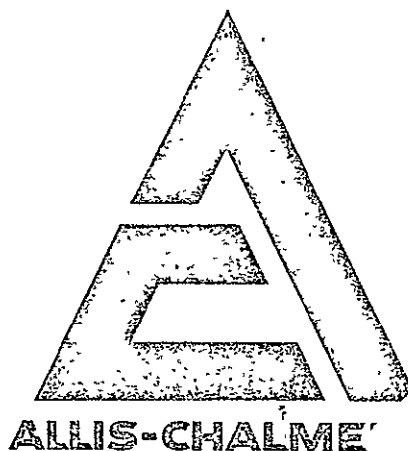
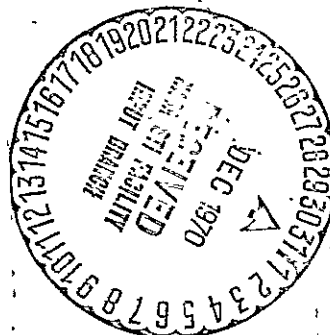

FINAL REPORT
CAPILLARY MATRIX AND
FUEL CELL DEVELOPMENT STUDY

Contract NAS9-10443



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FINAL REPORT

FOR

CAPILLARY MATRIX AND FUEL CELL

DEVELOPMENT STUDY__

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Document No. 80045-165
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1.0 INTRODUCTION

1.1 PROGRAM OBJECTIVES

The objectives of the NASA Extended Life Fuel Cell Development Program were:

- To initiate development of fuel cell systems having the capability of operating 10,000 hours and having a power-to-weight ratio of 40 lbs per kilowatt.
- To initiate development of concepts of maintainability and reuseability consistent with spacecraft requirements of the 1970's.
- To initiate development of fuel cell systems and components consistent with the requirements of the 1970's.
- To review the 2 kW system and component test history for problem isolation and solution development.
- To demonstrate system improvements through the initiation of a 10,000 hour life test.

The demonstration system was to contain as many of the developmental improvements as possible consistent with the schedule which targeted 500 hours of system operation prior to the end of the contract.

1.2 WORK BREAKDOWN STRUCTURE

The work breakdown structure for the proposed program is shown in Figure 1-1. The program consists of three major tasks:

- 1.0 Technology Improvement
- 2.0 Advanced Systems Engineering
- 3.0 Management and Data

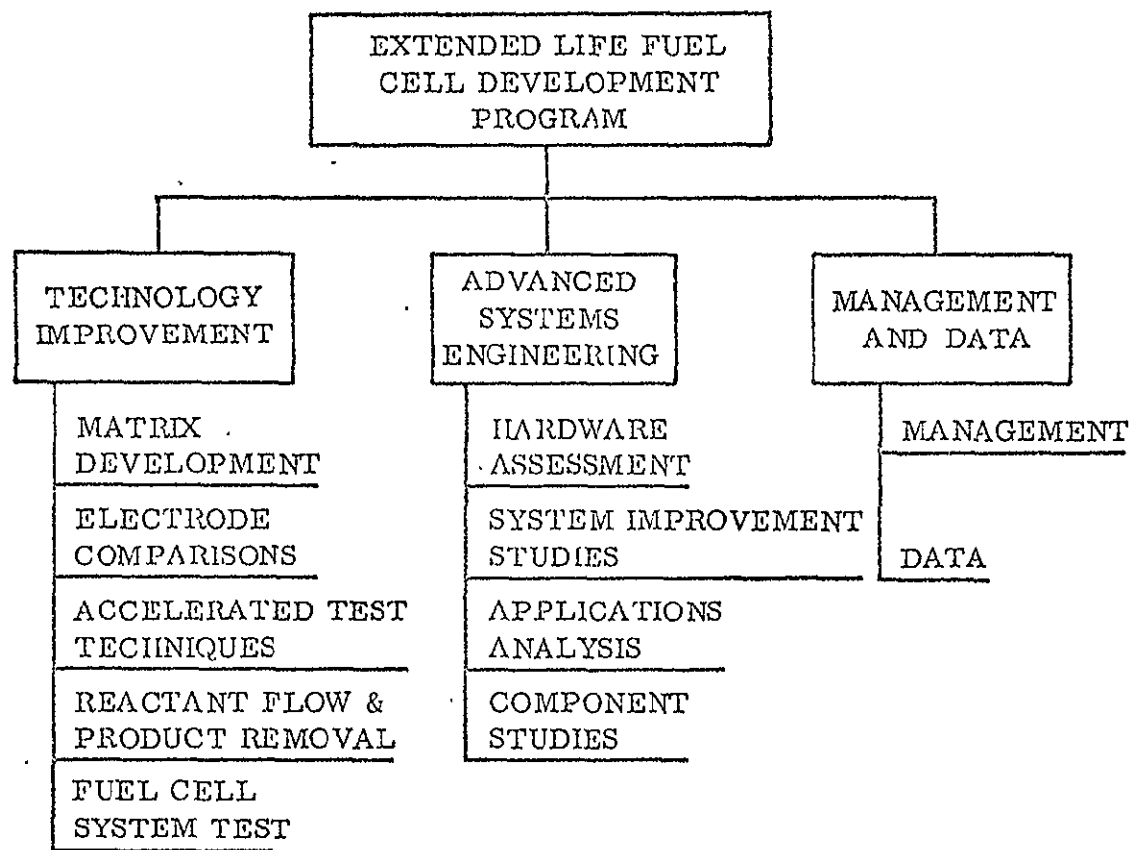


Figure 1-1. Work Breakdown Structure

Each task is broken down into additional levels of detail to define individual work items.

The emphasis in Task 1.0 is on basic fuel cell technology developments in the areas of electrodes, matrices, and cell performance. Task 2.0 effort is more closely related to the total fuel cell system and the associated engineering development.

Task 3.0 includes the program management and the data activities. Program management consists of a Program Manager and Task Managers. The data effort included in Task 3.0 represents the technical writing, editing, and art work for the submitted reports.

2.0 SUMMARY

This report documents the results of effort under NASA contract NAS9-10443 "Extended Life Fuel Cell Development" and covers a period from January 5, 1970 through July 31, 1970.

RESULTS SUMMARY BY MAJOR WORK TASK

WORK TASK 1.0 - TECHNOLOGY IMPROVEMENT

Work under this task concentrated on developing improvements in the stack which would extend life toward 10,000 hours and improve performance for better voltage - power control. The effort centered around the fuel cell matrix, electrodes water removal methods, and electrolyte concentration gradients. The major accomplishments were as follows:

- An asbestos reforming technique was developed which produces a tougher, more uniform asbestos matrix than that previously available. Less asbestos can, therefore, be loaded into the matrix to produce the required cross leak pressure resistance. This in turn permits a greater electrolyte loading per matrix which improves performance and should provide longer life than the 3000 hours demonstrated to date.
- A successful method of asbestos leaching with hot KOH was employed to produce asbestos leached over a range up to 33% weight loss. This asbestos was formed into matrices and evaluated in small stack tests. Evaluation of the results indicates that the reaction of KOH and asbestos continues until the solution is saturated with corrosion products. This means the use of a leached asbestos matrix is of questionable value since fresh electrolyte added during the stack loading operation will produce more corrosion products and asbestos deterioration.
- No new matrix materials were discovered, but long fiber potassium titanate, zirconia and ceria appear to be potential candidates. Special matrix fabrication techniques will have to be developed for these materials.

