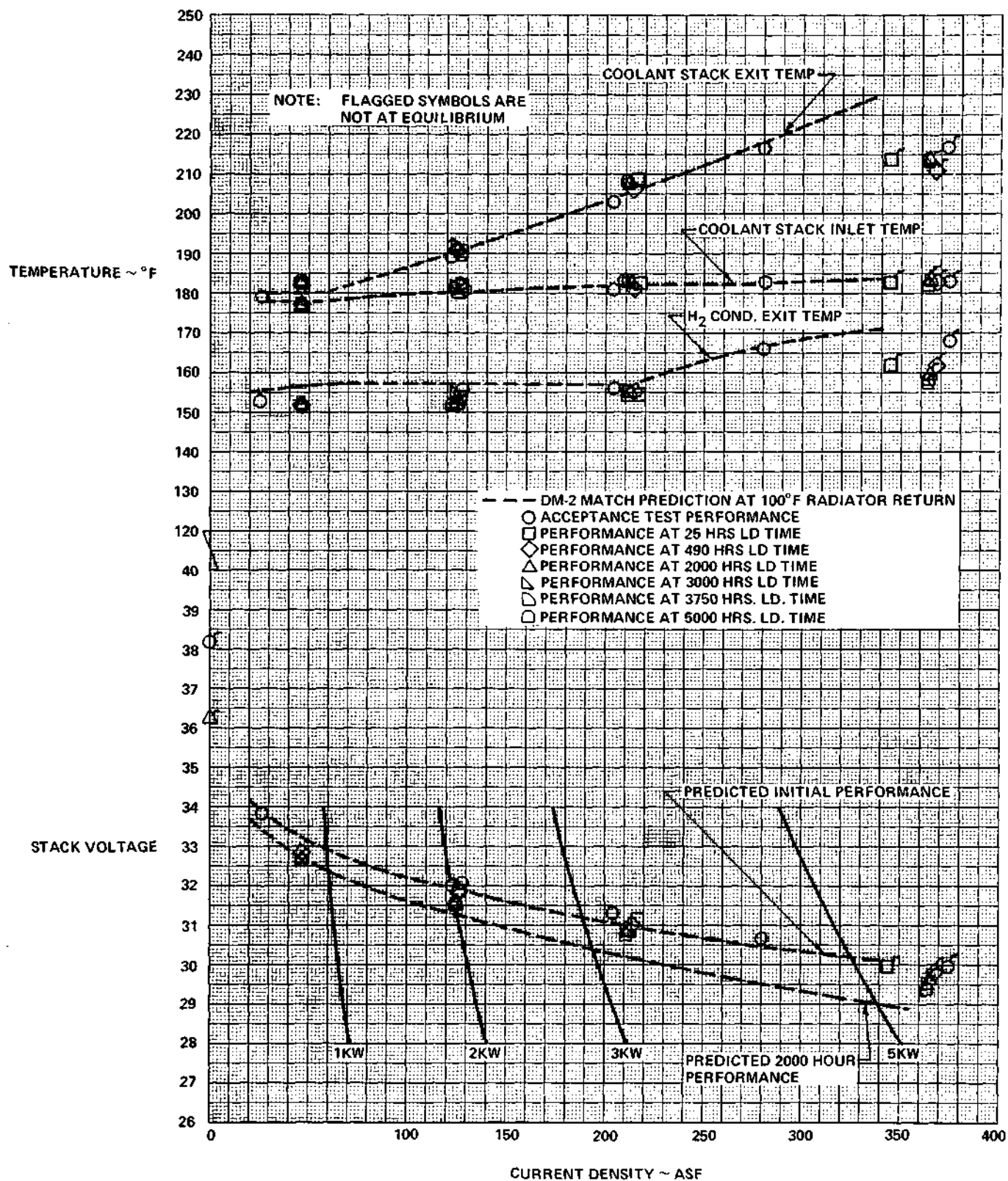
Figure 7 - DM-2 Powerplant Operating Parameters

Two unscheduled shutdowns occurred during the 5000-hour test program, both due to faults within the facility Automatic Data Acquisition and Recording (ADAR) system. The power-plant was restarted normally with performance continuing the same as before the shutdown in both instances.

NASA/JSC supplied Pratt & Whitney Aircraft with a piece of 316 stainless steel tubing, representative of the tubing to be used in the spacecraft water system, and requested it be installed in the water discharge line from the powerplant. The tube was installed on 25 August 1972 at 381 load hours. On 19 March 1973, after completion of the 5000-hour test, the tube was removed and sent to NASA for their analysis. The appearance of the tubing was excellent showing no signs of corrosion.

The final calibration showed that the individual cells were all performing normally. The test was concluded on 13 March 1973, at the end of the thirty-first simulated 7-day mission cycle and 5072.5 load hours. A log of the endurance test is shown in Figure 8. At this time, the powerplant appeared to be in excellent condition and capable of additional endurance operation.

## 2.6 CONCLUSIONS

As a result of the test program it is concluded that:

- The primary objective of demonstrating technology readiness for the Space Shuttle has been achieved as demonstrated by:

    - 5072.5 hours accumulated while operating to the NASA-approved mission profile (Thirty-one 7-day missions).

    - 21 normal start and shutdown cycles performed with no affect on performance.

    - Automatic instantaneous response to all load changes.

    - Normal performance of the individual cells at the end of the test. (Initial voltage spread of the 34 cells was 0.012 volts. The 5000-hour voltage spread was 0.017 volts).

- Depending on reactant purity, hydrogen purging may be eliminated and oxygen purging reduced to one purge per mission during a 7-day Space Shuttle mission.

- Useful maintenance data can be obtained from normal flight type instrumentation, and maintenance actions can be performed between missions.

- Powerplant readiness for flight can be determined by analysis of performance data taken during ground checkout.
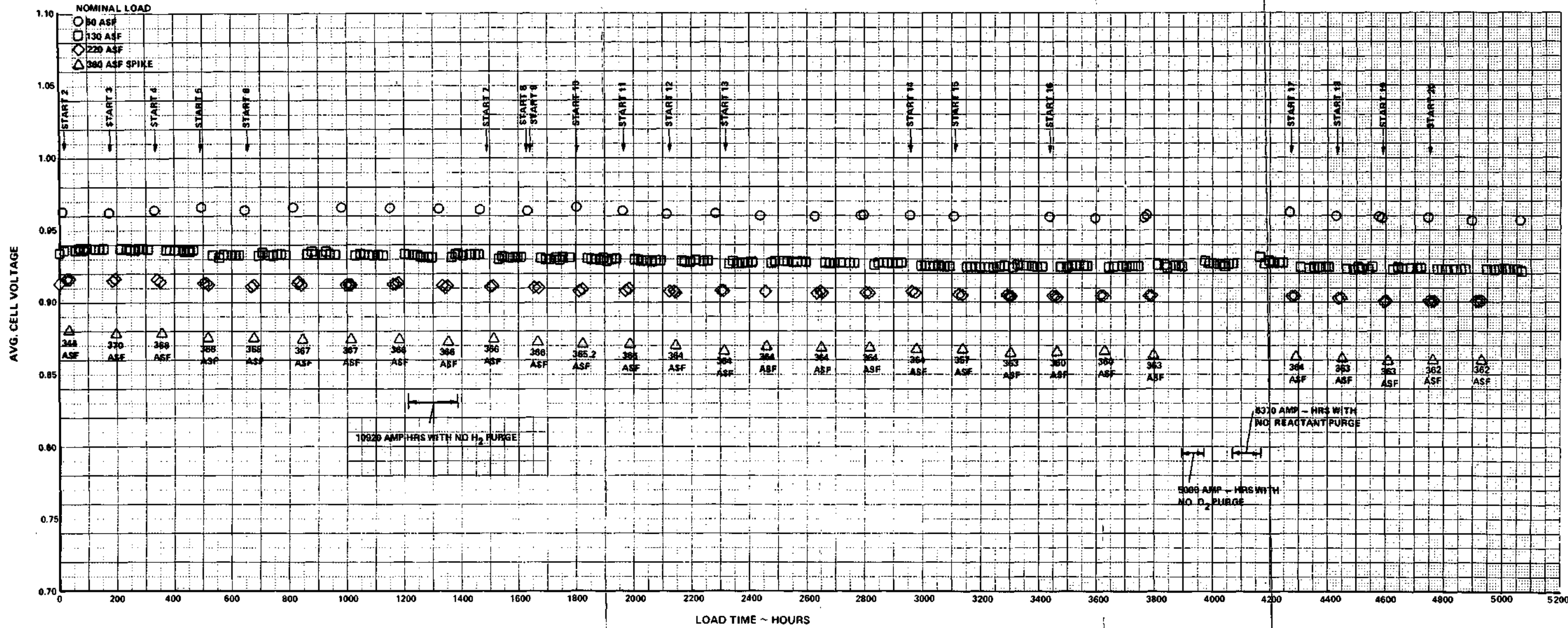
Figure 8 - DM-2 Powerplant Endurance Log

## 3.0 HYDROGEN DRAG PUMP

An Apollo Block II hydrogen pump separator unit was used on the DM-1 powerplant. At the DM-1 operating conditions, the plastic pinion drive gear exhibited excessive wear because it was too lightly loaded. As a result, a decision was made to design a direct-drive drag-type pump for the DM-2 and the Space Shuttle application and also to run an endurance test on a breadboard drag pump with a 2000-hour objective.

The design for a flight-weight pump was completed and a layout provided to NASA/JSC in March 1972. A sketch of the pump is shown in Figure 9. A non-flight-weight unit for the DM-2 powerplant was constructed. This pump did not have flight-weight housings around the pump section and the water discharge valve was not integral with the end housing.

Performance and endurance testing of a breadboard hydrogen drag pump was conducted to evaluate the pump at DM-2 and Space Shuttle operating conditions. The general test plan was to establish the effects of speed and impeller-face clearance on flow and differential pressure characteristics on the flow bench and then rebuild the unit for initial performance calibration and endurance test. Performance results exceeded design requirements by a considerable margin. Figure 10 indicates performance at various speeds.

Pump calibrations and performance mapping were conducted and the endurance test was started on January 18, 1972. The test was conducted under the following conditions:

- Saturated hydrogen

- $160°F$ pump temperature

- $60°$ psia system pressure

- 7.5 inches of water pump head rise

- Separation rate of 6 pph of water

- Nominal motor speed of 8000 rpm

Calibration results at 7000, 8000 and 9000 rpm at 0,679, and 2000 hours are shown in Figure 11.

To further evaluate endurance capability, the test was continued. The test was interrupted at 6700 hours because of an increase in noise and vibration detected by a vibration analyzer which provided first indications of vibration approximately 900 hours prior to the decision to interrupt the test. Post-endurance calibration at this time showed a flow reduction of approximately 3.5 percent of the initial flow value, which is insignificant in terms of powerplant operation.

H₂+H₂O IN

IMPELLER

STATOR

DRIVE MOTOR

H₂O REGULATOR VALVE

H₂O COLLECTION TUBE

CENTRIFUGAL SEPARATOR

H₂ OUT
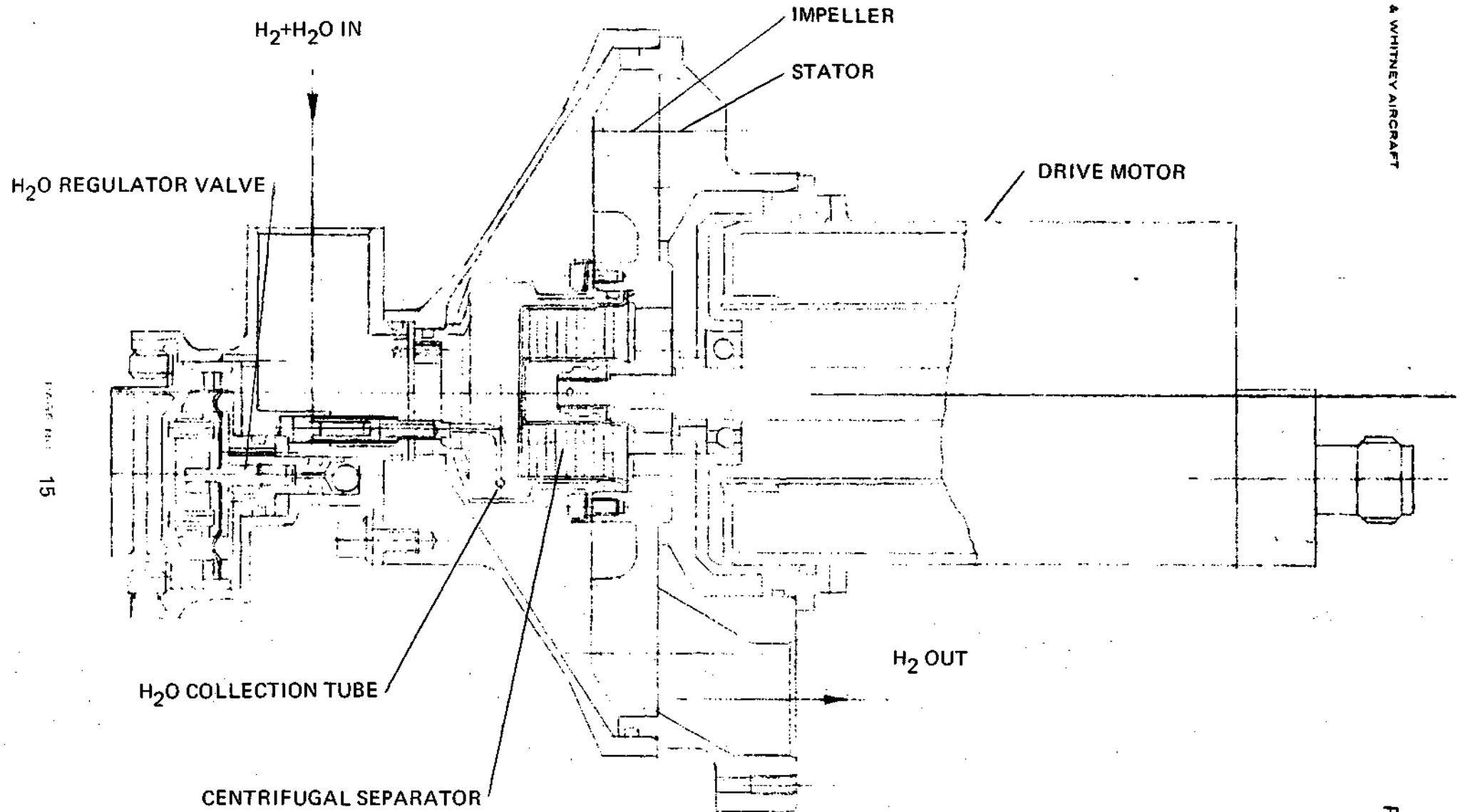
Figure 9 - Schematic of Flight Weight Pump
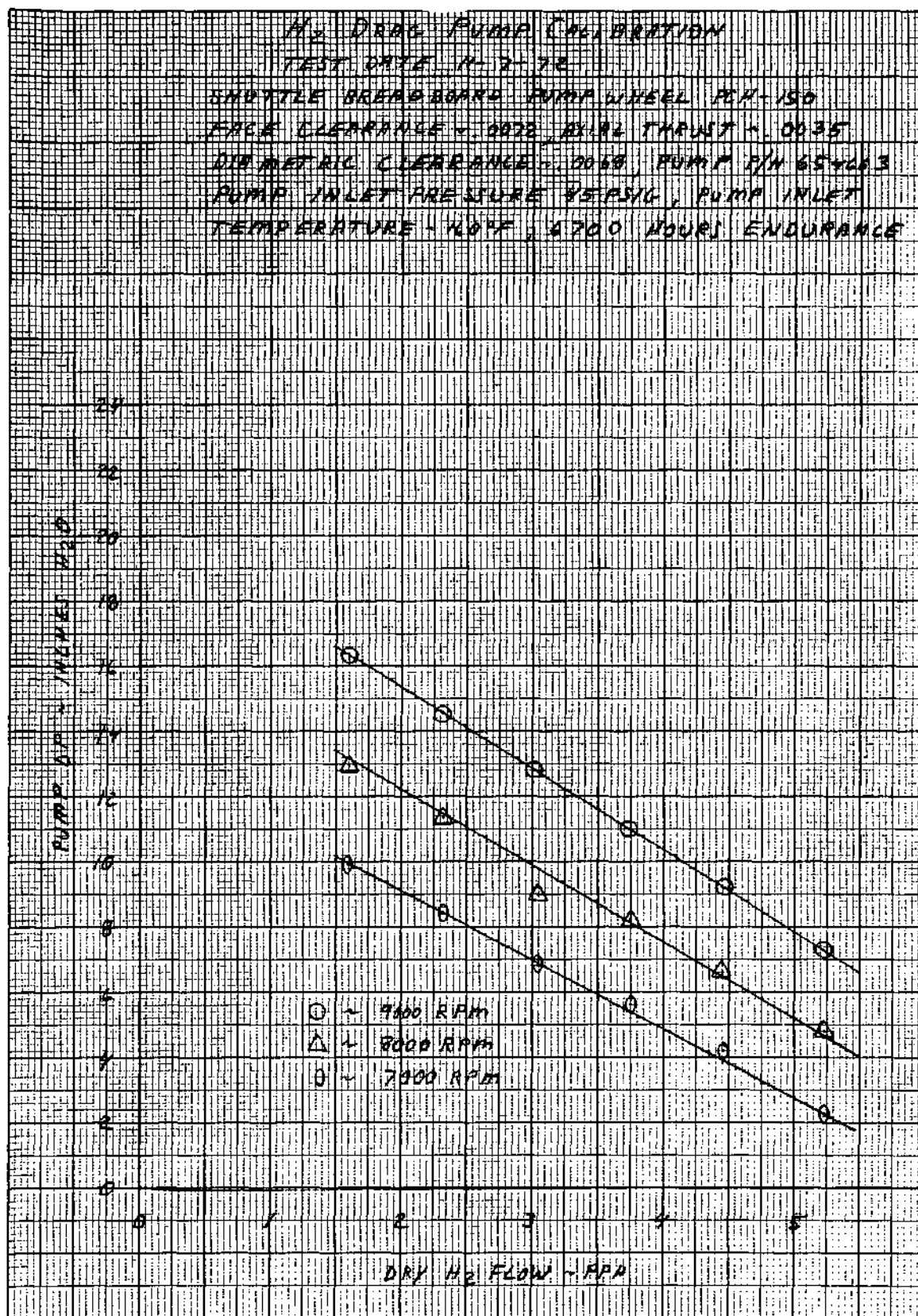
Figure 10 - Speed Versus Performance Calibration