- A precision electrolyte loading technique for an individual electrode-matrix assembly (EMA) was devised and proved so successful that it was utilized in the full size MSC stack. The technique permits accurate, consistent loading of an individual EMA that can be easily checked by weighing, stored indefinitely and has the potential of simple electrical testing to evaluate its performance capability prior to assembling into a stack.
- An A-C Type XIV platinum electrode was operated as both a cathode and anode in a two-section stack. The initial performance was about 60 mv below a stack with an A-C Hysac silver cathode. A test bench mishap damaged the cell beyond repair, and the contract expired before the replacement stack could be gotten on test.
- A gold-copper catalyst developed by Pennsylvania Research Associates was discovered as a possible alternate electrode material. Because of cost and schedule it was impossible to obtain this material and develop electrode fabrication techniques.
- Through experience in small stack testing we developed the capability of tracking the electrolyte concentration with respect to optimum by periodically monitoring the internal cell resistance. This method provides a reliable and accurate method of determining the condition of the cell with regards to optimum electrolyte concentration.
- Although the program did not develop suitable load or temperature conditions for accelerated fuel cell testing it did amply demonstrate that a fuel cell employing the static moisture removal system can be operated for prolonged periods (> 150 hours) at loads of 400 ASF with little or no performance degradation simply by adjusting to the proper electrolyte concentration consistent with water removal requirements. Calculations indicate that the water removal limitation for the present 50 mil matrix is about 800 ASF and on a projected 30 mil matrix the level is probably in excess of 1300 ASF.
- A tradeoff study conducted on the three prominent methods of water removal from a fuel cell (circulating electrolyte, recirculating reactant and static moisture removal) concluded that the static moisture removal method

was the best selection for an A-C aerospace fuel cell. Factors evaluated included control sensitivity, weight, parasitic power, reliability, maintenance, operational versatility and cost.

- Reactant flow model tests verified the adequacy of the existing fuel cell plate design during a purge cycle. Additional baffling will not improve the uniformity of the inert gas "sweep" during a purge cycle.
- The MSC system was fabricated, successfully acceptance tested and operated for over 200 hours. In general, the performance of the system was exceptional. Cell uniformity was outstanding with only cells 1 and 2 showing any significant variation from the others. Cell one appears to be on the "wet" side of optimum, and its performance was somewhat below the average. Based on past testing, it is anticipated that this cell will improve with life. Cell two is an exceptional performer. Its output is as much above the norm as cell one is below. There is no apparent explanation for cell two's performance at this time. In the course of the 200 hours of testing the system was subjected to three high power runs; the first two produced an average of 5 kW for 3 minutes each at about 26 volts. The third run produced an average of more than 5 kW at an average voltage over 26 volts for 6 minutes. These tests correspond to a loading of approximately 500 ASF. Subsequent testing indicated that the high power runs had not affected the system performance.

WORK TASK 2.0 - ADVANCED SYSTEM ENGINEERING

- A hardware assessment survey was conducted on all failure reports written during the NASA, MOL, AAP and RCFC programs. The results were categorized by component, type of failure, etc., and then the development status of each component was summarized. The detailed effort was previously reported in topical report number 80045-147 but a summary is also included in this document.
- A Part III Design Requirements Document was prepared for the Advanced System based on information obtained from the potential prime contractors

and the recent NASA RFP for a Shuttle fuel cell. Over 100 contacts were made with thirteen potential prime contractors and NASA agencies to request and discuss Advanced System information.

- Based on the Advanced System requirements, an Advanced System concept was evolved and the 2 kW improvements necessary to meet these needs identified major improvements included the following:
 - improved fuel cell matrices and electrolyte loading
 - cold plate cooling for the stack
 - weight reduction for the condenser and potable water pump
 - proportional moisture removal valve
 - addition of a power conditioner
 - modularization of two 2.5 kW stacks
 - variable reactant inlet pressure
 - reactant prehumidification

Preliminary costs and schedules are included for the improvements.

- Functional diagrams and requirements were developed for each subsystem and their principal components. These requirements form the basis from which the detailed component design specifications would be prepared.
- Maintenance concepts were studied using the shuttle flight planning and a configuration approach was evolved which matched the shuttle scheme. The configuration approach features Line Replaceable Units (LRU) that can be isolated and quickly replaced if a failure is detected by the on-board fault detection system. Conceptually, each functional subsystem is self-contained in a separate LRU that is a plug in rack mounted unit allowing easy access for maintenance.
- The Advance System goals include the utilization of low pressure (20 psia), propellant grade reactant gases to supply the fuel cell. Trade-off studies concluded that it is more advantageous to add cells to the stack and operate

on low inlet pressure gas than to compress the gas to 150 psia maximum and regulate to the A-C standard cell pressure of 37 psia. The compressor approach imposes both a weight and volume (size) penalty. The results of this trade-off study however, must be considered in conjunction with the reactant purity study.

- Based on inputs from the Hardware Assessment effort (2.1), the System Improvement Studies (2.2), the Application Analysis(2.3) and specific component investigations, twenty-five (25) major components were identified for the advanced system and considered in the development plan. These components were defined relative to existing hardware and prior applications. In addition, sixteen (16) of these components were identified as requiring significant development. A test matrix identifying the types of tests required for each of the sixteen components was also prepared and included in the development plan.
- An electro-mechanical moisture removal valve definition was prepared and vendor responses solicited. A feasible design was obtained.
- An integrated reactant control subsystem concept was established. This included component identification and packaging approaches.
- The stack compression was reviewed and design modifications were established. In addition, alternate compression device concepts were evaluated.

In conjunction with the stack compression area of study, the stack seals were investigated. Alternate materials and seal configurations were evaluated.

- The product water pump was investigated. Alternate methods were evaluated for possible use and it was concluded that the present pump approach with a minor amount of simplification was superior.
- An unsuccessful attempt was made to establish an alternate supplier of the glycol coolant pump.

3.0 DISCUSSION

3.1 WORK TASK 1.0 - TECHNOLOGY IMPROVEMENT

3.1.1 Subtask 1.1 - Matrix Development

The objective of this subtask was to evaluate potential non-asbestos matrix materials for an advanced aerospace fuel cell. It was also an objective of this subtask to improve the asbestos matrix by leaching with potassium hydroxide and reforming asbestos mats to obtain greater uniformity. The processes for leaching and reforming mats were to be developed and the leached asbestos was to be given fuel cell tests and chemical/physical property tests.

3.1.1.1 Matrix Material Evaluation

The evaluation of new matrix materials consisted of a review of several comprehensive studies of matrix materials, selecting the most promising materials, procuring some of these materials, and performing a limited analysis on these materials.

The reports that were reviewed were:

- 1) TRW
First Summary Report December 28, 1966
NAS 3-8522
- 2) TRW
Second Summary Report July 3, 1967
NAS 3-8522
- 3) Cyanamid
Final Report June 31, 1966
NAS 3-6477
- 4) TRW
Final Report December 1968
NAS 3-8522

- 5) Allis-Chalmers
Summary Report - Research Project No. 284
May 5, 1961

Some of the non-asbestos materials discussed in the reports are:

- Potassium Titanate
- Zirconia
- Ceria
- Silicon Carbide Fiber
- Titania

The reports indicated that ceria and zirconia are the most resistant to attack by KOH. Titania and potassium titanate react very slowly with hot KOH.

Resistance to attack by KOH was the criteria used as a basis for selecting the materials that would be acquired for further analysis. Samples of zirconia, long-fibered potassium titanate (Tipersul) and short-fibered potassium titanate (PKT) were obtained. A physical property of a fuel cell matrix, equally important as stability in KOH, is the ability to keep the reactant gases separated. A measure of the ability to keep the reactants separated is the matrix's cross leak pressure. The pressure differential at which gas starts leaking through a matrix is its cross leak pressure. A matrix, which will not allow gas permeation at pressures of 50 psid or less are acceptable matrices.

Zirconia obtained in the form of a 100 mil thick mat, was given cross leak pressure tests and revealed a 2.5 psid capability. The zirconia in the mat was yttria stabilized, and the mat is very resistant to attack by KOH. DuPont reported only a 4% weight loss in 75% KOH at 400°F in 300 hours. This material has the potential of extending fuel cell life at reduced voltage degradation rates.

The PKT (also received in mat form) was given cross leak tests and revealed a 4 psid capability for a 40 mil mat and a 14 psid capability for a 60 mil mat. This PKT mat consists of short-fibered potassium titanate and aluminum silicate as a binder. Although

the cross leak pressure tests indicate that these mats will keep the fuel cell reactants separated, the low cross leak pressures and the inclusion of aluminum silicate renders these mats unacceptable as this silicate is soluble in KOH.

Tipersul (long-fibered potassium titanate) is more desirable for matrix application than the short-fibered PKT but the production of Tipersul has been discontinued. Some Tipersul was obtained as a constituent of Saturn vehicle hydrogen tank insulation received through efforts of personnel at MSFC. This insulation also contained a silicate binder.

Some of the insulation, as received, was formed into mats using the asbestos mat forming technique developed under this subtask. The resultant mats were very non-uniform, i.e., some areas were thin and other areas were very thick. In view of the fact that the insulation was not compatible with KOH (because of the silicate binder) no further attempts were made to form mats of this material.

Attempts were made to remove the silicate binder. A portion of this insulation was leached in 45% KOH for 72 hours. Approximately one-half of the binder dissolved in the KOH leaving the insulation with practically no tensile strength. Again the developed asbestos mat forming technique was not applicable and a new technique was not sought.

Although the efforts to use the insulation were not successful the previous studies indicate that potassium titanate has the potential of extending fuel cell life at reduced voltage degradation rates.

3.1.1.2 Procedure for Reforming Asbestos Mats

A summary of the procedure for reforming asbestos mats, as it was developed for this contract, is as follows:

1. Place the desired quantity of shredded asbestos in a blender along with at least 80 ml of alcohol per gram of asbestos.
2. Blend the asbestos/alcohol slurry for approximately 30 seconds.
3. Place the asbestos/alcohol slurry in a vacuum chamber and deaerate the slurry.

4. Pour the asbestos/alcohol slurry into a filtration box and agitate the slurry to remove trapped air bubbles.
5. Apply a slight vacuum to the lower half of the filtration box and remove the excess alcohol from the asbestos.
6. Remove the asbestos mat from the filtration box and dry the mat.

NOTE: Mats of unleached asbestos may be dried in a draft oven at approximately 150°F.

Mats of leached asbestos must be dried at room temperature to prevent wrinkles.

3.1.1.3 Cross Leak Tests of Reformed Asbestos Mats

Cross leak tests were given to nominal 30 mil asbestos mats of varying asbestos loading in an attempt to determine the minimum quantity of asbestos per unit volume required to maintain the desired differential pressure capability. The differential pressure capability of the 30 mil, Johns-Manville asbestos mat was found to be approximately 60 psi. The 30 mil J-M mat contains .4 to .425 gms of asbestos per square inch. Figure 3.1-1 shows the differential pressure capability of various reformed mats. It can be seen in this figure that the reformed mats need only contain 0.275 gms of asbestos per square inch to maintain the same differential pressure capability as the 30 mil J-M mats.

3.1.1.4 Fuel Cell Tests of Reformed Asbestos Matrix (RAM)

Two single section stacks (Numbers 1.1A and 1.1BR) were tested to determine the effect of reformed asbestos mats on fuel cell performance. The tests were conducted on test benches modified under this contract. A description of the test benches is in Appendix B. The results of the tests of these two stacks are discussed below and indicate improved V-A performance due to using reformed asbestos matrices.