PRATT & WHITNEY AIRCRAFT
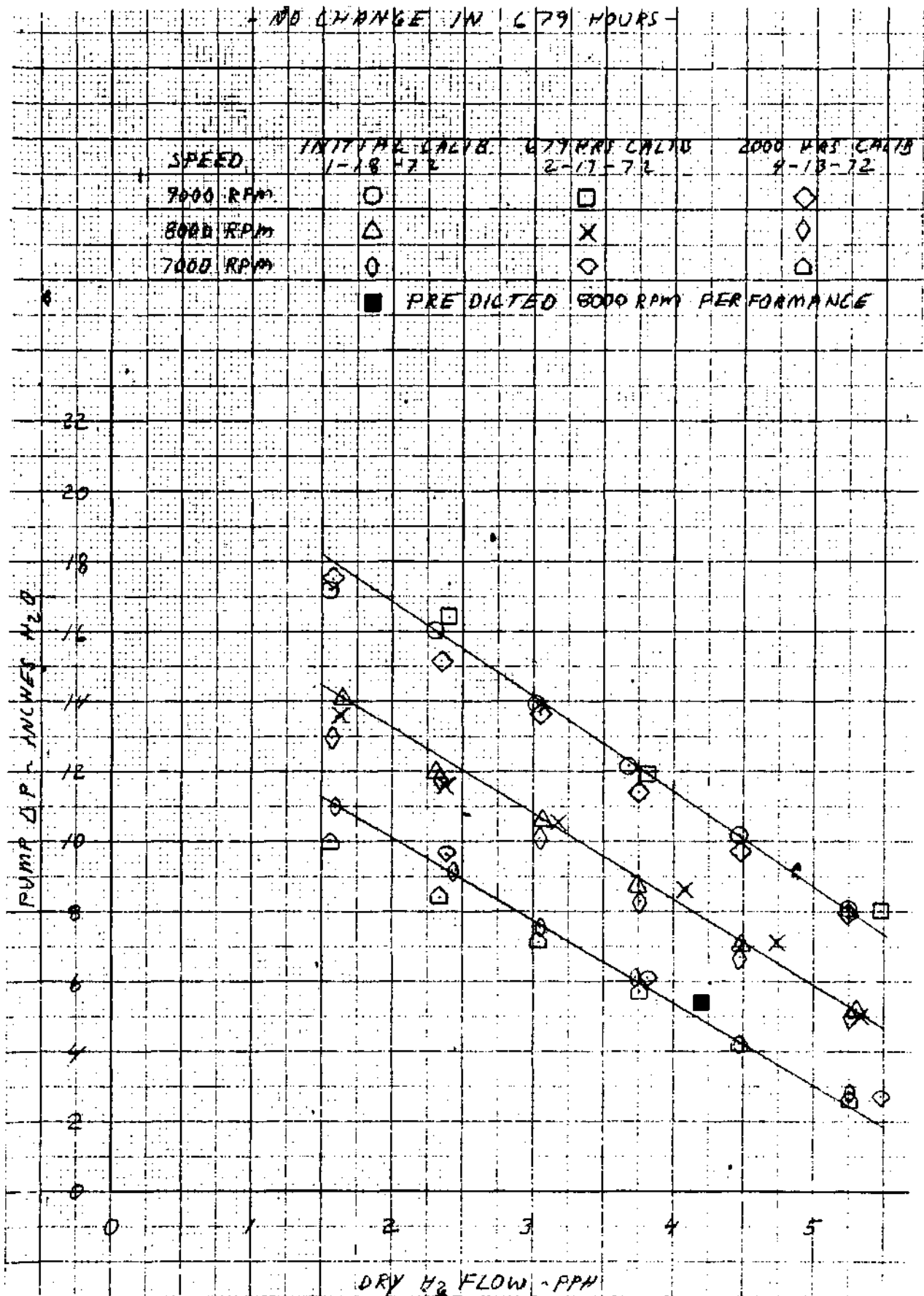


Figure 11 - Breadboard Hydrogen Drag Pump Performance

Disassembly observations showed the general overall condition of the pump details to be very good. The bearing preload mechanism was found to be stuck which resulted in the loss of bearing preload and was considered the probable cause of the increase in pump noise and vibration level.

The pump was rebuilt with new bearings and the endurance test resumed. At 10,000 total hours, the test was voluntarily terminated. Teardown inspection showed the pump details to be in excellent condition and the unit showed no signs of operating distress. A log of the vibration analyzer results for the 10,000 hours of testing is shown in Figure 12.
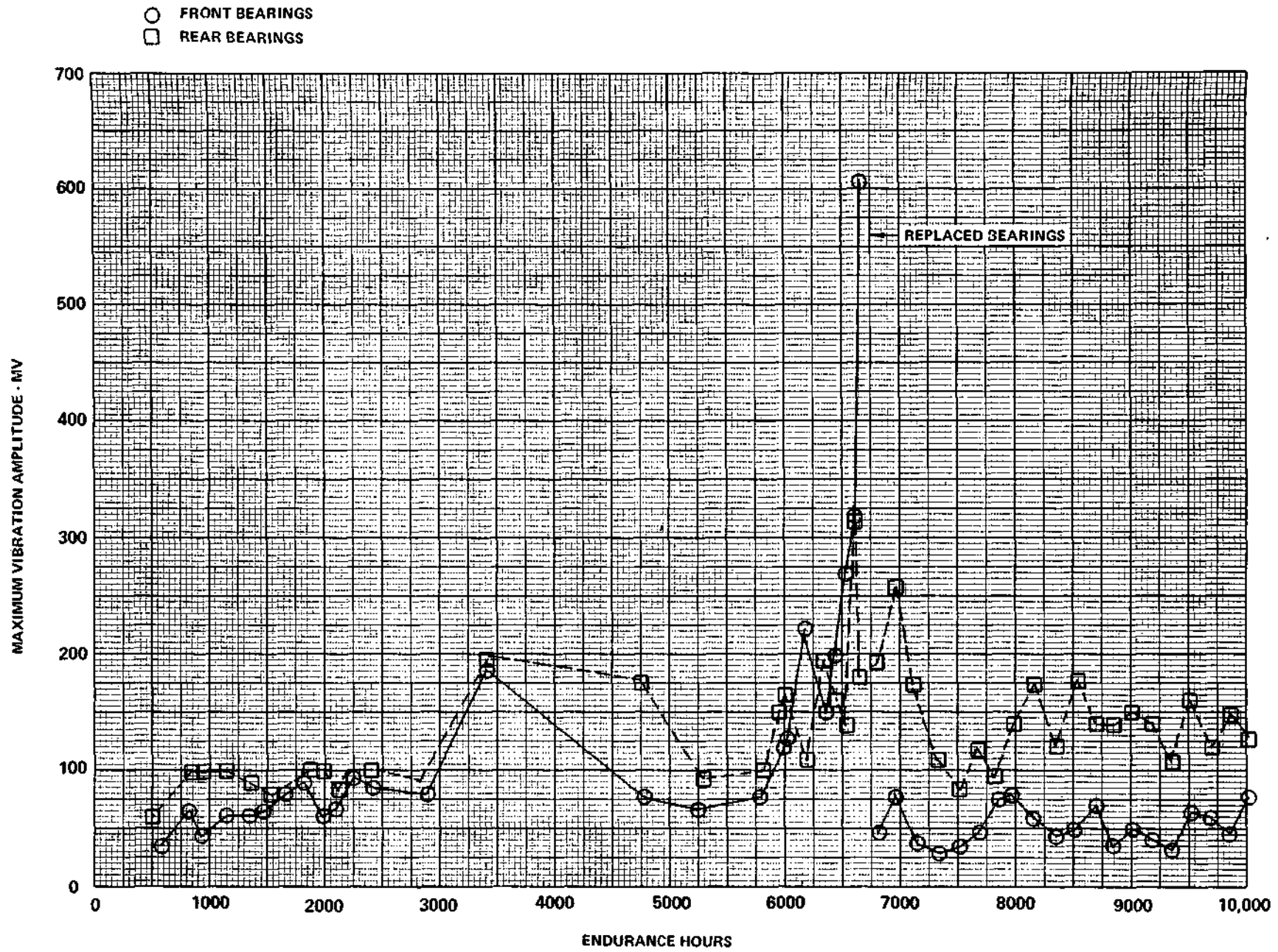
Figure 12 - Breadboard Hydrogen Drag Pump Maximum Vibration Amplitude Trends

## 4.0  BASELINE CELL TECHNOLOGY

The DM-1 test program and the post-test analyses identified the requirement to improve cell structural tolerance to cross-pressure. The analyses also indicated the desirability of eliminating or reducing the rate at which metals deposit in the matrix. The primary objective of the baseline cell technology program was to define a cell configuration capable of a minimum of 2000-hours life and increased tolerance to reactant cross-pressure. A comprehensive program of trade and design studies, supported by design information testing, was conducted to develop the improved cell design. The program included: 1) structural studies to identify cell and separator plate configurations, 2) studies to reduce metal deposits in the matrix, 3) flow studies to establish the separator plate manifolds, ports, and field flow patterns, and 4) thermal studies to determine the general cooling configuration.

A multicell stack program was planned to verify the results of the selected configuration prior to incorporation into the DM-2 powerplant stack. This program was planned with two test units. The objective of the first unit, designated the prototype configuration, was to get early verification on as many of the design changes or concepts as hardware-procurement lead times would allow. The objective of the second test unit, designated the Scheme I configuration, was to verify the configuration which would go into the DM-2 powerplant with all the changes incorporated.

## 4.1  TRADE STUDIES AND DESIGN INFORMATION TESTING

### 4.1.1    Structural

Structural design study objectives were to identify a cell and separator plate configuration with tolerance to reactant cross-pressures and uniform cell assembly compression under initial assembly pinch. Static tests performed on DM-1 hardware had indicated that a hydrogen overpressure of 45 psig can cause a permanent deformation of the cathodes as large as 0.012 inches under the coolant plate pins. Factors influencing the structural capability of a cell are the electrode substrate configuration and electrode support. A structural model was developed to analytically predict electrode deformation due to reactant overpressure as a function of substrate strength and substrate support coverage. For the improved cell configuration, a design criteria of less than 0.001 inches permanent electrode deformation under a full reactant cross-pressure of 45 psid was established. Trade-off studies were conducted for both of these parameters in support of the separator plate design to establish an acceptable configuration.

4.1.1.1    Separator Plates - The first step, to meet the design criteria, was to define an oxygen separator plate configuration with a particular area coverage and pin size. The next step was to select a unitized electrode assembly with a cathode substrate of a strength consistent with the oxygen-plate pin-size and area coverage for hydrogen overpressure, and an anode substrate and ERP field support geometry to sustain an oxygen overpressure. The DM-1 ERP pin size and area coverage of 27.5 percent was considered adequate based on the static tests performed on DM-1 hardware.

The cathode separator plate on the DM-1 had 0.055 inch diameter pins on a 0.135 inch pitch square array providing a nine percent area coverage for cathode support. Pin sizes up to 0.096 inch diameter (40 percent coverage) and a triangular array pin arrangement were considered for additional cathode support. A triangular array is desirable from a structural viewpoint because, for a given pitch, it minimizes the maximum distance between pins compared to a square array. The disadvantages of the triangular array were 1) a new tool for making the ERP and new masters for chemical milling the pattern on the magnesium plates were required to have pin alignment, and 2) flow pressure drops for a given pin diameter and pitch were slightly higher than for the square array.

In addition to structural tolerance to cross-pressure, other factors influenced the oxygen plate design. The oxygen volume in the stack affects the inert buildup rate and purge interval requirements. Increasing the support area by increasing pin size decreases the oxygen volume and should, therefore, be kept to a minimum. On the basis of these studies, a square array oxygen plate configuration with 0.073 inch diameter pins, 23 percent nominal coverage was selected.

4.1.1.2 Electrode Substrates - Design information was obtained for use in the analytical structural model by running tensile tests for yield strength determination on candidate electrode substrate materials. These materials were:

100 mesh x 0.0025 inch diameter wire nickel screen (annealed) - DM-1 configuration
100 mesh x 0.0025 inch diameter wire nickel screen (unannealed)
100 mesh x 0.005 inch diameter wire nickel screen (unannealed)
5-Ni7-4/0 expanded metal nickel (unannealed)
5-Ni5-5/0 expanded metal nickel rolled to 0.0045 inch thick

Table I summarizes the deflection predictions from the analytical model of candidate anode substrates with the 27.5 percent electrode support provided by the electrolyte reservoir plate. Table II is a similar summary for the cathode with the 23 percent electrode support. The tables show that all substrates considered satisfy the criteria established for cross-pressure loading except the 100 mesh x 0.0025 inch nickel screen (annealed). Cross-pressure tests were conducted on the 2.5-mil wire in the unannealed condition in both the 100 and 150 mesh configurations. Both configurations yielded less than 1 mill additional permanent substrate deformation after being subjected to a 45 psi crosspressure differential.

The 100 mesh x 2.5-mil diameter wire screen (annealed) is the electrode substrate which was used in the DM-1. This configuration, in the unannealed condition, was selected for the Scheme I cell design. In addition to satisfying the basic structural requirement, it afforded the lowest potential stack weight relative to the other candidate substrate configurations and required no catalyst application process changes.

4.1.1.3 Matrix - The matrix used in the DM-1 cell was 0.010 inch thick fuel cell grade asbestos with a gas/bubble pressure of approximately 20 psi. It was concluded from the DM-1 analysis that a 0.010 inch thickness provided insufficient margin against manufacturing tolerances and assembly-handling for the DM-2 type of stack. Also, the 20 psi gas bubble/pressure

capability of the matrix did not meet the 45 psi cross-pressure capability criteria established for the Scheme I cell. NASA/JSC recommended that a thicker asbestos matrix reconstituted in accordance with a procedure they provided be considered. Fabrication and shop trials at Pratt & Whitney Aircraft resulted in a simplified reconstituting procedure. Tests on 0.010 inch, 0.020 inch and 0.030 inch thick matrices produced to this process were tested and were found to have gas/bubble pressure in excess of 55 psi, which met the requirement. A 0.020 inch thick reconstituted asbestos matrix (RAM) with bubble pressures of 70 to 90 psi was selected for the Scheme I design.

## TABLE I

### REVIEW OF ANODE SUBSTRATE LOAD DEFLECTION DETERMINATION WITH 27.5 PERCENT SUPPORT

| Substrate | Yield Strength lbs/in | Average Deformation Under 45 psid Cross Pressure | Reactant Pressure For 1 Mil Def. PSIA |
|---|---|---|---|
| 100 x 100 x 0.0025 Ni Screen (Annealed) | 7.0 | 1.8 mils | 40.0 |
| 100 x 100 x 0.0025 Ni Screen (Unannealed) | 15.0 | 0.7 mils | 79.0 |
| 100 x 100 x 0.005 Ni Screen (Unannealed) | 45.0 | 0.1 mil | 250.0 |
| 150 x 150 x 0.0025 Ni Screen (Unannealed) | 12.0 | 0.5 mils | 105.0 |
| 5-Ni7-4/0 X-Met (Unannealed) | 22.0 | 0.6 mils | 90.0 |
| 5-Ni5-5/0 X-Met Rolled to 4.5 Mils (Unannealed) | 19.0 | 0.7 mils | 79.0 |

Conclusion — All Substrates Except Annealed 100 x 100 x 0.0025 Screen Meet Structural Requirements

TABLE II

REVIEW OF CATHODE SUBSTRATE LOAD DEFLECTION
DETERMINATION WITH 23 PERCENT SUPPORT

| Substrate | Yield Strength lbs/in | Average Deformation Under 45 PSID Cross Pressure | Reactant Pressure For 1 Mil Def. PSIA |
|---|---|---|---|
| 100 x 100 x 0.0025 Ni Screen (Annealed) | 7.0 | 2.3 mils | 35 |
| 100 x 100 x 0.0025 Ni Screen (Unannealed) | 15.0 | 0.9 mils | 65 |
| 100 x 100 x 0.005 Ni Screen (Unannealed) | 45.0 | 0.1 mil | 250 |
| 150 x 150 x 0.0025 Ni Screen (Unannealed) | 12.0 | 0.6 mils | 90 |
| 5-Ni7-4/0 X-Met (Unannealed) | 22.0 | 0.7 mils | 77 |
| 5-Ni5-5/0 X-Met Rolled to 4.5 Mils (Unannealed) | 19.0 | 0.9 mils | 68 |

Conclusion — All Substrates Except Annealed 100 x 100 x 0.0025 Screen Meet Structural Requirements