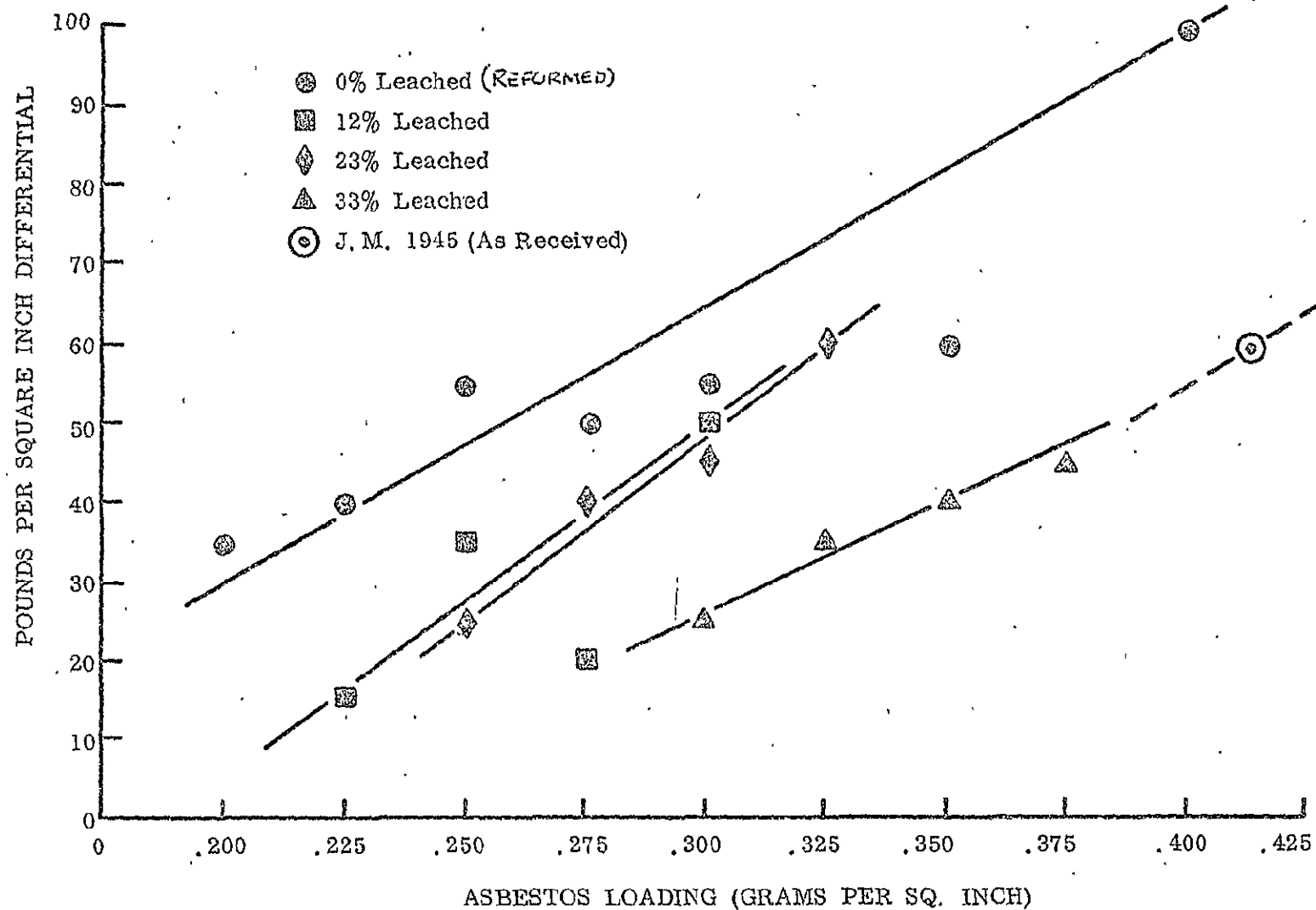


Figure 3.1-1. Cross Leak Pressures of Various Asbestos Mats (30 mil)

STACK 1.1A

Objective

To evaluate fuel cell performance with a cell matrix of reconstituted asbestos for a period of 500 hours.

Construction

Number of cell sections	One
Anode Type	AB-40 (Cyanamid)
Cathode Type	HYSAC-4a (A-C)
Matrix	30 Mil RAM
% KOH Loaded	35%
KOH Loading Method	Flush

Test Results

The cell was operated at 80 amps (200 ASF) for 517 hours. The average initial voltage was above 0.940 V for 160 hours - this was one of the best single cell performances to date. The initial optimization test showed maximum cell voltage occurred over an electrolyte range of 48% to 52% which was higher than expected; the cell was flush loaded with 35% electrolyte. Based on the optimization, the life tests were initiated at 47% concentration and 0.930 V at 80 amps. A second optimization test was performed from 353 to 380 hours; the optimization range was unchanged indicating little or no loss of electrolyte over the 200 hours of operation between optimizations. The 80 amp load test was continued to 417 hours at which time the voltage was about 0.920 V. This completed the test objective and indicated that the reconstituted asbestos mats were a highly satisfactory substitute for the Johns-Manville .030 mil asbestos mats. During this period, the cell encountered a total of 5 unscheduled automatic shutdowns with a resulting ΔP across the matrix of 5 to 10 psi.

At approximately 500 hours, the cell was operated for a total of 4 hours continuously at 400 ASF - the performance was stable at about 0.800 V. Testing was continued to 644.5

hours at 40 amps (100 ASF) during which time one more automatic shutdown occurred. The test was terminated due to a matrix cross leak after an oxygen regulator failure subjected the matrix to a sudden differential pressure up to a 80 psi for about 2 to 3 minutes.

STACK 1.1B-R

Objective

To evaluate the performance of a 10-mil Reconstituted Asbestos Matrix (RAM) for a period of 500 hours. This test was added to the program to demonstrate the greater uniformity and performance capability of the Reconstituted Asbestos Matrix prepared this process.

Construction

Number of cell sections	One
Anode Type	AB-40 (Cyanamid)
Cathode Type	HYSAC 4a (A-C)
Matrix	10 Mil RAM
% KOH Loaded	35%
KOH Loading Method	Flush

Test Results

The cell was flush loaded with 35% electrolyte and optimized over a range from 49% to 53% KOH. Life testing was initiated with a performance of about 0.940 V at 50 hours and 50% concentration. The cell was subjected to three automatic shutdowns (and accompanying 5 to 10 psi differential) within the first 335 hours at which time the voltage was 0.916V. Life testing was continued for another 1000 hours with a KOH concentration range from 49% to 47%. The cell voltage at 1325 hours was 0.895 V. Within the final thousand hours of testing, four automatic shutdowns occurred. The last automatic shutdown produced an excessive pressure differential across the matrix and resulted in a cross leak.

The 500-hour performance capability objective was successfully demonstrated, and the potential life of the 10-mil reconstituted asbestos matrix was further demonstrated by the extended testing to 1326 hours.

Reformed asbestos mats were also installed in the 32-section MSC fuel cell stack. The improved performance of this stack was attributed to these mats. More details of the test of this stack can be found in the discussion of Subtask 1.5.

3.1.1.5 Procedure for Leaching Asbestos

A summary of the procedure for leaching asbestos, as it was developed for this contract, is as follows:

1. Shred approximately 50 grams of Johns Manville fuel cell asbestos and place in a 4L beaker in a vacuum chamber.
2. Pull a hard vacuum (> 28 in. Hg) on the asbestos for at least 5 minutes.
3. While still under vacuum, slowly admit 1800 ml of 60% KOH ($\approx 50^{\circ}\text{C}$) to the 4L beaker.
4. After the 1800 ml KOH have been admitted, release the vacuum and allow the asbestos to soak in the KOH for at least 5 minutes.

NOTE: The above series of steps prevent air from being trapped in the asbestos-KOH mixtures:

5. Stir the asbestos-KOH mixture with a propeller stirrer to form a smooth slurry.
6. Transfer the slurry from the 4L beaker to a 1/2 gallon Teflon bottle. Insert bottle stopper.

NOTE: The Teflon bottles were fitted with Teflon stoppers that allowed for a release of pressure.

7. Insert the filled Teflon bottle in an oven preheated to 150°C . The percentage of asbestos dissolved is a function of time and a plot of this relationship is shown in Figure 3.1-2.
8. Remove the filled Teflon bottle from the oven after the appropriate length of time.

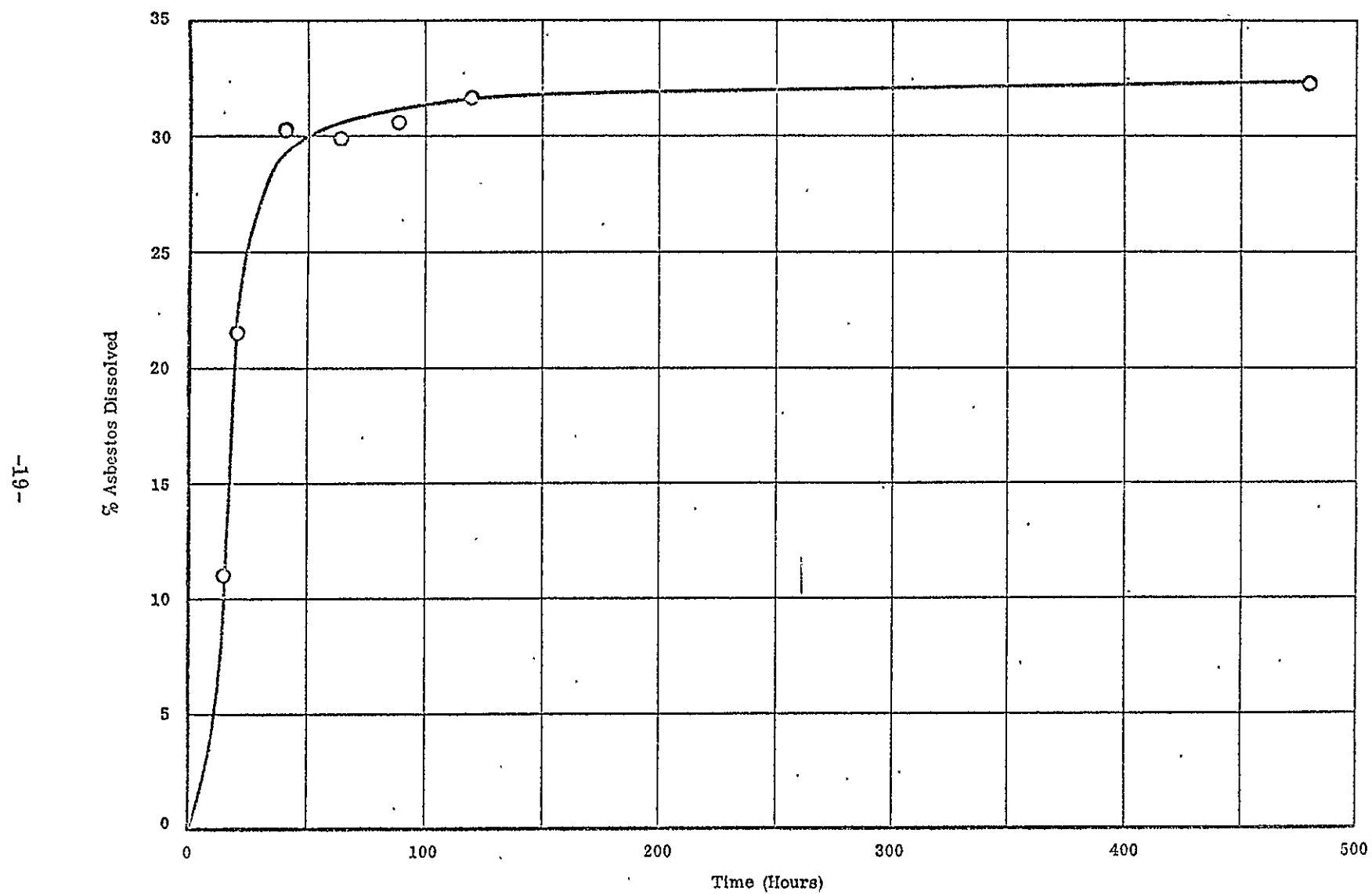


Figure 3.1-2. Dissolution of Asbestos in 60% KOH (150°C) as a Function of Time

9. Wash the leached asbestos with hot ($\approx 60^{\circ}\text{C}$) deionized water until the water after washing has a pH of less than 9.
10. Remove the wash water from the leached asbestos and dry the asbestos.

3.1.1.6 Chemical and Physical Properties of Leached Asbestos Mats

Leached and unleached asbestos samples were given the following analysis:

- | | |
|-------------------------------------|--------------------------|
| 1. Chemical Composition | - Emission Spectrograph |
| 2. Surface Area | - Mercury Porosimeter |
| 3. Specific Gravity | - Air Pycnometer |
| 4. Pressure Differential Capability | - Cross leak test device |

The results of the spectrographic analysis are shown in Table 3.1-1, and the results of the surface area determinations are shown in Table 3.1-2. The results of the spectrographic analysis indicates that asbestos consists mainly of magnesium (88 to 95%) and silicon (5 to 10%), and that there is no evident change in chemical composition due to leaching in KOH. However, the surface area and specific gravity of asbestos are affected by leaching. The surface area determinations indicate that a small amount of leaching (12%) causes an increase in surface area whereas, continued leaching (33%) drops the surface area below that of unleached asbestos.

The results of the specific gravity determinations, shown in Table 3-3, indicate that material is removed in the leaching process since the specific gravity for leached asbestos (2.52) is less than that for unleached asbestos (2.79).

A sample of 33% leached asbestos was releached in 60% KOH at 150°C for 92 hours. The sample lost only 4.8% (by weight) during the releach but it lost at least one-half the volume and nearly all of its cohesive properties. This test indicates that the reaction between asbestos and KOH will continue even if the asbestos has been previously treated with KOH.

<u>SAMPLE</u>	<u>% Mg</u>	<u>% Si</u>	<u>% Al</u>	<u>% Ca</u>	<u>% Mn</u>	<u>% Ni</u>	<u>% Fe</u>	<u>% Pb</u>	<u>% Sn</u>
Unleached Asbestos Mat	88 - 95	5 - 10	.001 - .01	.1 - .5	.1 - .5	.01 - .5	.1 - .5	ND	ND
Shredded Unleached Asbestos	88 - 95	5 - 10	.001 - .01	.001 - .01	.1 - .5	.01 - .2	.1 - .5	ND	ND
Leached Asbestos (12%)	88 - 95	5 - 10	.001 - .01	.001 - .01	.1 - .5	.01 - .2	.1 - .5	ND	ND
Leached Asbestos (23%)	88 - 95	5 - 10	.1 - 1	.1 - .5	.1 - .3	.01 - .2	.1 - .5	ND	ND
Leached Asbestos (33%)	88 - 95	5 - 10	.1 - 1	.1 - .5	.1 - .3	.01 - .2	.1 - .5	ND	ND

Table 3.1-1. Spectrographic Analysis of Asbestos

Unleached Asbestos Mat	28.26	Square Meters per Gram
Shredded Unleached Asbestos	29.86	Square Meters per Gram
Leached Asbestos (12%)	55.23	Square Meters per Gram
Leached Asbestos (23%)	45.88	Square Meters per Gram
Leached Asbestos (33%)	18.41	Square Meters per Gram

Table 3.1-2. Surface Area of Asbestos

0% leached	2.79
12% leached	2.75
23% leached	2.72
33% leached	2.52

Table 3-3. Specific Gravities of Asbestos

The cross-leak pressure of various leached and unleached asbestos mats as a function of asbestos loading was studied. The data from the tests is presented in Figure 3-1. As expected, the cross-leak pressures were directly related to the asbestos loading (grams per square inch) and inversely related to the percent leached. The average cross-leak pressure of several tests of the as-received J.M. 1945, 30-mil asbestos mat was 60 psid. The reformed mats containing 0%, 12%, and 23% leached asbestos have greater cross-leak resistance than the 30-mil J.M. mat.