4.1.1.4 Pinch Determination - A program was conducted to determine the assembly pinch requirements for the Scheme I cell. The approach was to simulate cell pinch by coolant overpressure and relate cell performance to coolant overpressure and then, coolant overpressure to cell pinch. Single cells constructed with 100 mesh x 5-mil wire and 2.5-mil wire were built with different initial cell pinch known to be less than required for maximum performance. These cells were put on test at a steady 150 ASF load. Output voltage was recorded as coolant pressure was increased from 0 to 45 psi over the reactant pressures. Test results are given in Figure 13 and show performance improvement with increasing coolant overpressure up to approximately 17.5 psi. Above this level, both the 2.5-mil wire and 5.0-mil wire substrates showed no improvement. Also, the lighter substrate (2.5-mil wire) showed less
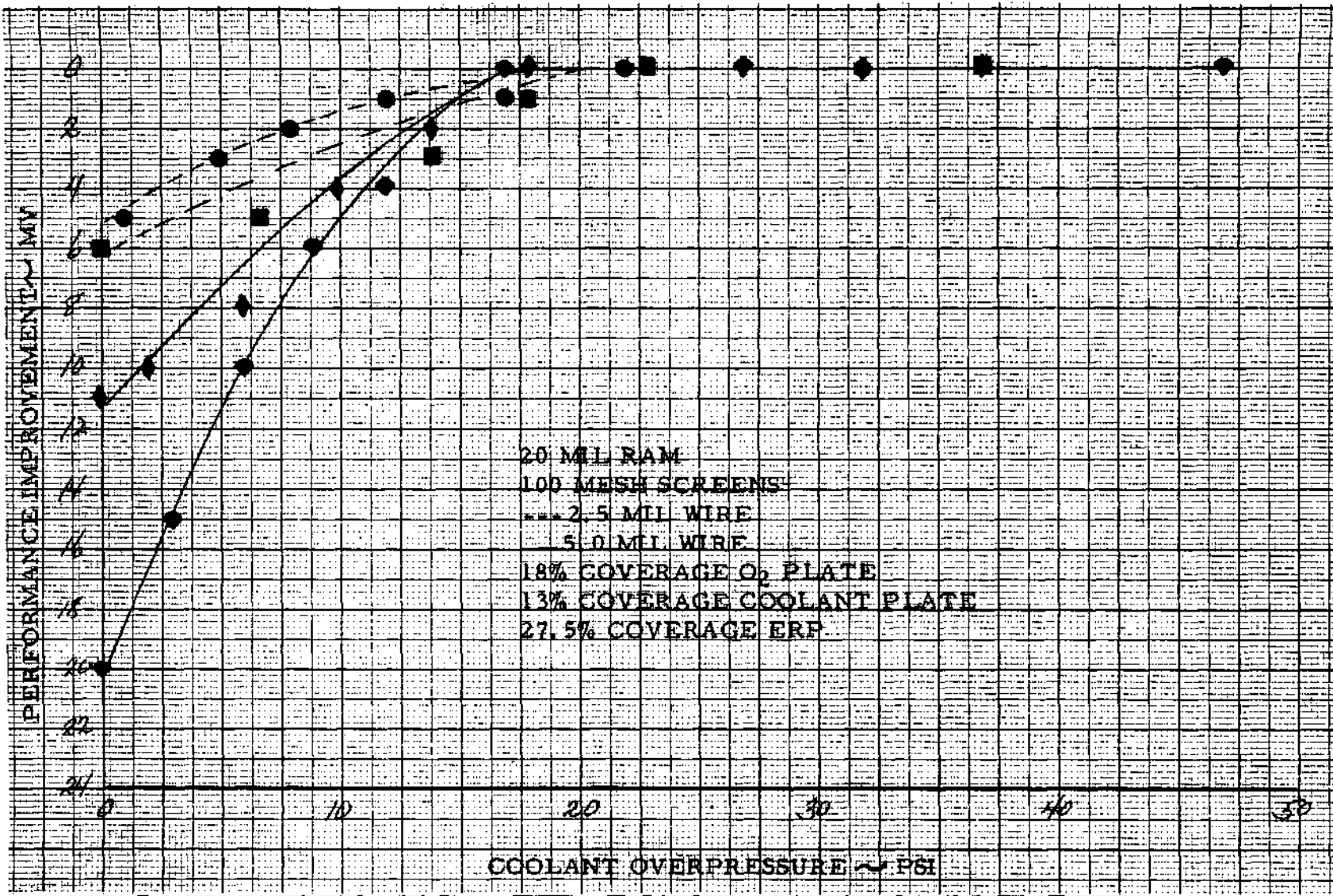
Figure 13 - Effect of Coolant Overpressure on Performance Improvement

sensitivity in this range of coolant overpressure than the heavier substrate (5.0-mil wire). Figure 14 shows the relationship of cell pinch to coolant overpressure obtained from load compression analysis and testing conducted on the substrates and cell details. The figure indicates that the pinch corresponding to a 17.5 psi coolant overpressure is 6.7 mils for the 2.5-mil wire and 3.4 mils for the 5.0-mil wire. The dotted line on Figure 14 represents a 23 percent coverage oxygen plate, which is the selected Scheme I plate design. A nominal 7-mil pinch was selected for the Scheme I cell.

### 4.1.2 Reduction of Metal Deposits in the Matrix

The post-test analysis of DM-1 cells indicated metal deposits in the matrix. Silver and palladium were two of the elements found. The DM-1 separator plates and the electrode substrates were silver plated. To eliminate this source, gold-plating was substituted for silver in the Scheme I cell configuration, gold being more corrosion resistant in the fuel cell environment.

Palladium was used in the electrode catalyst to facilitate the catalyzing process. It was felt that a palladium free catalyst (platinum only) would meet the fuel cell requirements provided it could be applied uniformly to the electrode substrates. The program to eliminate palladium from the electrodes considered three major catalyzing variables; pH level of the catalyst/Teflon suspension; isopropyl alcohol leach to remove the wetting agent; and the method of transferring the catalyst/Teflon to the substrate.

The colloidal catalyst/Teflon suspension has a pH level of approximately five which is the pH of the deionized water used in the suspension. Close control of the pH level of the suspension was not critical in the manufacture of standard electrodes which contained a mixture of platinum and palladium as the catalyst. However, when platinum only was used as the catalyst, it became apparent that the pH of the colloidal suspension became more important.

The second variable considered was the use of an alcohol soak to completely remove the wetting agent, which is used in the standard process for electrode manufacture to stabilize the catalyst colloidal suspension. The wetting agent was normally removed from the finished electrode by drying in a vacuum oven. Electrodes manufactured to this process exhibited a rise in performance during the first several hundred hours of operation. A suspected partial cause of this characteristic was that the electrodes were not completely cleaned of the residual wetting agent by the vacuum drying process. The revised technique consisted of soaking the catalyzed electrodes in isopropyl alcohol, used as a solvent for the wetting agent, followed by a water rinse.

In addition to pH control of the colloidal suspension and isopropyl cleaning of the electrodes, tests were conducted to evaluate the effects of changing the method of transferring the catalyst to the substrate. In the one-sided loading method, the total catalyst loading was pressed onto the substrate from one side; in the two-sided loading method, the total catalyst loading was divided in half and pressed onto each side of the substrate.

A series of laboratory tests resulted in the conclusion that although it showed promise, the procedure for removing palladium could not be reduced to practice in the time available to
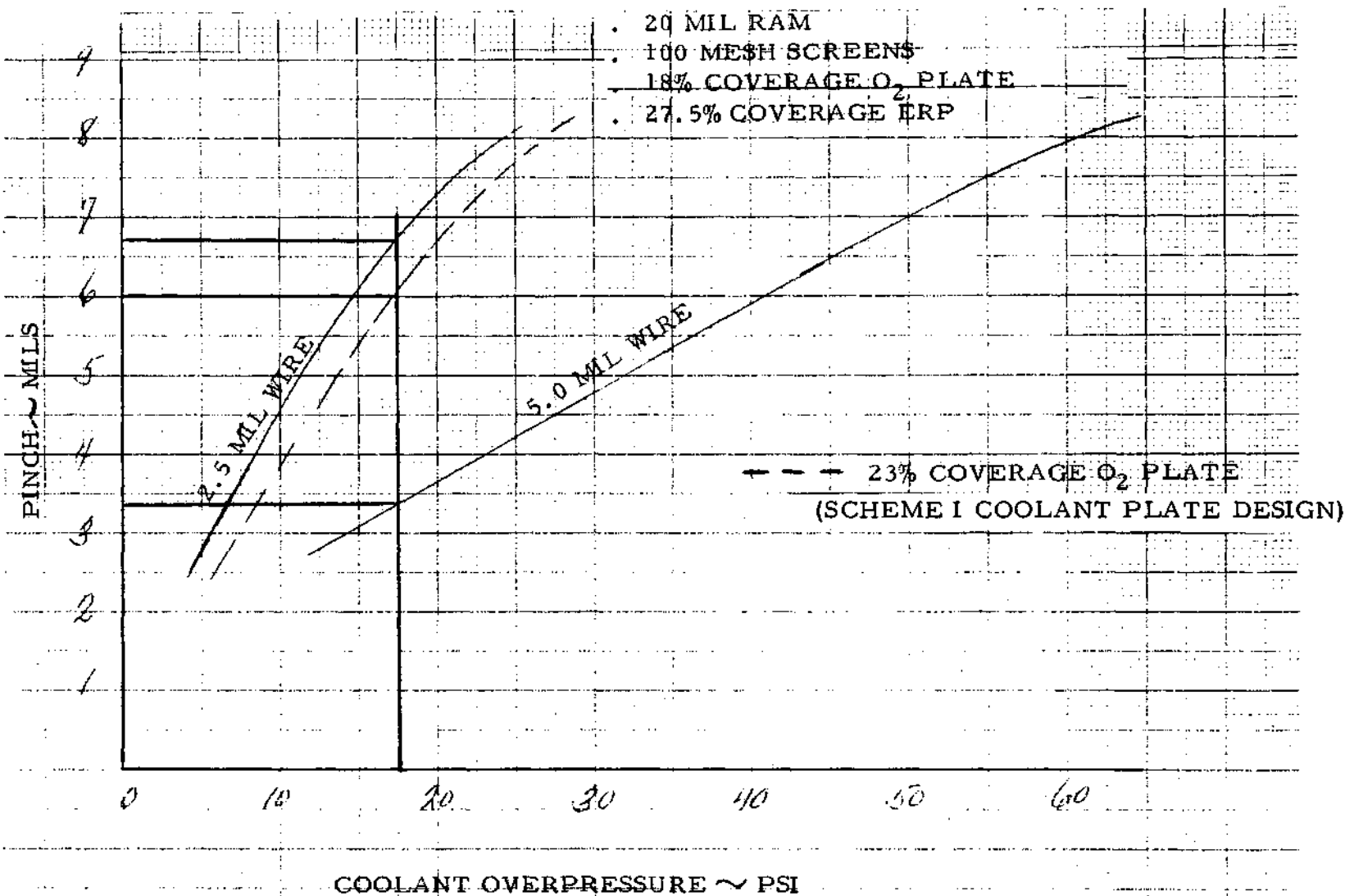
Figure 14 - Effect of Coolant Overpressure On Cell Pinch

incorporate it into the Scheme I configuration. Since only 10 percent of the total catalyst is palladium, it was felt that the standard platinum/palladium mixture was adequate for the Scheme I design. The testing did show that the isopropyl cleaning of the electrodes gave higher initial performance and eliminated the initial performance rise. This cleaning process was incorporated into the Scheme I design. Also, it was concluded from the testing that for substrates made from wire thicker than 0.0025 inches in diameter, two-sided catalyst loading produced a more uniform electrode. However, one-sided loading was determined adequate for the 0.0025 inch diameter 100 mesh wire selected for the Scheme I.

### 4.1.3    Manifold, Field and Port Geometry

Flow studies were conducted in support of the separator plate design to establish manifold, field and port geometry for the hydrogen, coolant, and oxygen. A review of cell experience on port plugging showed that there were no instances of exit port plugging on high power density cells such as used on the DM-1. There have been several instances of hydrogen-inlet port plugging due to hydrogen pump gear and vane material and water carryover from the condenser. Oxygen-inlet port plugging with water occurred on the DM-1 because of improper operation of the oxygen ejector. Although component and system operating improvements were considered as the primary means of eliminating the problem, an increased number of inlet ports was selected for the DM-2 to minimize inlet port plugging.

Hydrogen flow studies considered the effect of manifold size and number of ports on pressure drop and flow distribution. The DM-1 and PC15 hydrogen manifolds were compared. The conclusion from this study was that the larger PC15 hydrogen manifold size is more suitable for the DM-2 application than the smaller size manifold. Four inlet ports and three exit ports were selected to insure uniform distribution and a system pressure drop compatible with the selected hydrogen drag pump.

Oxygen flow studies included options for DM-2 with and without an oxygen ejector. It was concluded that oxygen co-flow with the coolant and hydrogen is desirable with or without an oxygen ejector. The oxygen co-flow arrangement puts the inlet ports on the cold side of the cell. With an ejector, co-flow humidifies the inlet oxygen to near equilibrium conditions; without an ejector, oxygen enters where the water vapor partial pressure is the lowest, thus providing the lowest driving force for local evaporation and drying.

Pressure drop variations were evaluated for different field coverages and inlet and exit port arrangements. The conclusion is that since the inlet port-pressure drop is a small fraction of the cell pressure drop, pressure drop and flow distribution are relatively insensitive to the number of inlet ports, and that using a large number of inlet ports makes the distribution insensitive to inlet port plugging. The selected oxygen port configuration is 11 inlet ports. The maximum number of ports was selected consistent with port spacing for the Unitized Electrode Assembly frame support and consistent with manifold length. Two exit ports were selected to insure good distribution when an oxygen ejector is not used. Using only two ports at the exit limits the possibility of backflow into the cell thus providing a more uniform distribution of inerts between purges. In the unlikely event that an oxygen exit port should become plugged with liquid, the pressure drop required to clear a plugged port

is 0.38 to 0.76 inches water. The purge flow required to clear exit ports is 0.4 to 1.0 pph/cell. For example, to clear a 70 cell stack would require oxygen flow up to 70 pph. Options for achieving exit port blowout (70 pph purge) were explored. One method is to use an oxygen regulator with adequate capability. Another method is to use a regulator similar to PC15 (Navy DSV fuel cell powerplant) which has a capacity of 51 pph and to allow the system to depressurize during purge. The conclusion is that methods to clear plugged exit ports exist for cells which have adequate cross-pressure tolerance.

Coolant flow studies for alternate cell cooling were conducted. Various port numbers were considered for a manifold size of 1.5 inches x 0.7 inches. The selected port configuration is four inlet and four exit ports because this design provides low cell stack pressure drop and good distribution.

The field, manifold and port configuration selected for the DM-2 is shown in Table III compared to the DM-1 and PC15 plates.

### 4.1.4 Cell Cooling

Thermal studies considered two approaches for cell cooling. One approach used a cooler for every cell and was the one used in the DM-1. The second approach used a cooler for every other cell, which is presently used in the PC15 for the DSV program. The advantages of every other cell cooling were reduced stack length, reduced weight, reduced coolant inventory and accumulator size, and improved reliability by eliminating one-half the number of coolant seals. The disadvantage was that the electrodes operate at a slightly higher temperature relative to the coolant. A one-dimensional thermal analysis predicted that the electrodes would be only 7°F hotter than the coolant for the every other cell cooling configuration at the 8.5 kw DM-2 condition compared with 3.5°F for the cooling approach on the DM-1. Tests on an instrumented 10-cell rig for the PC15 indicated only 4.5°F at near DM-2 conditions. The slightly higher electrode temperature was factored into the system match conditions for electrolyte concentration control. Every other cell cooling, shown in Figure 15 was selected for the Scheme I because of its weight and reliability advantages.

## 4.2 MULTICELL TESTS

### 4.2.1 Prototype Multicell Stack Test

The objective of the test was to provide early verification of a technology baseline for selection of the Scheme I cell configuration. Significant cell configuration details were as follows:

Separator Plates - 0.508 square feet, gold-plated magnesium plates with DM-1 pin size and support area (hardware procurement lead times precluded using the increased support area plates for this stack) oxygen counterflow to the hydrogen and coolant

Substrate - 0.005 inch diameter unannealed nickel wire, 100 mesh screen, gold-plated (0.005 inch diameter wire was used in conjunction with the DM-1 type coolant plates to provide structural characteristics equivalent to the selected Scheme I configuration.)

# TABLE III

## DM-2 CELL SEPARATOR PLATE DESIGN DESCRIPTION

## COMPARISON OF DM-2 AND DM-1 FLOW FIELDS, MANIFOLDS AND PORTS

$H_2$ in    $H_2$ out

$C_{in}$    C out

$O_2$ in    $O_2$ out
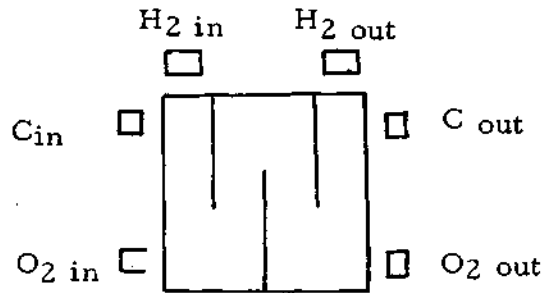
|  | DM-2 | DM-1 | PC15 (for info) |
|---|---|---|---|
| **HYDROGEN** | | | |
| MANIFOLD LXW | 2"x1" | 1.1"x0.45" | 2"x1" |
| NUMBER OF INLET PORTS | 4 | 8 | 3 |
| NUMBER OF EXIT PORTS | 3 | 3 | 3 |
| PORT/FIELD DEPTH | 0.050" | 0.060" | 0.050" |
| PIN SIZE COVERAGE | 0.055" (13%) | 0.048" (10%) | 0.055" (13%) |
| **OXYGEN** | | | |
| MANIFOLD LXW | 1.5"x0.5" | 1.1"x0.45" | 1.5"x0.5" |
| NUMBER OF INLET PORTS | 11 | 5 | 5 |
| NUMBER OF EXIT PORTS | 2 | 2 | 2 |
| PORT/FIELD DEPTH | 0.050" | 0.060" | 0.050" |
| PIN SIZE (COVERAGE) | 0.073" (23%) | 0.048" (10%) | 0.055" (13%) |
| **COOLANT** | | | |
| MANIFOLD LXW | 1.5"x0.7" | 1.1"x0.45" | 1.5"x0.7" |
| NUMBER OF INLET PORTS | 4 | 5 | 2 |
| NUMBER OF EXIT PORTS | 4 | 2 | 2 |
| PORT/FIELD DEPTH | 0.034" | 0.040" | 0.034" |
| PIN SIZE COVERAGE | 0.055" (13%) | 0.0525" (12%) | 0.055" (13%) |

Figure 15 - Scheme 1 Cell Assembly Schematic Showing
Alternate Cell Cooling Concept

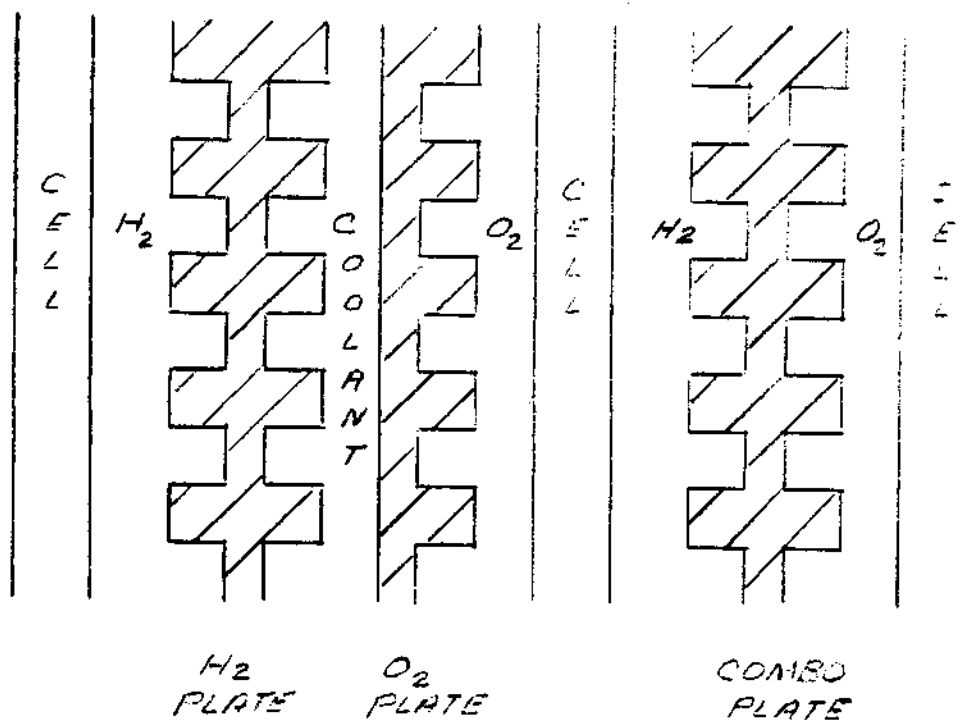Catalyst - 90 percent platinum, 10 percent palladium, transferred to both sides of the substrate at a loading of 12 mg/cm$^2$.

Matrix - 0.020 inch thick RAM

Frame - Glass fiber, epoxy impregnated

Electrolyte Reservoir Plate - 0.100 inch thick sintered-nickel (same as DM-1) with flow field pins located to align with the pins of the oxygen side separator plate.

Cell Active Area - 0.508 square feet

Cell Cooling - One cooler per two cells

Testing was begun on February 2, 1972 and, after a brief test period, the stack was shut down to replace the stand coolant fluid with FC-40 to provide a pressure drop through the stack more representative of an operating powerplant.

Following initial calibration and diagnostic tests, the prototype stack was put on endurance at 50 amps and 175°F coolant inlet temperature. Performance calibration and diagnostic tests were conducted at 500-hour intervals throughout the test.

At approximately 8000 hours, the open circuit voltage of cell No. 1 was found to be approximately 30 mv below average, and was believed caused by carbonate buildup. A saturator was installed in the oxygen system; the oxygen dew point was set to simulate an oxygen ejector and the open circuit voltage of cell No. 1 slowly improved. Within 500 hours, the open circuit voltage of cell No. 1 was within 5 mv of the average. Cell No. 2 exhibited a similar behavior at approximately 9200 hours.

At approximately 10,200 hours, the 50 amp performance level started to show an increasing drop-off rate. The 10,500-hour calibration showed Tafel slope to be normal, and the performance level of all cells at approximately 0.898 volts, down from 0.915 volts at 10,000 hours. After the calibration data high separate load points were taken, one cell, No. 5, would not hold a load without the voltage falling off. The test was terminated on 26 April 1973 at 10,497 load hours. The performance curves show the increasing rate of performance loss typically associated with the end of useful load bearing capability because of carbonate build-up in the electrolyte.

A log of the endurance test is shown in Figure 16. The performance increase, indicated in this figure at 10,150 hours load time, was caused by putting the stack on load after a nitrogen/oxygen diagnostic test without purging all the nitrogen out of the oxygen system. This polarized the cathodes and resulted in a performance increase when clean oxygen was reintroduced to the system. The phenomenon has been observed before on this (at approximately 8000 hours) and other stacks and is under investigation. The performance calibrations, which were conducted at 500-hour intervals, are presented in Figure 17. Figure 18 shows

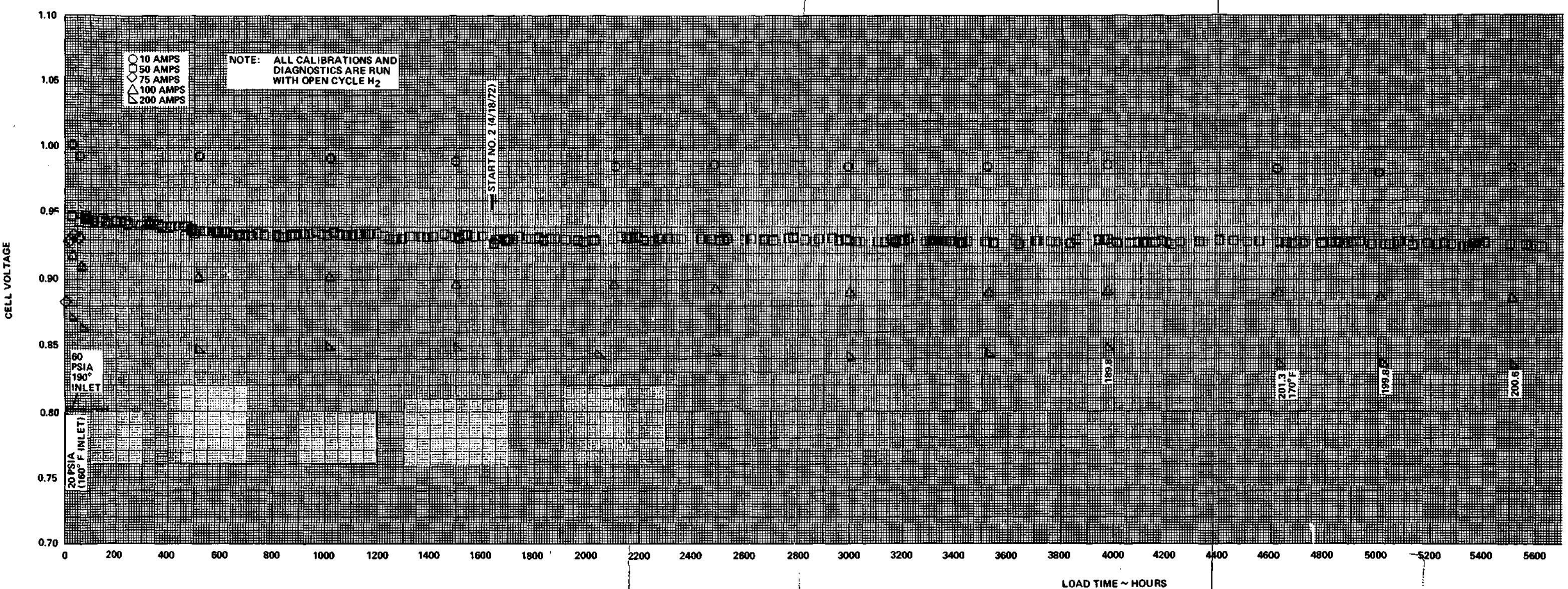Figure 16 - 6-Cell Prototype Stack Test Endurance Log

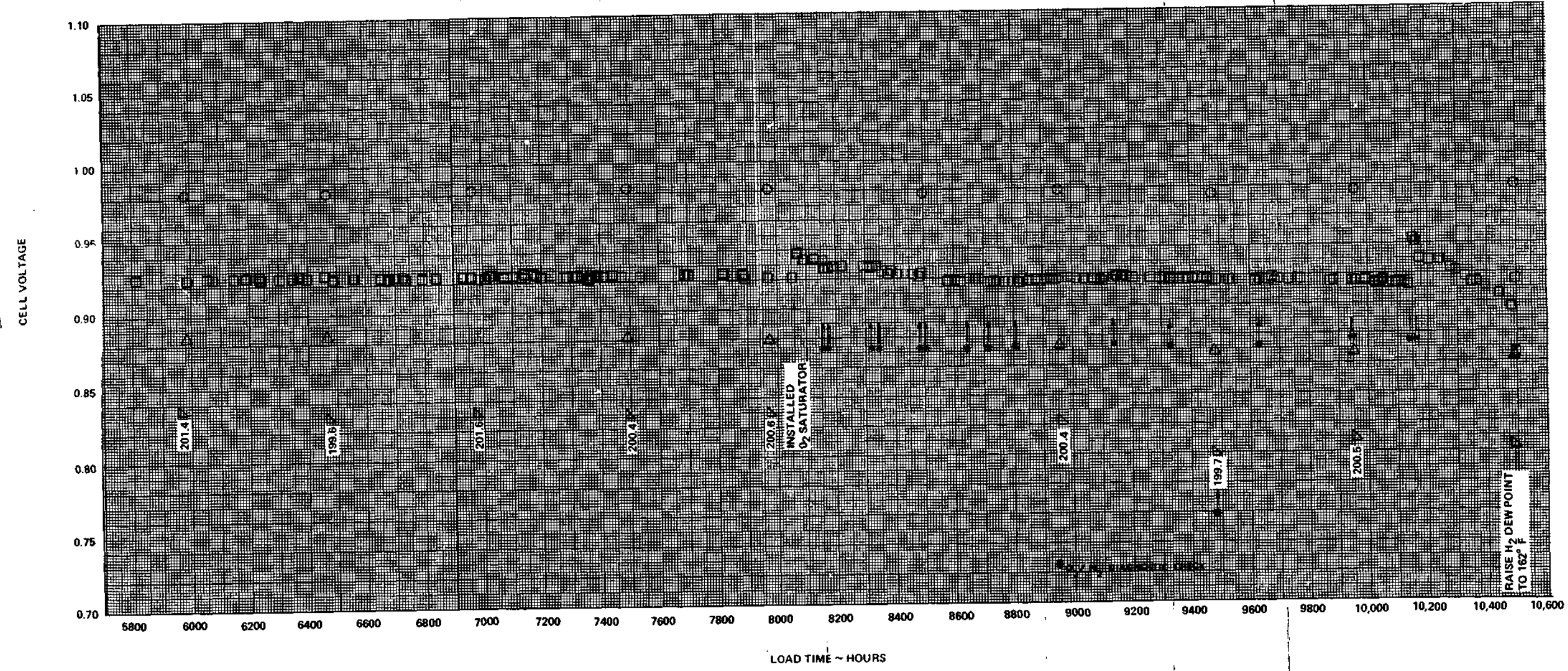Figure 16 - 6-Cell Prototype Stack Test Endurance Log (Cont.)
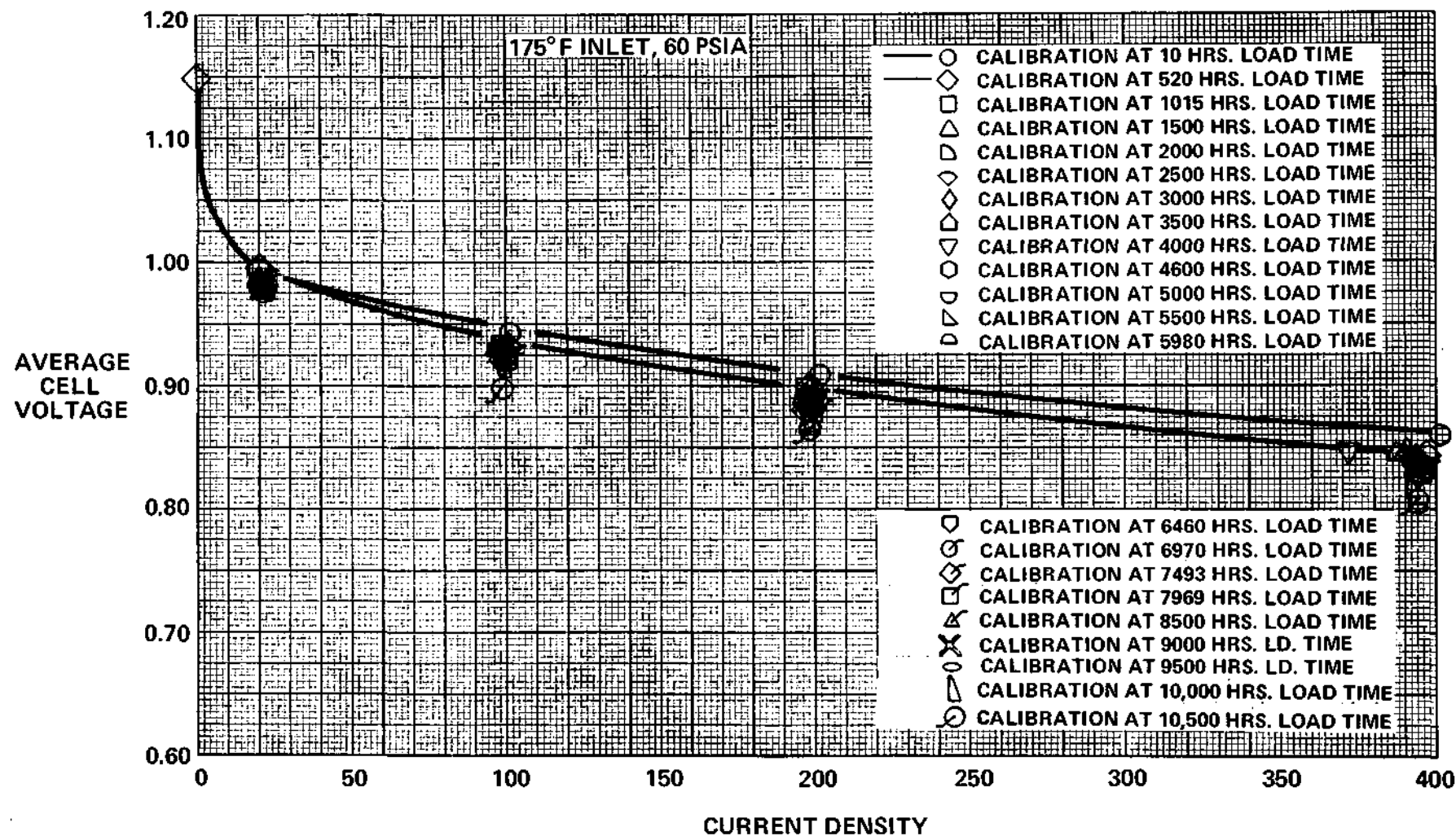
Figure 17 - 6-Cell Prototype Stack Test 500-Hour Performance Calibration

175°F
32%
DATA CORRECTED FOR IR

CELL VOLTAGE

CURRENT DENSITY ~ ASF

□ AVERAGE CELL, 2/11/72 @ 1347, 97 LD. HRS, IR @ 100 ASF = 13.15 MV
○ AVERAGE CELL, 3/1/72 @        , 535 LD. HRS, IR @ 100 ASF = 15.4 MV
◇ AVERAGE CELL, 3/22/72 @ 1440, 1042 LD. HRS, IR @ 100 ASF = 14.6 MV
△ AVERAGE CELL, 4/11/72 @ 0853, 1500 LD. HRS, IR @ 100 ASF = 16.25 MV
▽ AVERAGE CELL, 5/5/72 @ 1502, 2041 LD. HRS, IR @ 100 ASF = 17.5 MV
◊ AVERAGE CELL, 5/24/72 @ 1536, 2497 LD. HRS, IR @ 100 ASF = 14.75 MV
△ AVERAGE CELL, 6/14/72 @ 1531, 2994 LD. HRS, IR @ 100 ASF = 14.70 MV
○ AVERAGE CELL, 7/6/72 @ 1620, 3526 LD. HRS, IR @ 100 ASF = 15.2 MV
○ AVERAGE CELL, 7/25/72 @ 1554, 3983 LD. HRS, IR @ 100 ASF = 13.75 MV
▷ AVERAGE CELL, 8/21/72 @ 1602, 4626 LD. HRS, IR @ 100 ASF = 12.45 MV
▷ AVERAGE CELL, 9/6/72 @ 0726, 5000 LD. HRS, IR @ 100 ASF = 14.1 MV
○ AVERAGE CELL, 9/27/72 @ 1443, 5508 LD. HRS, IR @ 100 ASF = 14.3 MV
◊ AVERAGE CELL, 10/17/72 @ 1417, 5988 LD. HRS, IR @ 100 ASF = 15.7 MV
● AVERAGE CELL, 11/6/72 @ 1502, 6468 LD. HRS, IR @ 100 ASF = 13.9 MV
◨ AVERAGE CELL, 11/27/72 @ 1730, 6973 LD. HRS, IR @ 100 ASF = 12.8 MV
◈ AVERAGE CELL, 12/19/72 @ 1532. 7497 LD. HRS, IR @ 100 ASF = 13.9 MV
◈ AVERAGE CELL, 1/8/73 @ 1502, 7976 LD. HRS, IR @ 100 ASF = 13.9 MV
◁ AVERAGE CELL, 1/30/73 @ 1433, 8480 LD. HRS, IR @ 100 ASF = 16.5 MV
◑ AVERAGE CELL, 2/17/73 @ 8953 LD. HRS., IR @ 100 ASF = 18.0 MV

▽ AVERAGE CELL, 3/13/73 @ 1535, 9476 L.H. IR @ 100 ASF = 16.3 MV
◹ AVERAGE CELL, 4/2/73 @ 1400, 9950 LD. HRS., IR @ 100 ASF = 18.1 MV
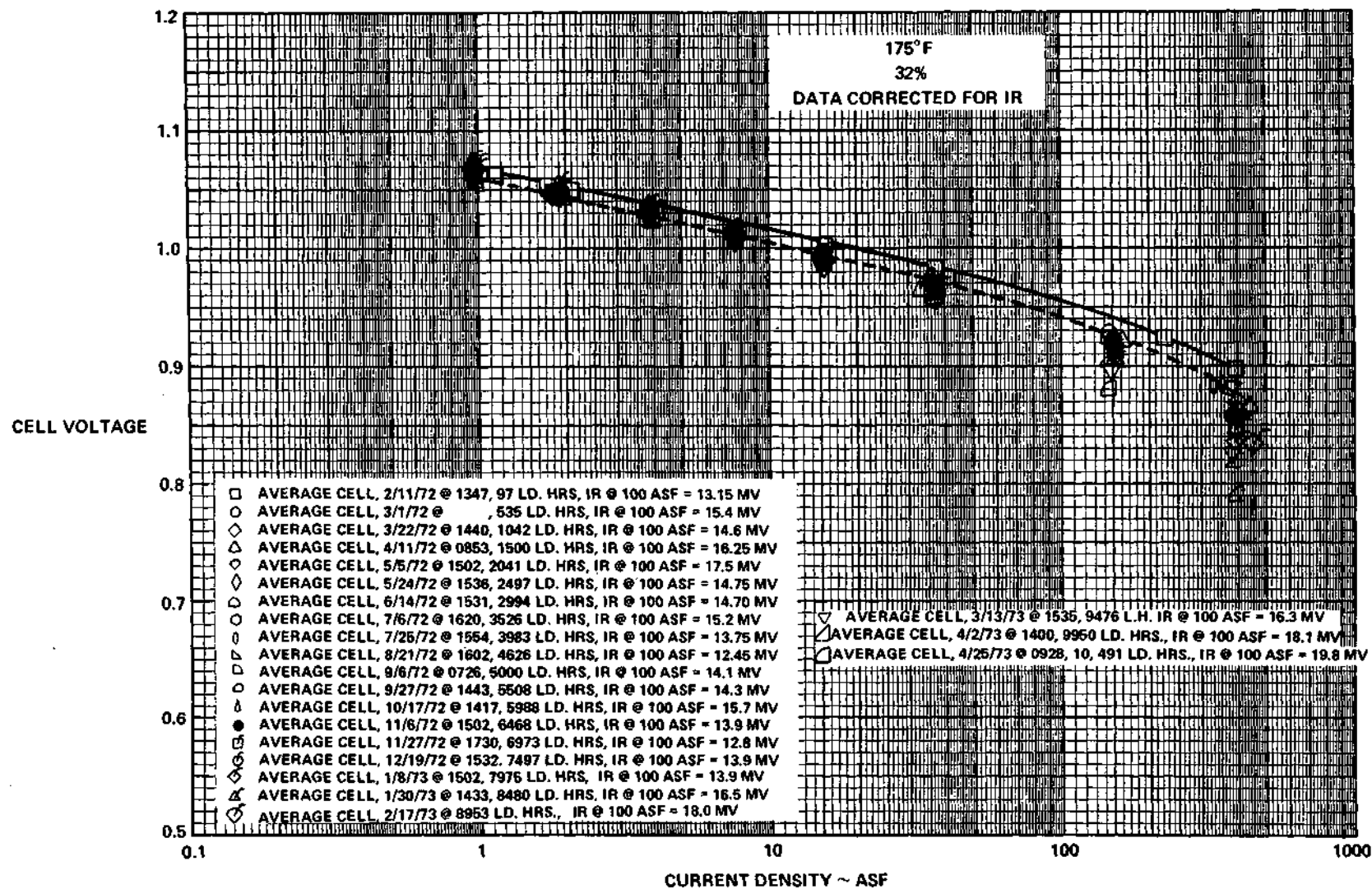◖ AVERAGE CELL, 4/25/73 @ 0928, 10, 491 LD. HRS., IR @ 100 ASF = 19.8 MV

Figure 18 - 6-Cell Prototype Stack Test Tafel Data Corrected for IR Polarization Loss

the average Tafel data corrected for IR polarization losses. No reactant gas crossover nor cell shorting is evident on any cell. Although the test objective was satisfied at 2000 hours of endurance time, the test was continued to establish the performance characteristics associated with endurance testing up to and beyond the 5000-hour Space Shuttle requirement.