3.1.1.7 Fuel Cell Tests of Leached Asbestos Mats

Four small stacks were tested to determine the effect of leached asbestos on fuel cell performance. The tests were conducted on test benches modified under this contract. The stacks were all to be 4-section stacks but the thermal control, normally adequate for single section stacks, proved to be too sensitive for a 4-section stacks. Also, electrical load is applied to a small stack by varying the compression on a series of carbon wafers. This method has no inherent control and, with the higher voltage and power capability of multiple-section stacks, the load has displayed a tendency to drift. The varying load, in turn, produces a change in thermal load - usually beyond the capability of the automatic temperature control system on a multiple-section stacks. As the stack temperature changes, the electrolyte concentration will also change as the vacuum regulator is not temperature compensated.

Consideration of all these factors leads to the conclusion that the test benches are adequate for one- and two-section performance tests, but not three- or four-section stacks.

The original test bench design imposed a differential pressure across the cell matrix on automatic shutdown due to differences in consumption rates between hydrogen and oxygen. This condition was corrected by the addition of a volume chamber on the hydrogen side.

With these facts in mind a description of the test benches can be seen in Appendix A.

A discription of the tests of the small stacks with leached asbestos matrices follows.

STACK 1.1C

Objective

To evaluate fuel cell performance with matrices of 0%, 12%, 23%, and 33% leached asbestos. This test was planned for 500 hours.

Construction

Number of cell sections	Four
Anode Type	AB-40 (Cyanamid)
Cathode Type	HYSAC 4a (A-C)
Matrix	30 Mil - See Objective
% KOH Loaded	29.8%
KOH Loading Method	EMA

NOTE: EMA denotes a method for loading the fuel cell components external to the cell. It is described more fully under Subtask 1.2.

Test Results

This four-section stack contained one cell section of each matrix described above and was EMA loaded at 29.8% electrolyte concentration. This stack configuration was selected to minimize the effects of test variables and accelerated testing. Large thermal gradients (up to 20°F) were experienced in the stack during the preconditioning operation. When placed on load, one cell reversed at 60 amps (Cell Number 1, 0% leached). The performance of the other three sections was very poor. This stack was removed from test and split as follows:

- Sections numbered 1 (0% leached) and 2 (12% leached) were removed and visually examined.
- Sections numbered 3 (23% leached) and 4 (33% leached) were placed back on test as a two-section stack.

STACK 1.1CS

Objective

To evaluate the performance of a fuel cell having matrices of 23% to 33% leached asbestos. The two cells in this stack are the original cell number 3 and number 4 of Stack 1.1C.

Construction

Number of cell sections	Two
Anode Type	AB-40
Cathode Type	HYSAC 4a
Matrix	30 Mil (See Objective)
% KOH Loaded	29.8%
KOH Loading Method	EMA

Results

The stack was installed in a test bench and commenced optimization starting at 36%.

The stack was optimized over a range from 36 to 46% KOH concentration and commenced life test at E.T. 210 hours at 40% KOH.

The original objective was to test stack to 200 hours. However, the stack was tested for 667 hours.

The performance of the stack at the start of the life test was 1.815 volt at 200 ASF, and after 457 hours of life testing the performance was 1.830 volts at 200 ASF. The test was terminated due to expiration of contract time and funds.

STACK 1.1D

Objective

To evaluate the performance of a fuel cell having an electrolyte matrix of 12% leached asbestos.

Construction

Number of sections	Two
Anode Type	AB-40
Cathode Type	HYSAC 4a
Matrix	30 Mil (See Objective)
% KOH Loaded	31%
KOH Loading Method	EMA

Test Results

A severe wet-down of this stack occurred during the first 2.5 hours under load. The stack was removed from test at E.T. 3.7 hours because the stack lost KOH because of the wet-down and any test data would be suspect.

STACK 1.1E

Objective

To evaluate the performance of a fuel cell having an electrolyte matrix of 23% leached asbestos.

Construction

Number of cell sections	Two
Anode Type	AB-40
Cathode Type	HYSAC 4a
Matrix	30 Mil (See Objective)
% KOH Loaded	31%
KOH Loading Method	EMA

Test Results

The testing of this stack was limited to an optimization due to an expiration of contract time and funds. The stack optimized in the range of 41.5% KOH to 43.5% KOH. The internal resistance of the stack at 42% KOH was 0.97 milliohms. The total time on test was 261.5 hours and the performance of the stack just prior to shutdown was 1.874 volts (an average of 0.937) at 200 ASF.

STACK 1.1F

Objective

To evaluate the performance of a fuel cell having an electrolyte matrix of 33% leached asbestos.

Construction

Number of cell sections	Two
Anode Type	AB-40
Cathode Type	HYSAC 4a
Matrix	30 Mil (See Objective)
% KOH loaded	31%
KOH Loading Method	EMA

Test Results

The testing of this stack was limited to an optimization due to an expiration of contract time and funds. The stack optimized at approximately 34% and at that concentration the internal resistance was 1.2 milliohms. Just prior to shutdown the performance of the stack was 1.826 volts (an average of .913 volts per cell) at 200 ASF. The total time on test was 189 hours.

3.1.1.8 Conclusions and Recommendations as a Result of the Effort Under subtask 1.1

- The two materials most stable in KOH are zirconia and ceria. A third material, potassium titanate, is also very stable in KOH. Considerable effort must be expended in order to develop suitable fuel cell matrices of any of these materials.
- Leaching asbestos is of questionable value. The leaching study indicates that the reaction between asbestos and KOH continues with a fresh supply of KOH. The fuel cell tests were too short to give any reliable data. The leaching studies indicated that the KOH became saturated with silicate ions. Consequently it is postulated that KOH saturated with silicate ions would no longer react with the asbestos matrix. Studies will have to be undertaken to determine the effect of silicate ions on fuel cell performance.
- Reforming the asbestos matrices improves the mats physical characteristics. Less asbestos per unit volume than standard J. M. asbestos mats can be used and still retain the same cross-leak pressure. Also with less asbestos per unit volume in the matrix the performance of the fuel cell is improved. It was postulated that life should also be greater because more electrolyte is available in the matrix and less material is present to react with the electrolyte.

3.1.2 Subtask 1.2 - Electrode Comparisons

The objectives of this subtask are to:

- Test non-silver cathodes in fuel cells comparing their performance with that of the HYSAC silver cathode
- Re-evaluate the performance of the A-C platinum electrode as an anode in a fuel cell
- Investigate an improved method for loading fuel cell components with electrolyte.

3.1.2.1 Re-Evaluation of the A-C Platinum Anode

Two small stacks were tested in an attempt to re-evaluate the Allis-Chalmers AC XIV electrode as an anode. The tests were conducted on test benches modified under this contract. The first stack consisted of four cell sections. It experienced thermal control problems early in life and was removed from test. The second stack was also built with four cell sections. It was then decided to stop testing four section stacks (because of the thermal control problems) so the second stack was split to make a two-section stack. This second stack also suffered from thermal control problems and a loss of performance. Because of these problems the stack was no longer typical and any future performance would be suspect. The test objective of this stack was then redirected to determining a relationship between internal resistance and the equivalent % KOH setting of the water removal cavity. Since the AC XIV anode was being evaluated in the MSC full stack and because of a shortage in remaining contract time and funds, no further efforts were made to evaluate the AC XIV anode in small stack tests. A discription of the small stack tests of the AC XIV electrode as an anode follows.