4.2.2    Scheme I Multicell Test

The Scheme I multicell test was conducted to verify the cell configuration selected for the DM-2 powerplant. The test was scheduled to provide at least 1000 hours of endurance time prior to commitment for procuring the DM-2 powerplant cells. Significant Scheme I cell configuration details were as follows:

Electrode Substrate - 0.0025 inch diameter unannealed nickel wire, 100 mesh screen, gold-plated

Catalyst - 90 percent platinum, 10 percent palladium transferred to one side of the substrate at 10 mg/cm$^2$ loading

Matrix - 0.020 inch thick RAM

Frame - Glass fiber, epoxy impregnated

Electrolyte Reservoir Plate - 0.062 inch thick sintered nickel (same as the PC15) with flow field pins located to align with pins of the oxygen side separator plate

Separator Plates - 0.508 square feet, gold-plated magnesium plates with increased oxygen side pin size and support area. Oxygen co-flow with the hydrogen and coolant.

Cell Active Area - 0.508 square feet

Cell Cooling - One cooler per two cells

The Scheme I endurance stack test was preceded by a manufacturing checkout stack test of six Scheme I cells conducted to verify stand functions, operating procedures, and cell integrity. The cells were subjected to 45 psi hydrogen above oxygen and coolant pressure and 45 psi oxygen above hydrogen and coolant pressure. Nominal pressures were then reestablished. Stack performance before and after the pressure excursions was normal. Post-test dimensional inspection of the coolant plate pin impressions on the electrodes showed no depression as a result of the 45 psi cross-pressure indicating that the design criteria of 0.001 inch or less allowable depression had been met. Four hundred load hours were accumulated during these checkout tests.
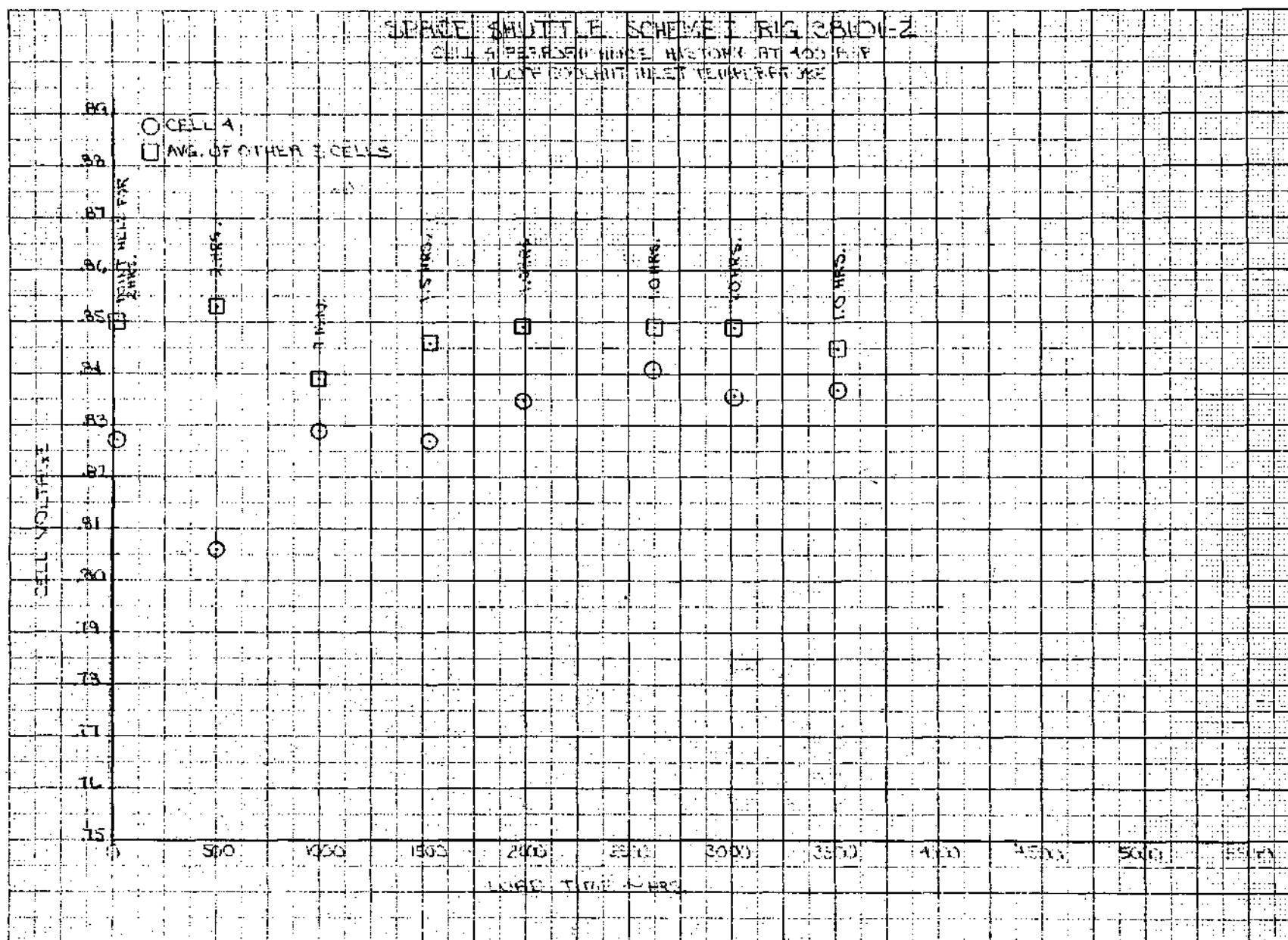
After the checkout tests, the Scheme I endurance stack was installed in the test stand and initial performance calibrations were conducted. Average cell performance compared favorably with the average performance of the prototype stack. However, at the 400-ASF calibration point, cell No. 4 oscillated about 3 mv and was approximately 15 mv below the average of the other five cells. At the 50 amp point, cell No. 4 did not exhibit the oscillating

characteristics and was the highest performing cell operating at 3 mv above the average. The stack was shut down and Cell No. 4 removed for further investigation. A new cell No. 4 was substituted and testing resumed. The replacement cell behaved the same as the original cell with performance slightly above average at the 50 amp point and below the average of the other five at the 200 amp point. It was concluded that this behavior would not affect stack endurance and testing was started at 50 amps and 160°F stack coolant inlet temperature. Diagnostic and performance tests were conducted at 500-hour intervals throughout the test.

The original cell No. 4, which was removed from the stack, was tested as a single cell with initial performance duplicating its performance in the stack. It was found that increasing the pinch on the cell by raising coolant pressure produced excellent 200 amp performance. The conclusion was that its stack performance was the result of low effective pinch probably caused by manufacturing tolerances in the coolant plates and stack hardware.

The performance of cell No. 4 was completely normal during all 50 AMP endurance testing. Its behavior during the 500-hour calibrations gradually improved until at approximately 2500 hours it was normal, as seen in Figure 19. It stayed normal through the remainder of the test.

The endurance test was continued to provide additional performance data associated with long time operation up to and beyond the 5000-hour Space Shuttle requirement. The test was voluntarily terminated at 10,000 hours of endurance load time. A log of the endurance test is shown in Figure 20. Performance of all cells has remained essentially unchanged. Figure 21 presents the performance calibrations conducted at 500-hour intervals. The open circuit and 15 ASF load points were obtained from the Tafel test and are consistent with the normal calibration conditions. Figure 22 shows the average Tafel data corrected for the IR polarization losses. The average cell data is typical of all cells. There has been no change of slope in the 1 ASF to 10 ASF region which means internal cell shorting is not present.
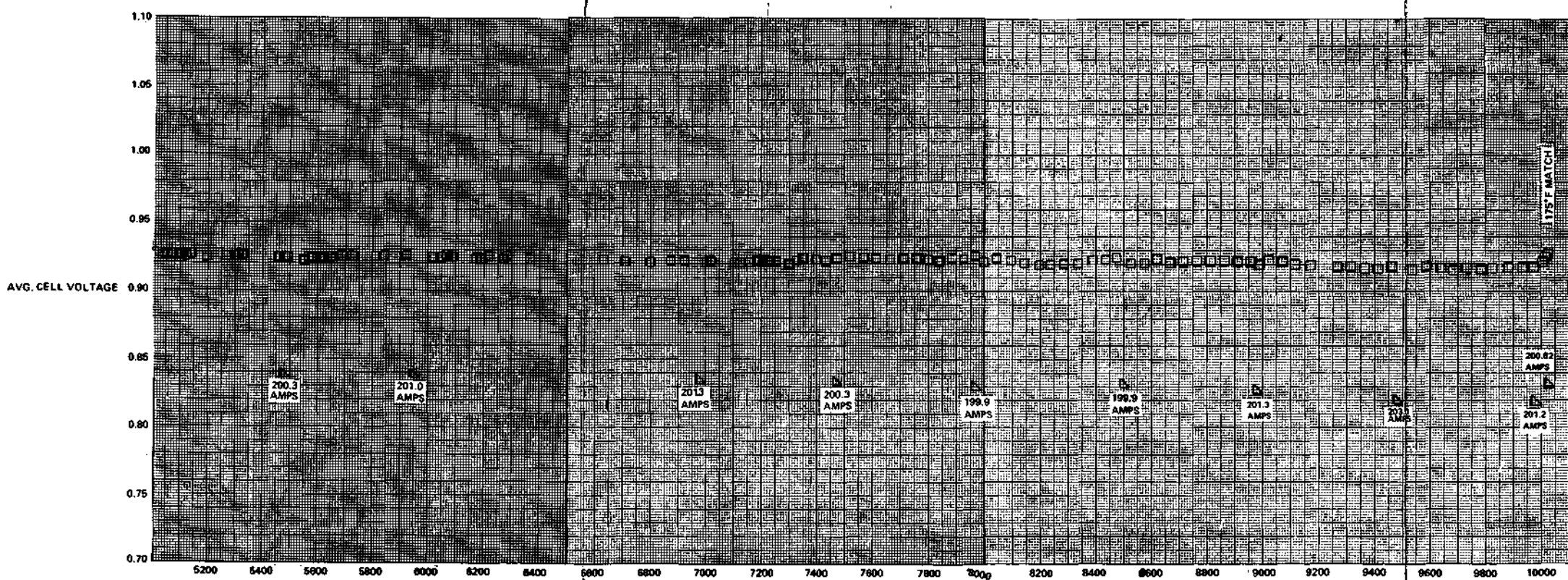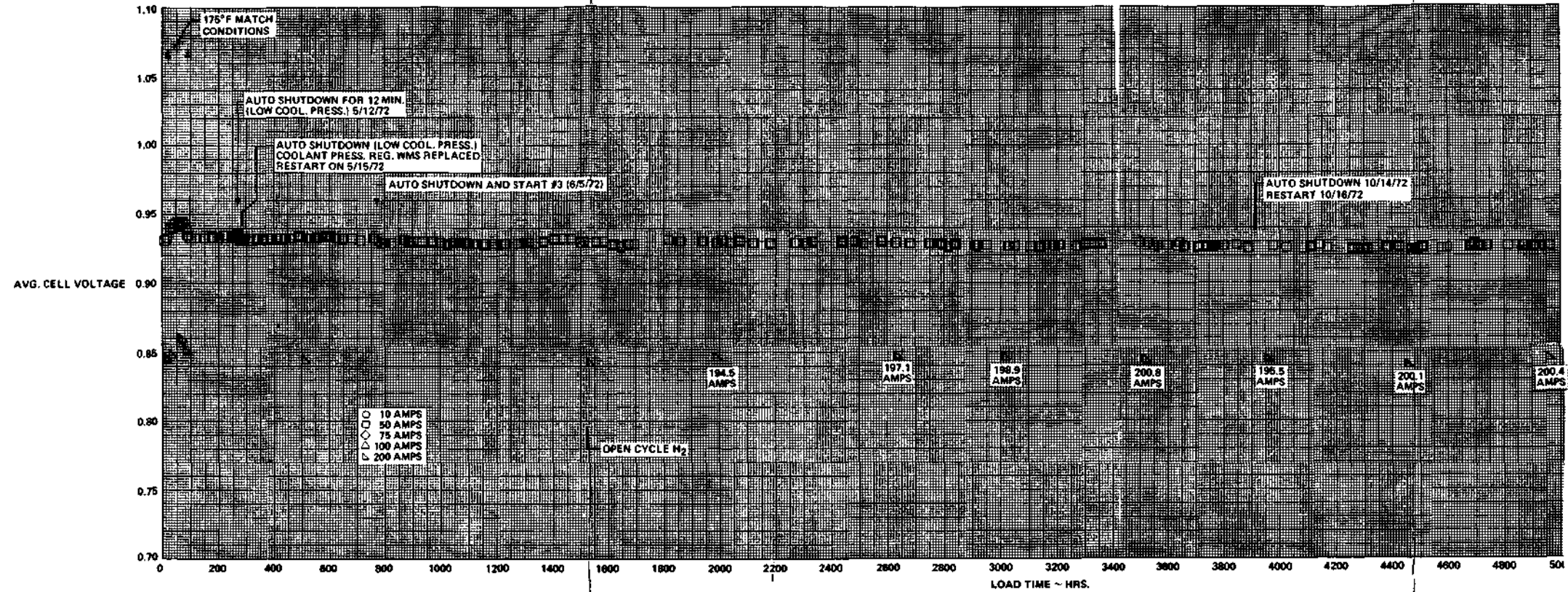
Figure 19 - Cell Number 4 Performance at 400 ASF Compared to Other 5 Cells in 6-Cell Scheme 1 Endurance Stack

Figure 20 - 6-Cell Scheme 1 Endurance Stack
Endurance Log

160°F INLET
60 PSIA

AVERAGE CELL VOLTAGE

CURRENT DENSITY ~ ASF

O CALIBRATION AT 16 HRS. LD. TIME
□ CALIBRATION AT 500 HRS. LD. TIME
◇ CALIBRATION AT 1000 HRS. LD. TIME
△ CALIBRATION AT 1500 HRS. LD. TIME
◁ CALIBRATION AT 2000 HRS. LD. TIME
▷ CALIBRATION AT 2600 HRS. LD. TIME
⊔ CALIBRATION AT 3000 HRS. LD. TIME
▽ CALIBRATION AT 3500 HRS. LD. TIME
◊ CALIBRATION AT 3960 HRS. LD. TIME
○ CALIBRATION AT 4460 HRS. LD. TIME
△ CALIBRATION AT 4964 HRS. LD. TIME
○ CALIBRATION AT 5467 HRS. LD. TIME
◊ CALIBRATION AT 5945 HRS. LD. TIME

▽ CALIBRATION AT 6506 HRS. LD. TIME
◊ CALIBRATION AT 6979 HRS. LD. TIME

⊗ CALIBRATION AT 7470 HRS. LD. TIME
✕ CALIBRATION AT 7969 HRS. LD. TIME
✛ CALIBRATION AT 8495 HRS. LD. TIME
○ CALIBRATION AT 8974 HRS LOAD TIME
□ CALIBRATION AT 9480 HRS LOAD TIME
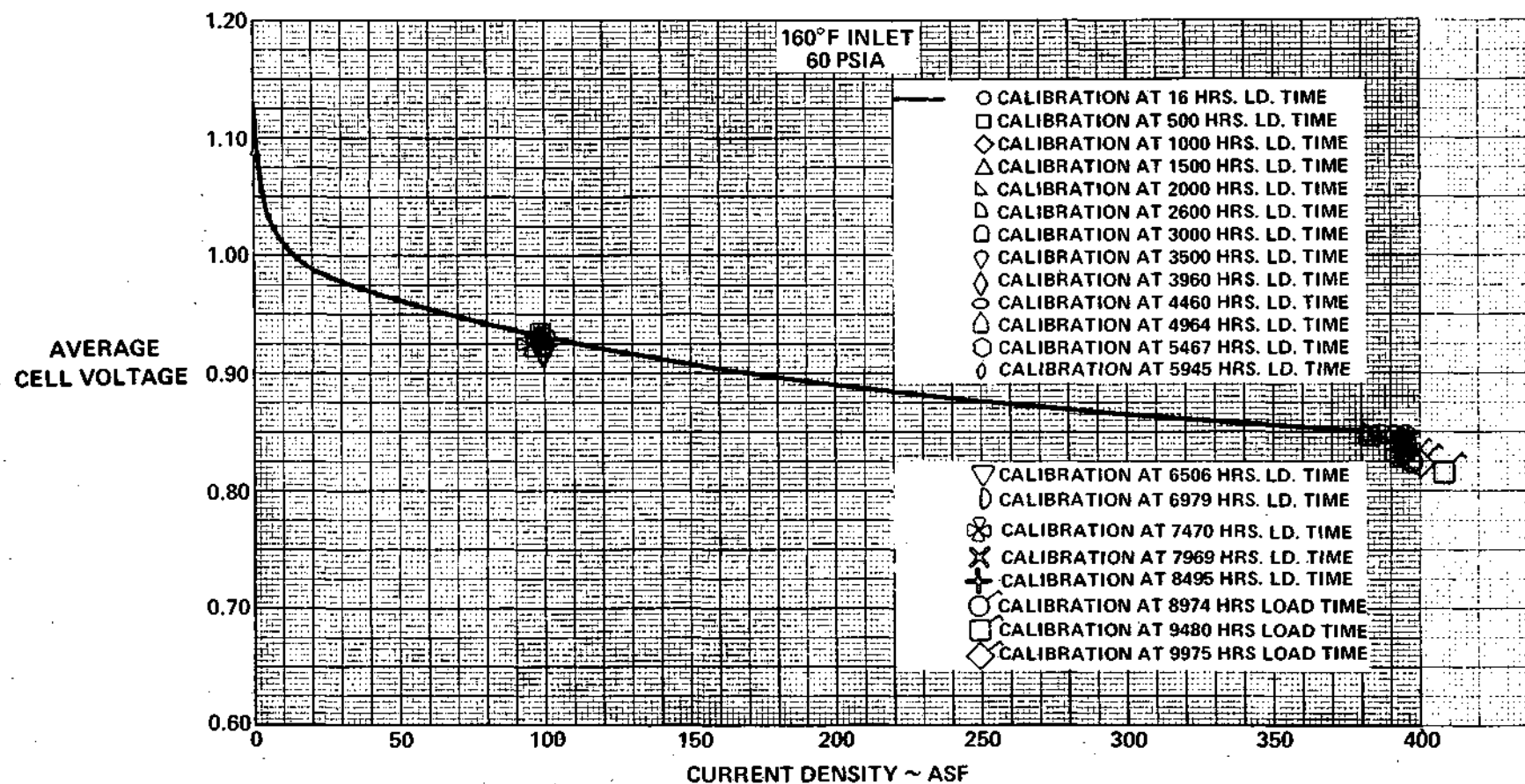◇ CALIBRATION AT 9975 HRS LOAD TIME

Figure 21 - 6-Cell Scheme 1 Stack Test 500-Hour Performance Calibrations
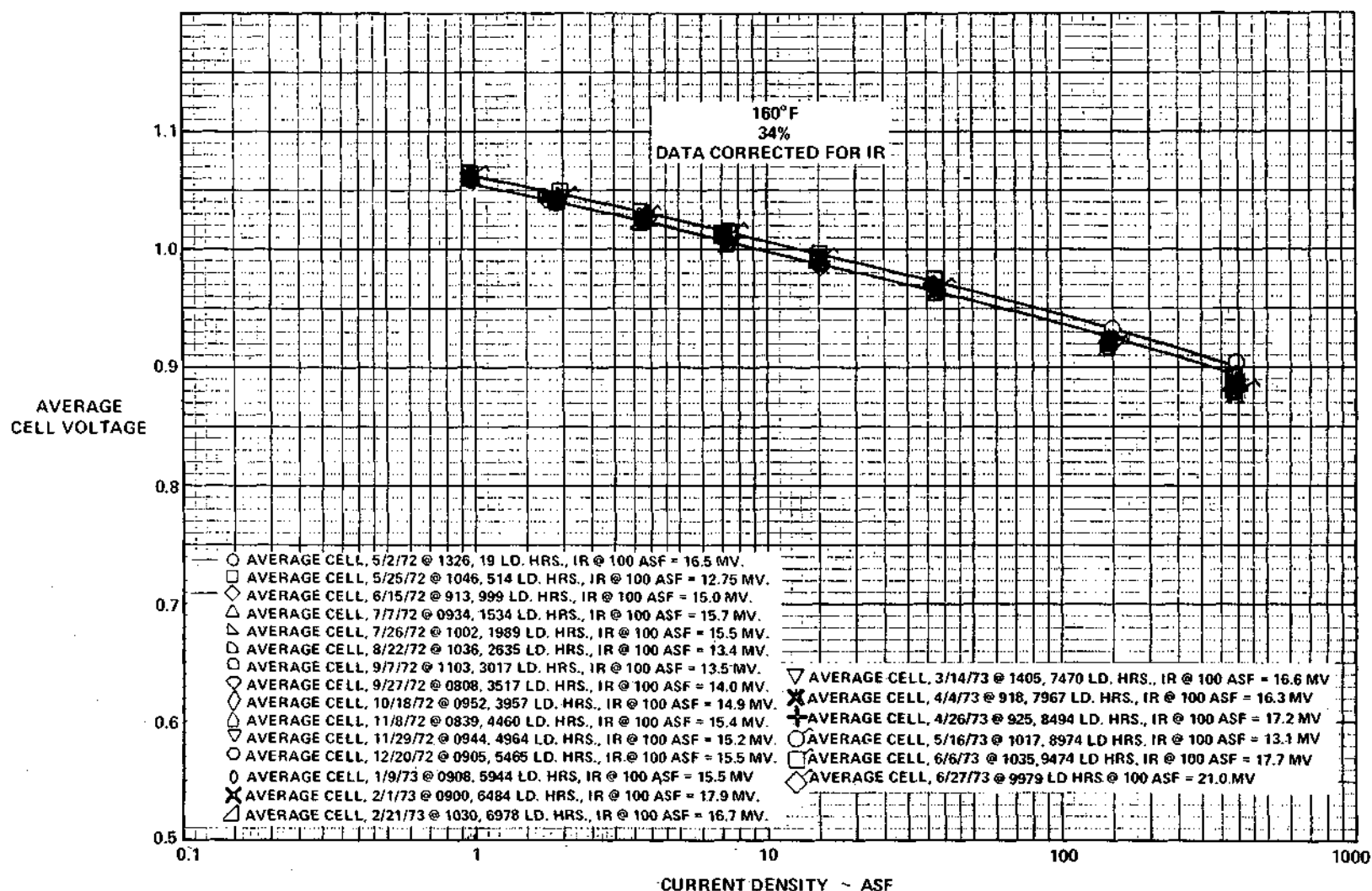
Figure 22 - 6-Cell Scheme 1 Endurance Stack Test Data Corrected for IR Polarization Loss

## 5.0 BASELINE TECHNOLOGY EXTENSION

A Baseline Technology Extension task was established to be conducted concurrently with the other program tasks. The specific goal of this task was the definition and selection of design approaches and materials leading to the design of a cell with a minimum 5000-hour life. Advanced approaches for improved cell life included improved magnesium separator plates and electrode catalysts and substitution of materials with better endurance characteristics such as, nickel coolant plates in place of magnesium and plastic electrode frames in place of fiberglass epoxy. A series of design studies and laboratory tests was planned to complement the baseline fuel cell technology in five areas:

- Improved separator plates

- Improved magnesium separator plates

- Improved electrode catalyst

- Improved cell frames

- Coolant plate spacing

### 5.1 Improved Nickel Separator Plates

Preliminary design studies showed that thin nickel separator plates fabricated by an electroforming process offered the potential of lower cost, lower weight, and a wider choice of compatible coolant fluids compared to magnesium separator plates. Structural analysis also showed the feasibility of obtaining the required strength and stiffness in electroformed plates as thin as 0.003 inches.

Effort to develop a nickel coolant plate was initiated in 1971. A plexiglass master was constructed from which electroformed nickel sheets with integral pin field, seal grooves, and manifolds were formed. Two of these formed sheets welded together formed a cooler assembly with a hydrogen field on one side, an oxygen field on the other side, and a coolant cavity in the middle. Difficulty was encountered in consistently welding the two halves together into a pressure tight assembly. Also, the welding process annealed the nickel plates in the heat affected zone reducing strength of the assembly. Other methods of assembling the two halves together such as with elastomer seals, adhesives and brazing were considered, but discarded as being too costly to develop within the scope of the program.

This led to the approach of unitizing two nickel pin field pieces in a fiberglass epoxy frame in the same manner in which the cell assemblies are unitized. This was considered feasible since the unitizing technology was well established. Manufacturing trials for this approach were carried out with no particular difficulty. One of the assemblies was heat cycled and found to be leak tight. Seal groove and port machining trials were conducted on the fiberglass frames and indicated that this was an acceptable manufacturing method.

Based on the results of this activity, design of a fiberglass unitized nickel coolant plate to meet Space Shuttle requirements was started. Structural, thermal and flow studies were conducted and a configuration was selected. Figure 23 shows the hydrogen/oxygen combination plate and the coolant assembly design which resulted.

As part of this program, strength and deflection tests and porosity tests of electroformed nickel samples of various thicknesses were conducted. The strength and deflection tests indicated that formed sheets as thin as 0.0035 inch satisfied the strength requirements. Initial porosity testing resulted in a high percentage of the samples showing leaks. Review of the results with the plating vendor defined plating process and tooling changes. At the end of the contract period, some improvement had been realized and other plating process and mold release changes had been identified which would produce non-porous parts.

A comparison was made between DM-2 magnesium separator plates and the final design nickel plates using a 4-mil thick nickel-field piece. The following table shows a detailed comparison with regard to plate weight, plate height, and hydrogen and coolant cavity pressure drops:

|  | DM-2 Magnesium Plates | 4 Mil Electroformed Nickel |
|---|---|---|
| Combination Hydrogen/ Oxygen Plate | 0.69 lbs. 0.12 inch height | 0.4 lbs. 0.064 inches |
| Cooler Assembly | 1.06 lbs. 0.174 inches | 0.78 lbs. 0.128 inches |
| Pressure Drop (Hydrogen cavity) | 5.3 inches water | 5.3 inches water (50-mil ports) 5.8 inches water (40-mil ports) |
| Pressure Drop (Cooler, 2 cells per cooler flow rate) | 0.7 psi | 0.56 psi |

A DM-2 stack with 4-mil nickel separator plates would be approximately 10 pounds lighter and 1 7/8 inches shorter.

## 5.2 Improved Magnesium Separator Plates

Improved magnesium separator plates offered the potential of reduced cost through a decrease in manufacturing lead time, simplification of fabrication procedures, and a reduction in scrap rates resulting from closer control of manufacturing tolerances. Four separate lines of investigation were pursued to improve plate configuration and fabrication techniques. The first of these was concerned with a revision to the purchase specification for the magnesium raw material. Experience had shown that inclusions in the base metal have an adverse effect on the
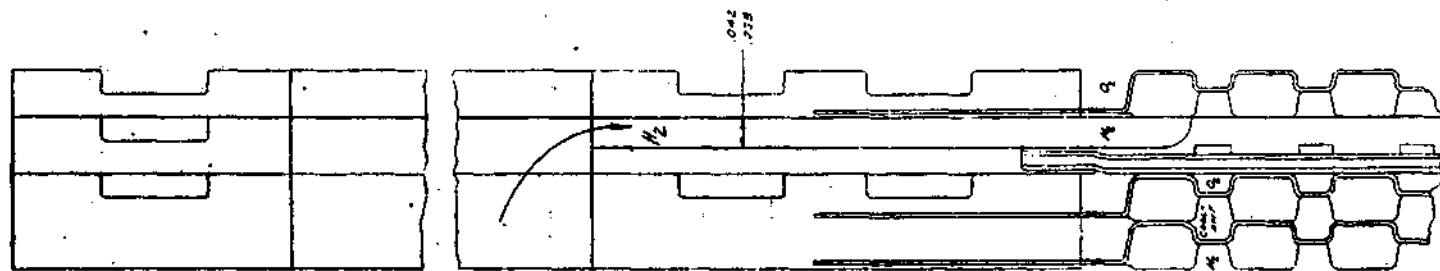
Section Through Hydrogen Manifold
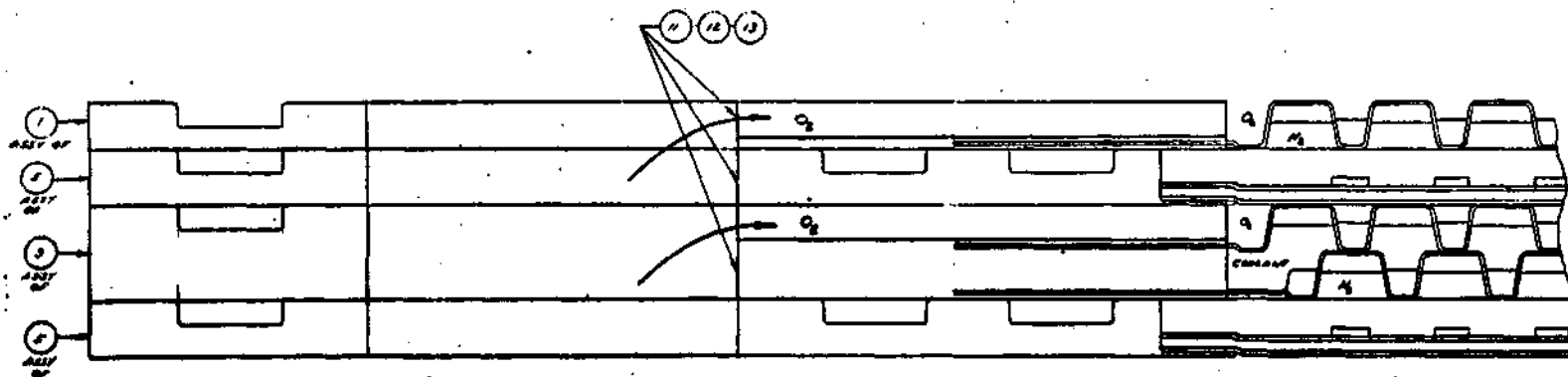
Section Through Oxygen Manifold
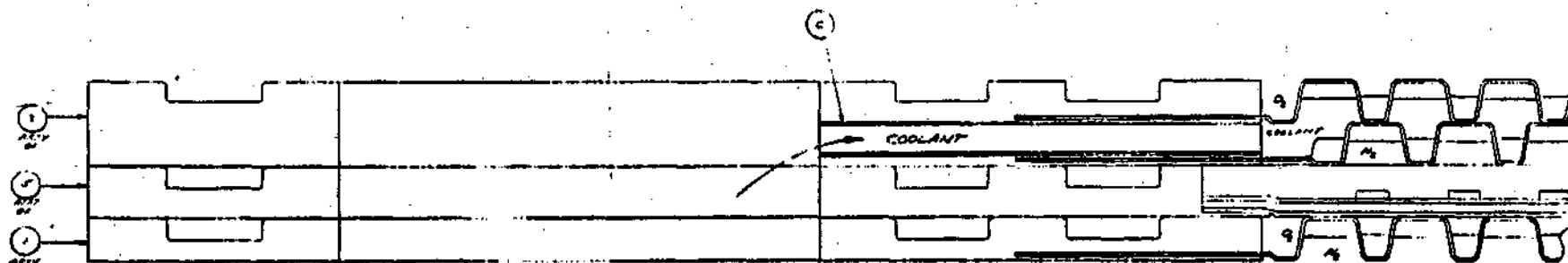
Section Through Coolant Manifold

Figure 23 - Hydrogen/Oxygen Combination Plate and Coolant Assembly

protective plating applied to the plates, thus a more stringent level of allowed agglomerated inclusions in the magnesium sheet was required. The second item was the use of seals installed into the plates rather than molded-in-place seals to eliminate a manufacturing step and reduce handling of the plates. A third area to be investigated was the machining rather than the chemical milling of the pin fields. This step would be performed at the same time as the machining of the seal grooves and fluid ports, eliminating another manufacturing step. An anticipated advantage of this approach was the potential to maintain closer control of pin size, height, and location and a corresponding decrease in scrap rate during plate fabrication. The fourth area to be investigated was the use of a protective gold-plating thinner than the Scheme I baseline to gain savings in both weight and cost.

The raw material purchase specification was revised to call for a maximum allowable limit of 0.25 percent non-metallics compared to 0.4 percent in the previous specification. Material samples and sheet stock were successfully produced to the revised specification by the vendor.

The baseline magnesium separator plate configuration has elastomer seals which are molded in place in the finished plate by a seal supplier. In this task, pre-molded seals were installed in magnesium plates and were tested. Initial test results with these seals showed they were sensitive to out-of-tolerance seal grooves in the magnesium plates. The molded-in-place seals did not leak under similar conditions because the molding process compensated for the groove variations. Additional testing showed that when the seal grooves were maintained within tolerance and the seals were installed with a supplier-recommended adhesive no leakage was experienced. This seal approach was subsequently used in the Pratt & Whitney Aircraft in-house demonstrator powerplant with excellent results.

Manufacturing trials were conducted for machining the flow fields in the plates by a tape controlled machining process. The process was found to be simpler, less costly, with a shorter manufacturing lead time and resulted in closer control of pin size and location. The scrap rate on the first lot of plates to be machined was found to be 10 percent compared to 20 percent for the chemical milling method normally used. Plates manufactured by this method were also used in the Pratt & Whitney Aircraft in-house demonstrator powerplant with excellent results.

The gold-plating, which was incorporated in the Scheme I baseline design, was 0.0004 inch thick. Samples of magnesium with plating 10 percent and 50 percent as thick as the baseline were prepared and subjected to corrosion and contact resistance testing. As expected, resistance checks showed a slightly lower voltage drop. Corrosion testing in a 42 percent KOH solution at $250°F$ showed no effect on the 50 percent thick plating, but caused blistering and peeling of the 10 percent sample. It was concluded from this testing that 0.0002 inch thick gold-plating can be used in the Space Shuttle fuel cell powerplant.