STACK 1.2.1A

Objective

To evaluate the optimization and performance characteristics of the Type XIV A-C anode with a HYSAC cathode in the standard NASA cell configuration for 2000 hours.

Construction

Number of cell sections	Four
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J. M.
% KOH Loaded	31%
KOH Loading Method	Flush

Results

This four-section stack was flush loaded with 31% electrolyte concentration and was placed on an 80 amp (200 ASF) load with an average cell voltage of 0.910 V and an electrolyte concentration of 41%. The stack performance was stable for over 300 hours at which time the average cell voltage was 0.892 V. A total of four automatic shutdowns occurred during this period - all attributable to test bench problems. In each instance, the shutdown was caused by high temperature (three instances) or low temperature (one instance). The final high temperature shutdown resulted in excessive temperature gradients between the center sections and the ends of the stack and caused a crossleak that terminated testing at 308.7 hours.

The stack optimized (maximum cell voltage) in the 41% to 45% range as predicted for this loading.

Internal resistance and pH data reviews indicated this stack optimization had been shifting toward the lower concentration range; however, we do not, as yet, have sufficient test data to use internal resistance as a concentration tracking parameter. Much of

the dryout can be attributed to the test equipment problems.

The stack achieved its performance demonstration objective but did not operate for the 2000-hour life. The stack was removed from the bench and rebuilt as a two-section stack for life demonstration under the electrode comparison objectives.

STACK 1.2.1AR

Objective

To evaluate the optimization and performance characteristics of Type XIV A-C anode with a HYSAC cathode in the standard NASA cell configuration.

Construction

Number of cell sections	Two
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J. M.
% KOH Loaded	31%
KOH Loading Method	Flush

Test Results

The cell was flushed with 31.5% KOH and optimized over a range from 37 to 43%. Life test commenced at E. T. 167 hours with an initial performance of 1.805 volts at 80 amperes and 41% KOH concentration.

At E. T. 194 hours an unscheduled shutdown occurred (during the night) caused by a drop in cell temperature. Due to a combination of the lower cell temperature and the automatic shutdown the stack lost electrolyte. On restarting the stack, poor performance was observed and thus the test was no longer typical. The test, relative to the above objective, was terminated.

Redirection

The test objective of this stack was redirected to determine the relationship between internal resistance and the cavity setting.

Test Results

The small amount of data obtained relative to this redirection indicated that once the initial operating cavity setting has been established and the corresponding internal resistance data has been obtained, maintaining this internal resistance by cavity adjustments will yield the most stable stack performance.

3.1.2.2 Evaluation of a Platinum Cathode

The platinum cathode evaluated was the Allis-Chalmers AC XIV electrode. Three fuel cell stacks were built to evaluate this type of electrode. The first stack was assembled incorrectly. Trouble was encountered in flush loading the second stack with electrolyte and it developed a cross-leak early in its life test. The third stack was loaded with electrolyte via the EMA technique, installed in a test bench, but because of the expiration of contract time and funds it never was put on test. Consequently, no life test data was obtained for the AC XIV electrode as a cathode. The stacks are further described below.

STACK 1.2.1B

Objective

To evaluate the optimization and performance characteristics of the Type XIV A-C anode with a Type XIV A-C cathode in the standard NASA cell configuration for 2000 hours.

Construction

Number of cell sections	Four
Anode Type	AC XIV
Cathode Type	AC XIV
Matrix	30 Mil J. M.
% KOH Loaded	31%
KOH Loading Method	Flush

Test Results

This four-section stack was flush loaded with 31% electrolyte concentration and placed on test. After approximately one and one-half hours of operation at 80 amps (200 ASF), it was obvious the water was not being removed from the stack. Cell Number 1 reversed. The stack was removed from the bench with less than three hours total operating time. Disassembly and inspection of the stack revealed the water manifold film breakers had been improperly installed such that the water removal EDM slots were completely blocked on three of the water removal plates. The stack was rebuilt as Stack 1.2.1B-R. It was difficult to flushload 1.2.1B-R with the proper quantity of electrolyte - possible because A-C XIV electrodes are used as both anode and cathode. Flushloading with two wet-proofed electrodes should probably be investigated further. In view of the problems associated with four-section stack operation and the flushing difficulties, the stack was split into two sections. One two-section portion was weighed to verify the KOH loading; indications are that the assemblies are about 12% to 15% low in electrolyte loading. The remaining two sections were placed on test as Stack 1.2.1BRS.

STACK 1.2.1BRS

Objective

To evaluate optimization and performance characteristics of the Type XIV A-C electrode used as both anode and cathode in the standard NASA cell configuration.

Construction

Number of cell sections	Two
Anode Type	AC XIV
Cathode Type	AC XIV
Matrix	30 Mil J. M.
% KOH Loaded	31%
KOH Loading Method	Flush

Test Results

The stack optimized in a range of 37% to 39% KOH. The life test began at E.T. 145, at a cavity setting of 37%, and with stack performance of 1.735 volts at 200 ASF. At E.T. 167 hours the stack underwent an automatic unscheduled shutdown due to "low stack voltage". It was found that the low voltage was due to a leak of hydrogen into the water removal cavity and the test was terminated.

STACK 1.2.1B-2R

Objective

To evaluate optimization and performance characteristics of the Type AC XIV electrode used as both anode and cathode in the standard NASA cell configuration.

Construction

Number of cell sections	Two
Anode Type	AC XIV
Cathode Type	AC XIV
Matrix	30 Mil RAM
% KOH Loaded	31%
KOH Loading Method	EMA

Test Results

This stack was installed in a test bench but was never tested because the contract time and funds were exhausted.

3.1.2.3 Evaluation of a Gold-Copper Cathode

A gold-copper catalyst, developed by Pennsylvania Research Associates (PRA), was to be investigated. Assuming favorable reports, sample material was to be procured, developed into an electrode, and possibly tested as a cathode. Conflicting reports as to the catalytic potential of this material caused its acquisition to be given a lower priority.

Later in the contract, personnel at PRA were contacted relative to the availability of this catalyst. They indicated that the catalyst could be available to AEPD one to two months after receipt of an order. Cost was \$30 per gram. Three types of gold-copper catalyst are available; AuCu with 15% Al, AuCu with 22% Al, and AuCu₃. The type suggested was the AuCu/15% Al because it has a face centered cubic structure, a surface area of less than 1 m²/gm, and is advertised to be 100 times as effective as Pt based on surface area.

The reported performance of fuel cells with this catalyst (0.9V at 465 ASF) makes this catalyst worth further investigation. Several factors, however, made further evaluation beyond the scope of this contract. The cost of the catalyst is extremely high (almost eight times as expensive as platinum black). Approximately 300 gms of material would be required to conduct a minimum program of fabrication and performance evaluation. Total cost of this minimum program would have been approximately \$15,000, which was beyond the scope of the contract allocation. In addition, procurement lead time of one to two months would have meant that an evaluation program would be in the initial stage at the completion of this contract. In view of these factors, Allis-Chalmers concluded it was not cost effective to enter into serious negotiations with Pennsylvania Research.