## 5.3 Improved Electrode Catalyst

The objective of this task was to develop an outside source for the manufacture of the gold/ platinum cathode catalyst developed in the Pratt & Whitney Aircraft laboratories and to reduce to shop practice the catalyst application procedures used in the laboratory. In addition, full sized cells were to be fabricated and tested.

Procurement requirements for the catalyst were prepared and a number of potential suppliers were contacted. Samples of the catalyst for evaluation were received from three suppliers. One supplier's initial sample (50 grams) gave surface area results consistent with those of in-house laboratory-prepared catalyst, and laboratory performance testing indicated that catalyst activity was equivalent. An endurance test of a sub-scale electrode made from this catalyst was performed for a 1000-hour period at 200 ASF with results equivalent to those of electrodes made from in-house catalyst. On the basis of these results, a larger batch (150 grams) of this vendor's gold-platinum catalyst was procured and was used to make cathodes for four cells of a full-size, six-cell checkout stack. This stack used improved magnesium separator plates and Scheme I unitized electrode assemblies with two differences; the cathode catalyst was gold/platinum instead of platinum/palladium and the ERP was 0.051 inch thick instead of 0.062 inches. Four of the six cells (Nos. 1, 2, 3 and 4) had the vendor-supplied catalyst and two (Nos. 5 and 6) had Pratt & Whitney Aircraft supplied catalyst. This was done to offer a direct comparison of the two catalysts.

The stack started test on 2 April 1973 and completed the initial performance calibration and acceptance test. On 25 April 1973, the 500-hour calibration was performed. This calibration consisted of an IR test, Tafel test, 40-ASF performance, 400-ASF performance and 700-ASF performance. During the 700-ASF performance point, a test stand problem occurred and water was carried over from the hydrogen saturator into the stack. When operating at the 700-ASF load point, the hydrogen flow was 2.04 pph and the dew point was 174°F as opposed to a 0.54 pph flow and 166°F dew point when operating at the 40 and 400-ASF load points. A hydrogen saturator flow rate of 1.5 pph was established as a maximum for a stable operation. This corresponds to the flow rate needed for a 4-cell stack at the current densities presently being run. The stack was refilled, Cell Nos. 3 and 4 were removed, and returned to test as a four-cell unit. The test was continued to 1500 hours at which time the stack was shut down because of low performance.

Figures 24 through 28 present performance data taken from acceptance calibration to the 1500 hour calibration. Figure 24 presents the performance calibrations taken during the test. Figure 25 shows the average Tafel data corrected for IR polarization losses. Figure 26 shows the individual cell performances by position in the stack. Figure 27 shows the tolerance of each of the cells to changes in dew point during acceptance calibration. Figure 28 presents a log of the endurance test.

## 5.4  Improved Cell Frames

The objective of this task was to develop unitized electrode assembly frames that do not contribute to carbonate formation in the cell electrolyte. Filled Teflon materials were identified as candidates for the fabrication of improved cell frames which would result in a lower rate of carbonate formation in the cell electrolyte than in the glass fiber-epoxy frames. Synthetic mica-filled and potassium-titanate-filled material samples were obtained and tests conducted to define compressive load deflection, tensile strength, load cycling effects, thermal expansion and compressive creep characteristics. Compatibility of sample materials with KOH, moisture, and cell temperature were determined in corrosion tests and bonding trials were conducted to establish techniques for joining the edge frame to other cell components.
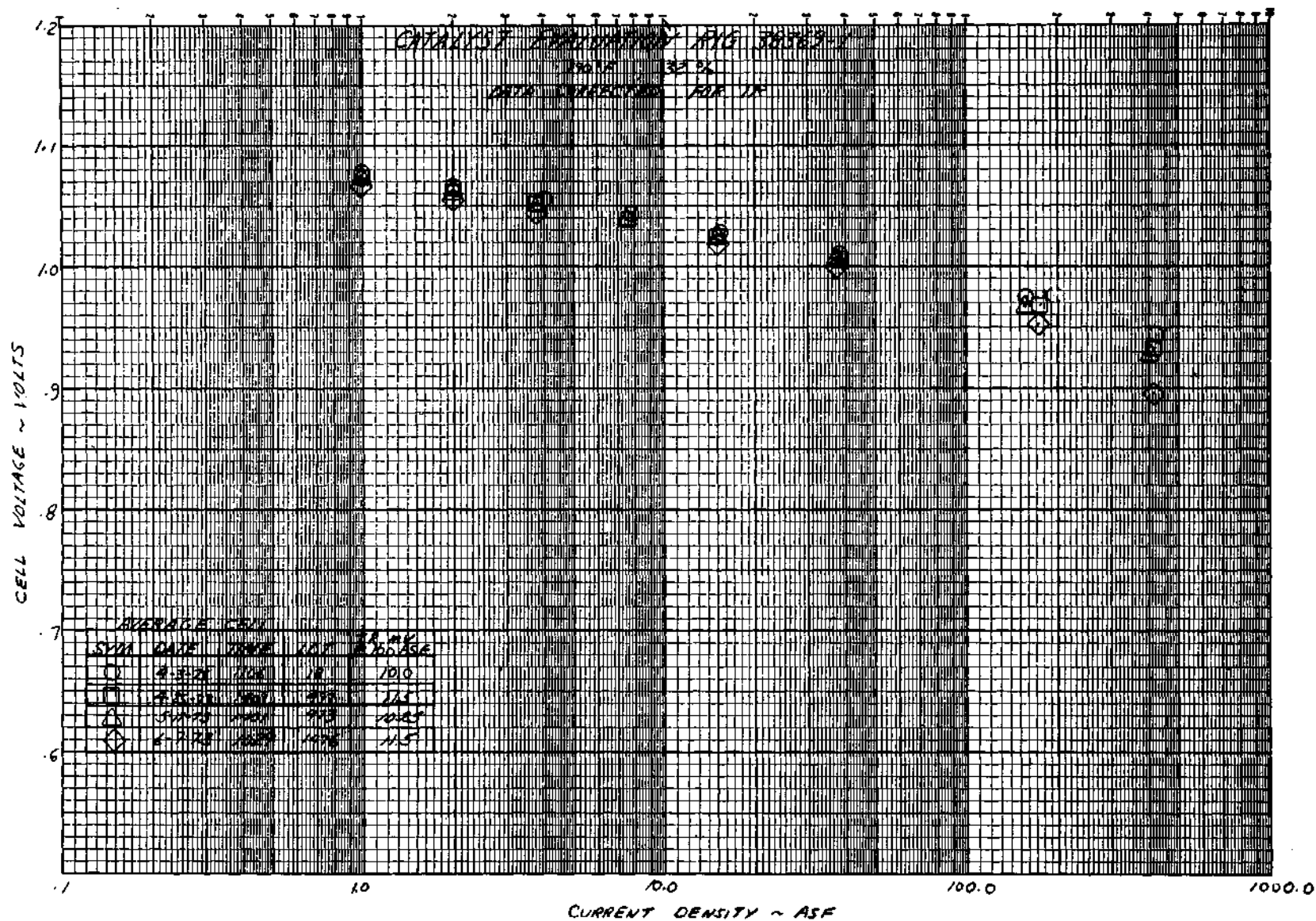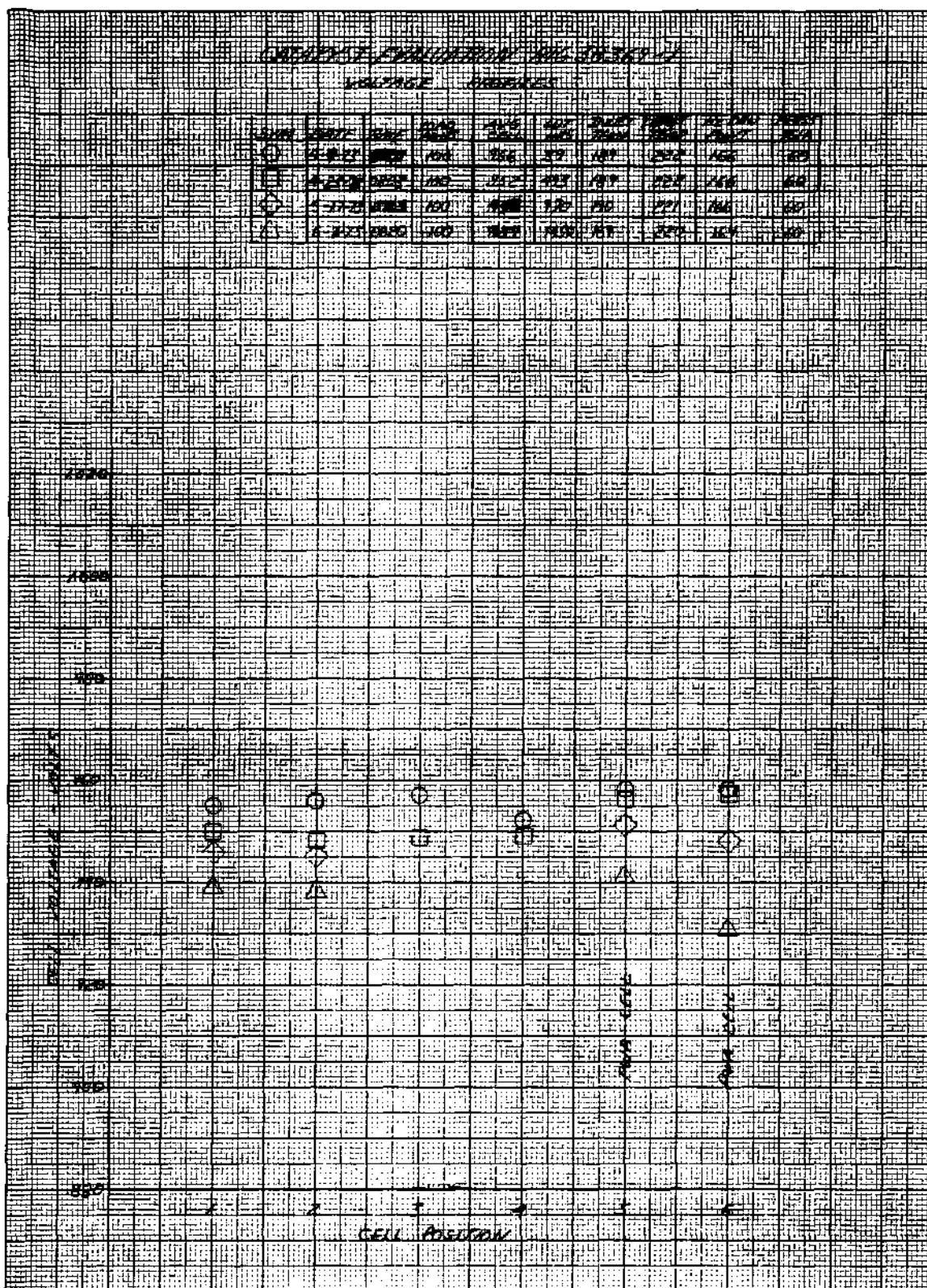
Figure 24 - Electrode Catalyst Performance Calibration
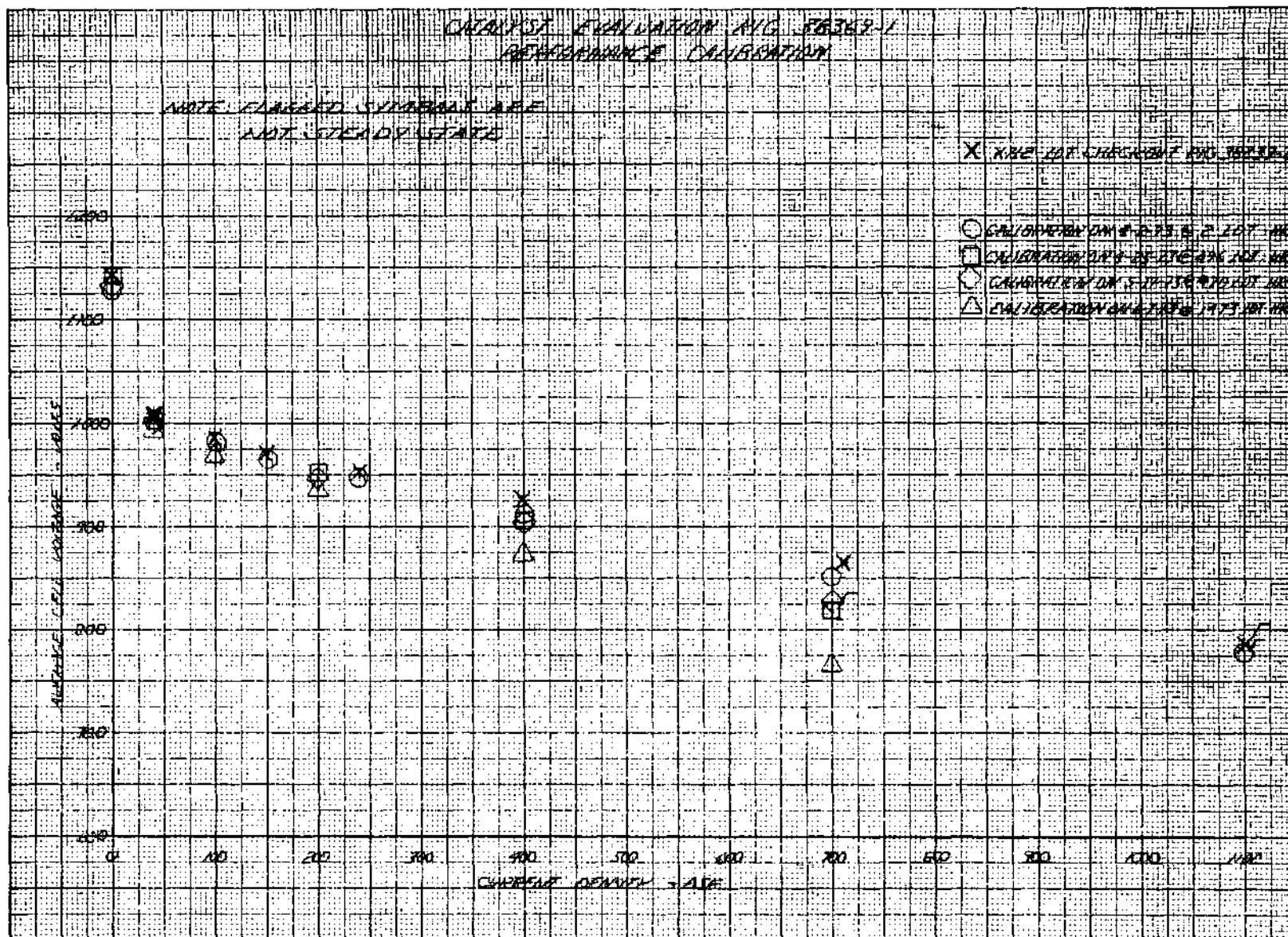
Figure 25 - Electrode Catalyst Data Corrected for IR
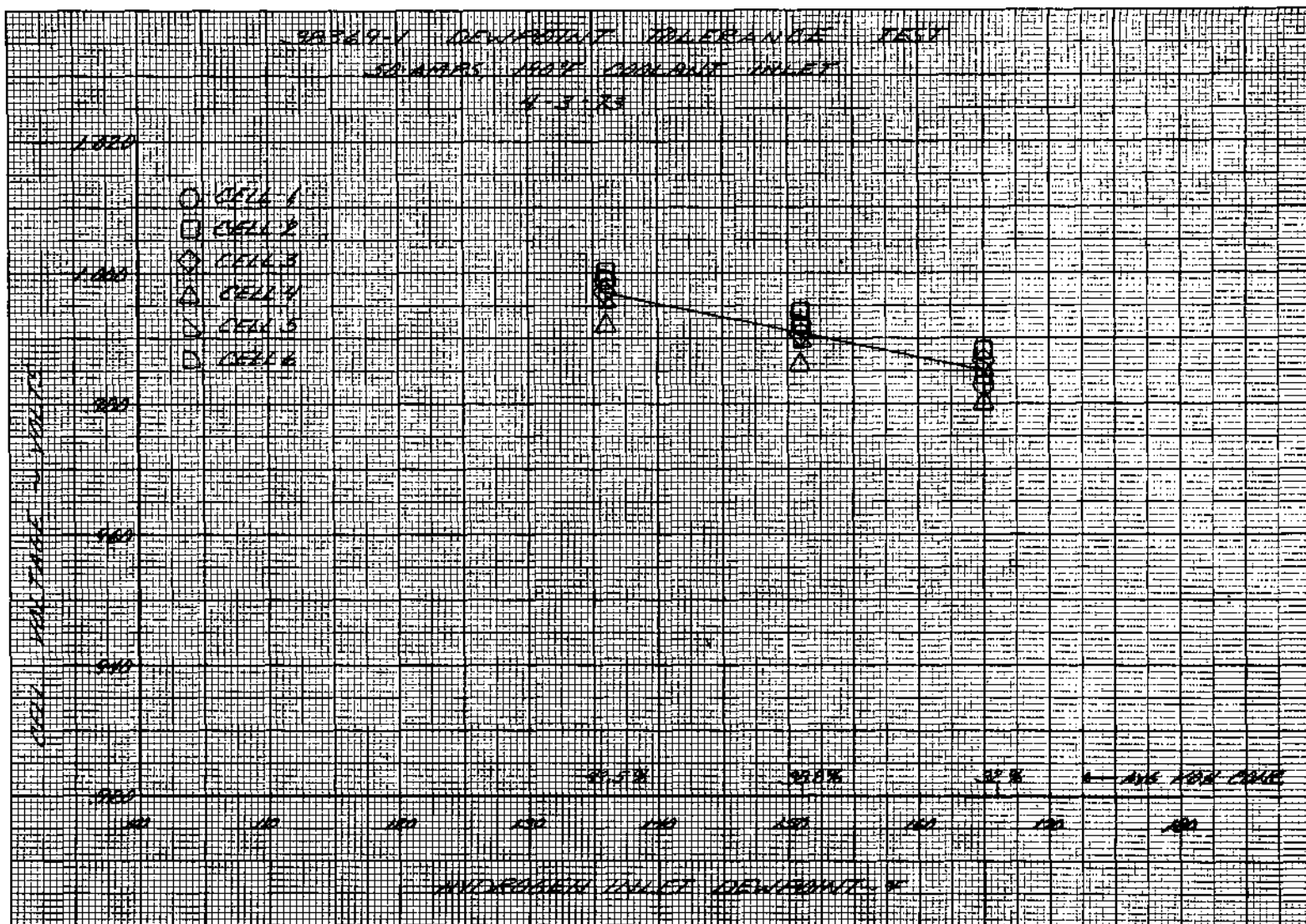
Figure 26 - Electrode Catalyst Evaluation
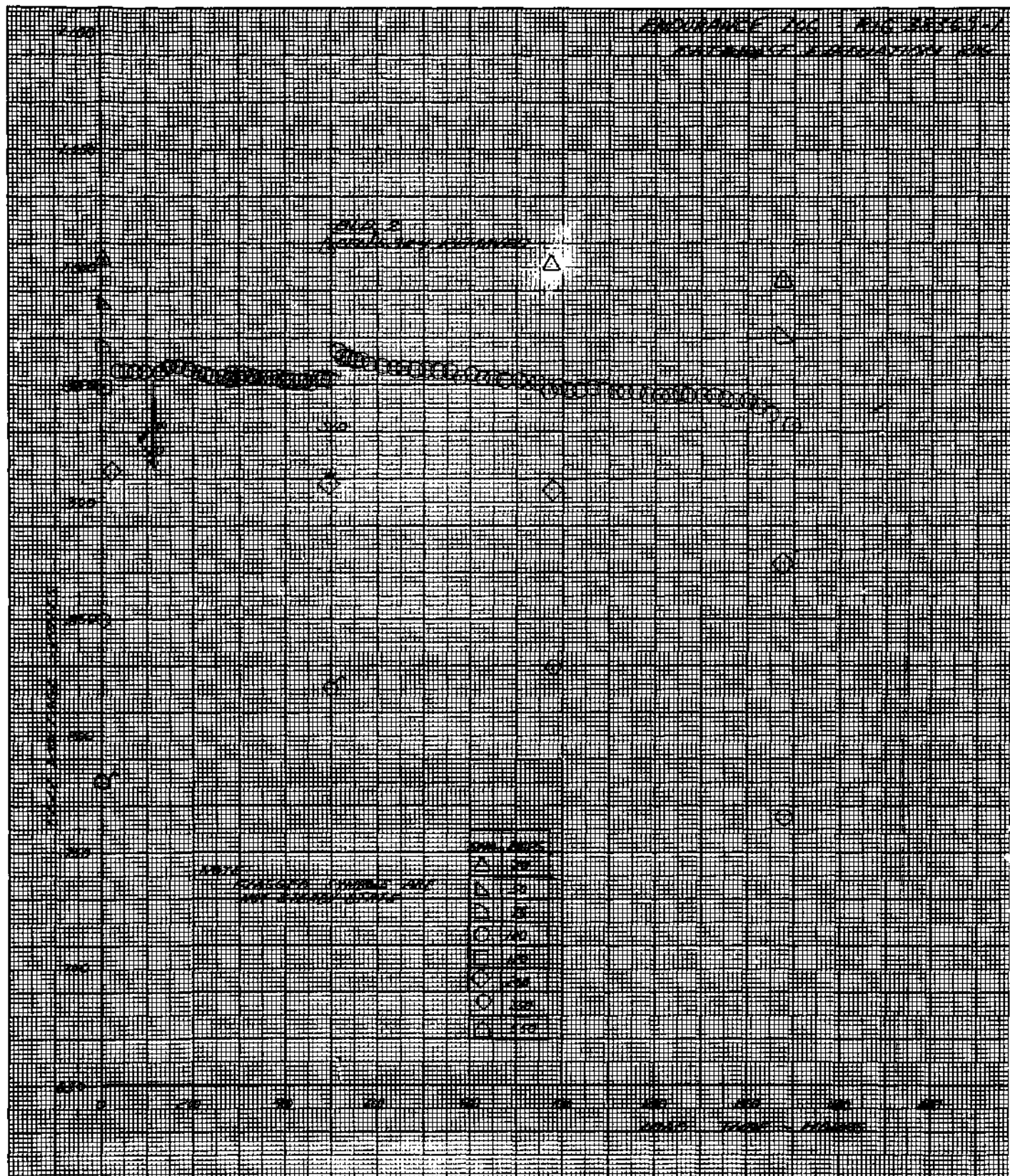
Figure 27 - Electrode Catalyst Tolerance Test

Figure 28 - Electrode Catalyst Endurance Log

As a result of these tests, it was concluded that, from a structural point of view, these materials could not be used as a frame material in a DM-2 type of stack because of their high creep rate which would affect the pinch on the cell with load and time. The investigation was refocused upon revision of the cure cycle used for the present epoxy-impregnated glass materials as the means for reducing material corrosion and carbonate formation in the electrolyte. Sample materials made with a revised curing cycle were obtained and lay-up trials performed. Unitized electrode assemblies, with the new cure, were tested in a 4-cell stack for 120 hours. No frame problems were encountered during the test.

Corrosion testing for 100 hours at 250°F under a 50 psia, 30 percent oxygen, 70 percent helium atmosphere was conducted and the results compared to a standard sample tested under the same conditions. Analysis of the atmosphere for carbon monoxide and carbon dioxide showed no significant difference. Mass spectrometer tests of revised cure and standard samples showed less unreacted epoxy in the revised cure cycle samples. Mechanical tests showed the revised cure cycle samples to have a lower creep rate than the standard cure cycle samples.

Two strip configuration cells were fabricated for corrosion testing at 200°F in a simulated fuel cell environment. One cell frame was cured with the revised curing cycle and the other with the standard cure. Following 230 hours of testing, the electrolyte of each cell was analyzed for $K_2CO_3$. There was no significant difference between the samples.

The revised cure cycle was adapted for all Pratt & Whitney Aircraft fiberglass epoxy-unitized cell assemblies because of its lower creep rate and lower amount of unreacted epoxy. The cells used in the Pratt & Whitney Aircraft in-house demonstrator powerplant incorporated this curing process.

### 5.5 Coolant Plate Spacing

The objective of this task was to establish a design prediction system for defining the number of cells per cooler within a power section in order to reduce powerplant weight. The approach was to establish an analytical heat transfer model to enable prediction of maximum cell temperature versus cooler spacing. The thermal conductivity of the cell and separator plates and the coolant film coefficients were identified as significant cooler prediction parameters.

Thermal conductivity testing of the cell and separator plates was performed in late 1972 at Dynatech, Industries of Cambridge, Massachusetts. Three basic configurations were tested; a cell sandwich, a dry electrolyte reservoir plate, and a wet electrolyte reservoir plate. The cell sandwich was a 2.5 x 2.5 inch DM-2 structure consisting of two magnesium plates and a Scheme I cell filled with 30 percent concentration KOH. The test was conducted at 250°F under varying compressive pressure loads of 20, 40, 60, 80, and 100 psi. Table IV summarizes the test results and Figure 29 shows the test configuration and the variation of cell thermal resistance with load. The dotted line shows the approximate loading used in a cell stack. This resistance $(28.6 \times 10^{-3} \text{ °F-hr/BTU})$ will be used in the analytical model to determine maximum cell temperature versus cooler spacing for specific Space Shuttle fuel cell design requirements.

## TABLE IV

## COOLANT PLATE SPACING STUDY

### Conductance Test Results

| SAMPLE NUMBER | LOAD (psi) | THERMAL CONDUCTANCE | | THERMAL RESISTANCE |
|---|---|---|---|---|
| | | $WM^{-2}K^{-1}$ | $Btu/hr.^{-1}-ft^{-2}\,°F$ | $°F-hr.-Btu^{-1}$ |
| 1* | 20 | $2.7 \times 10^2$ | 47.5 | $41.2 \times 10^{-3}$ |
| | 40 | $3.3 \times 10^2$ | 58.0 | $33.8 \times 10^{-3}$ |
| | 60 | $3.6 \times 10^2$ | 63.4 | $30.9 \times 10^{-3}$ |
| | 80 | $3.9 \times 10^2$ | 68.5 | $28.6 \times 10^{-3}$ |
| | 100 | $4.0 \times 10^2$ | 70.4 | $27.8 \times 10^{-3}$ |
| 2** | 80 | $7.8 \times 10^2$ | 137.1 | $14.4 \times 10^{-3}$ |
| 3*** | 80 | $12.0 \times 10^2$ | 211.0 | $9.4 \times 10^{-3}$ |

\* Base Cell Sandwich - 2 magnesium plates, 2 electrodes, 1 matrix and filled 0.062 inch ERP

\*\* Dry 0.062 inch ERP - 70% porosity

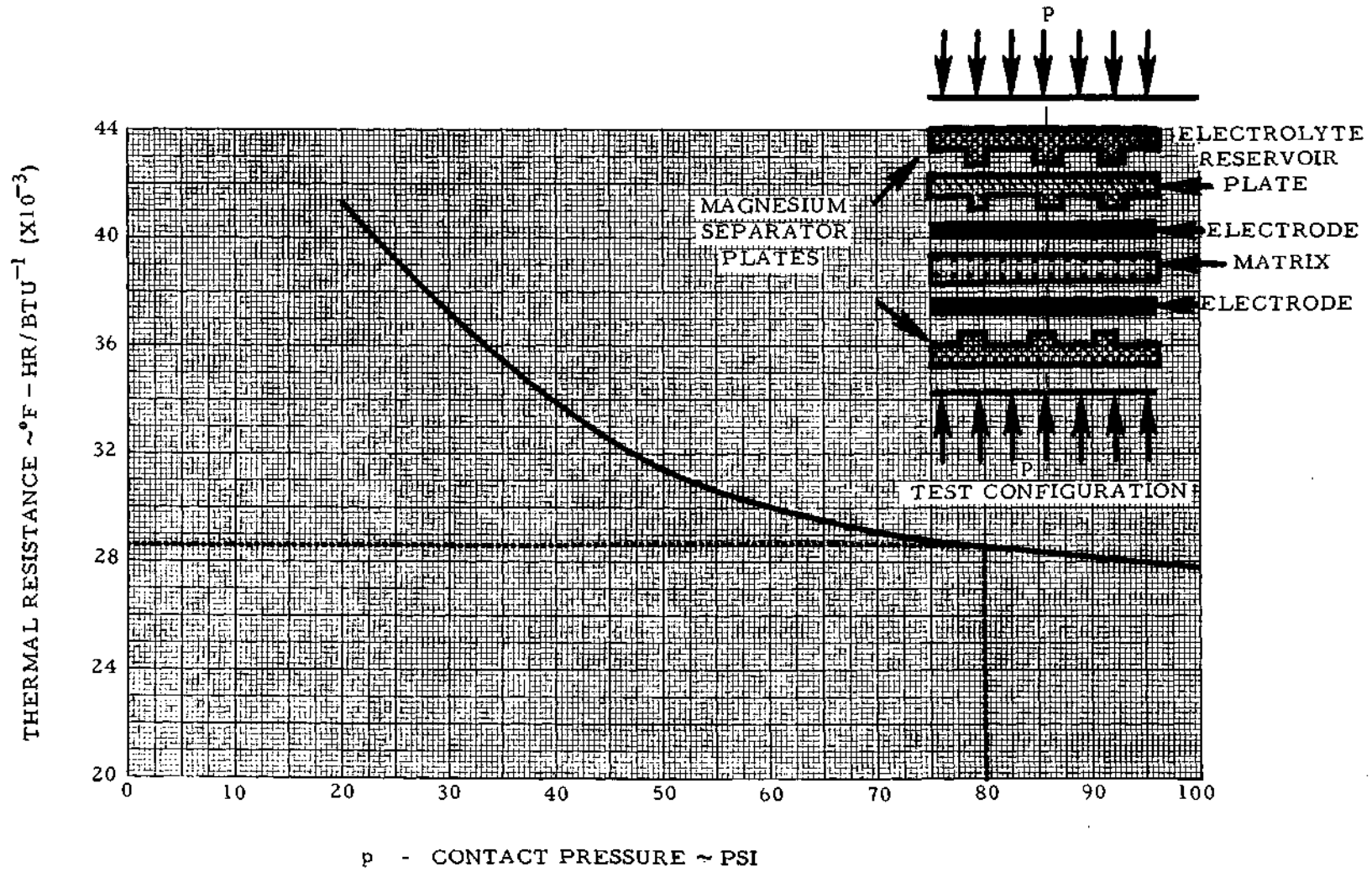\*\*\*Wet 0.062 inch ERP - 70% porosity - filled with 30% KOH solution

Figure 29 - Cooler Spacing Study Data

Coolant film coefficient testing was conducted at Pratt & Whitney Aircraft. The testing was hampered by instrumentation and rig hardware problems. The test was run twice but the data was insufficient for a reliable film coefficient determination. Coolant flows, representative of those anticipated in the Space Shuttle fuel cell, were demonstrated and coolant plate temperatures were measured. Predicted plate temperatures were in good agreement with measured plate temperatures.

Parameter studies performed on cooler spacing versus maximum cell temperature indicated that the controlling factor in the thermal model is the cell and separator plate thermal conductivity for which good data was obtained. The studies also indicated that there is little effect on cooler spacing for film coefficients in the 100 to 400 BTU hr-ft$^2$-$^\circ$F range. This is shown for typical conditions in Figure 30.

An analytical determination of the film coefficient for these conditions indicates it would be approximately 200 to 250 BTU hr-ft$^2$-$^\circ$F, which is well within the sensivity range. It is concluded that although a quantitative film coefficient was not determined, the design prediction system for cooler spacing has been essentially substantiated by the thermal conductivity and plate temperature measurements.
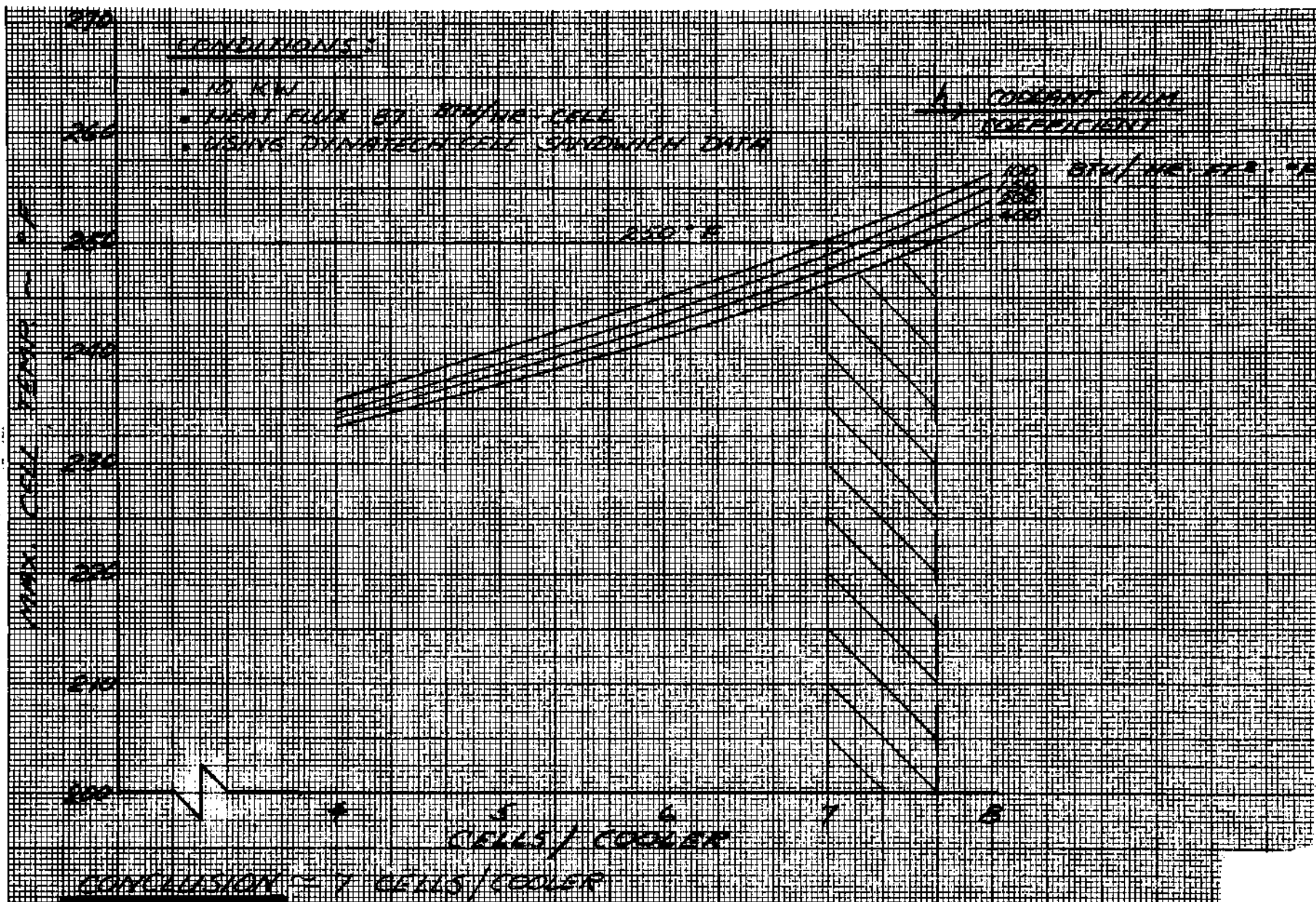
Figure 30 - Space Shuttle Cooler Spacing Study

## 6.0 DESIGN COST TRADE-OFF STUDY

The design cost trade-off study was conducted to: 1) determine the difference between the estimated costs of developing, qualifying, and producing a low-voltage and a high voltage fuel cell system and 2) to provide NASA with the means for making rough-order-of magnitude program cost trade-offs for changes in significant fuel cell specification items. The approach used was to develop mathematical models based on historical fuel cell program data and to use the models to predict the impact on program costs of specification variations. Statistical analysis of the data showed that the specification items of voltage regulation, operating life, and specific weight correlated with the costs of development, qualification, and production. Three models were developed using regression analysis to define program costs as a function of the appropriate technical parameters. The historical data base consisted of cost and program data from past Pratt & Whitney Aircraft fuel cell programs as well as estimated cost data from past program proposals. A Design Cost Trade-off Study Report, PWA-4452, containing the models was issued 23 May 1972.

## 7.0 MATERIAL FLAMMABILITY

This task was established as part of the NASA material safety verification program. It was required to provide NASA with a materials list for the DM-2 stack and the hydrogen drag-pump and separator. This list included identification of each part, its material and description, and its specific operating environment including temperature, pressure, and atmosphere. The listing was submitted to NASA as part of Monthly Report Number 6, PWA-4415, dated 17 March 1972.