3.1.2.4 Improved Electrolyte Loading Procedure (Development of Electrode/Matrix Assembly - EMA)

Vacuum loading of fuel cell electrodes and matrices with electrolyte (KOH) reduces the incidence of cross-leakage to almost zero, stabilizes the voltages from cell to cell in a stack, and showed indications of reducing degradation. To date loading the cell components with electrolyte by vacuum has been accomplished by flushing the entire stack with KOH. Excess KOH was then removed, to a large extent, by an inert gas flush and then a vacuum cleanup of accessible stack manifolds. However, some KOH remained

to potentially accumulate in restrictors, plate grooves and slots, and in some directly associated components (purge valves, moisture removal valves, etc.). The goal of the improved electrolyte loading technique, therefore, was to retain vacuum loading of the cell components without flushing electrolyte through the stack. This goal has been accomplished. The cell components are compressed and loaded with electrolyte external to the cell, and then as an assembly is installed in the cell. A summary of the procedure, which was developed, is as follows:

1. Assemble the electrodes, matrix, and seal frames, as they are in a typical fuel cell, in a special fixture. The fixture consists of two plates, which when bolted together, compress the cell components to the same thickness they would be in a typical cell. There are numerous small holes through the plates in the areas under the electrodes. The electrolyte passes through these holes during the impregnation step.
2. Place the assembly (of cell components and special plates) in a tank in a vacuum chamber.
3. Evacuate the air from the vacuum chamber.
4. While still under vacuum, admit electrolyte into the tank in the vacuum chamber, covering the assembly with electrolyte.
5. Release the vacuum and allow the assembly to soak in the electrolyte long enough to permit complete wetting throughout.
6. The assembly is then removed from the tank of electrolyte and subjected to a fine stream of high pressure nitrogen (≈ 100 psig). The excess electrolyte must be removed (blown off) from the assembly so that when the special fixture is opened up the cell components will not suck up additional electrolyte as they expand slightly.
7. After the excess electrolyte is blown off, the plates are opened and the cell components are removed for bagging and storage under refrigeration.

NOTE: This electrolyte loaded assembly of cell components is known as an electrode/matrix assembly (EMA).

3.1.2.5 Fuel Cell Tests of EMA's

Four small stacks were tested to determine the effect of loading electrolyte into cell components external to the cell. The tests were conducted on the test benches that were modified under this contract (see Appendix A). The objectives of these tests were to determine if this EMA concept was feasible and if so, what percent KOH should be loaded into the cell components. A description of the tests of the four stacks follows.

STACK 1.2.2A

Objective

To evaluate the optimization and performance characteristics of a standard NASA cell section which has been vacuum impregnated with electrolyte external to the test stack (EMA). Planned test time: 200 hours.

Construction

Number of cell sections	One
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J. M.
% KOH Loaded	37.6%
KOH Loading Method	EMA

Test Results

The electrode/matrix assemblies (EMA) and water sets (WSA) were vacuum impregnated with 37.6% electrolyte concentration. The cell optimized (maximum cell voltage) in the range from 50.5% to 53.5% concentration. The cell was placed on 80 amp (200 ASF) load at approximately 50% concentration and a section voltage of 0.906 V. At the end of 285 hours, the cell voltage was 0.901 V. For an unexplained reason (probably stuck cavity relay), the cell voltage dropped .025 V overnight. The cell was then operated until E. T. (Elapsed Time) 316 hours.

The stack demonstrated the EMA could be made and easily assembled into a stack. The performance was comparable to that of flush-loaded stacks, and the electrolyte concentration for initial loading could be predicted based on the same theory of electrode wetting fronts.

STACK 1.2.2B

Objective

To determine the optimization and performance characteristics of a two-section stack with electrode/matrix assemblies (EMA's) vacuum impregnated outside the stack using Reconstituted Asbestos Matrices (RAM's) for the first time. This stack is a prototype for the 32-Section MSC Stack and testing was planned for 200 hours.

Construction

Number of cell sections	Two
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil RAM
% KOH Loaded	32%
KOH Loading Method	EMA

Test Results

The stack initially optimized over a range from 43% to 46% and was placed on 80 amp (200 ASF) load at 43% concentration and an average voltage of approximately 0.919 V. The stack was operated over 1050 hours per our revised schedule, to gain maximum comparative information on the performance of the RAM in an EMA stack. Six automatic shutdowns occurred during the test period. The average section voltage at the time of test termination was 0.885 V. The test was terminated at E. T. 1057 hours.

The stack demonstrated the stable performance characteristics of the RAM installed in a stack using the EMA loading technique. Extended performance was satisfactory although test bench problems make it difficult to draw any firm conclusions. The optimization data furnished additional information regarding the electrolyte loading concentration for the MSC System.

As part of an additional experiment, the EMA in Section Number 1 was loaded with the normal compression in the fixture while the EMA for Section Number 2 was loaded with .003" less fixture compression, both using 32% electrolyte concentration. This was done to check the effects of compression on the contact resistance in the final stack assembly. It was noted the internal resistance of Section Number 2 was actually slightly higher after assembly. This fact, along with the comparable operation of Sections numbered 1 and 2, led us to conclude the baseline EMA loading technique is satisfactory.

STACK 1.2.2C

Objective

To evaluate performance and optimization characteristics of a single-section fuel cell constructed with Type XIV anodes, HYSAC 4a cathodes, and Reconstituted Asbestos Matrices (RAM's) loaded using the EMA technique. This stack is an MSC Prototype and was scheduled for 200 hours of operation.

Construction

Number of cell sections	One
Andoe Type	New AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil RAM
% KOH Loaded	31%
KOH Loading Method	EMA

Test Results

The stack was EMA loaded with 31% electrolyte and initially optimized over a range from 41% to 44% KOH. The stack was placed on 80 amp (200 ASF) load at a voltage of 0.937 V at 41% concentration. At 200 hours, the stack voltage was 0.918 V at 41% KOH. Two abnormal shutdowns occurred during this period. To gain additional performance data on this MSC Prototype, the test period was extended beyond 200 hours.

At E. T. (Elapsed Time) 257 hours, the manual water removal stop valve was inadvertently left closed and the cell was flooded. Since the performance data following this flooding was no longer representative of a normal cell, it was decided to utilize this stack for start-up/shutdown evaluation tests.

All the initial objectives of this stack were satisfactorily demonstrated.

STACK 1.2.2C SPECIAL TEST

Objective

Special test to determine effects of automatic shutdown on cell performance.

Test Results

The KOH concentration was maintained at 36% as determined by second optimization. Two automatic shutdowns were manually induced by tripping the voltage control meter relay. There was no significant decrease in performance noticed during restart subsequent to the aforementioned automatic shutdowns; i.e.:

<u>Automatic Shutdown Number</u>	<u>mV Before</u>	<u>mV After</u>
1	899	888
2	897	894

The cell was re-optimized with results shown in Figure 3.1-3 (third optimization). The KOH concentration setpoint was maintained at 42% (dry side of optimum). Two automatic shutdowns were manually induced as explained in the first paragraph above. The results are as follows:

<u>Automatic Shutdown Number</u>	<u>mV Before</u>	<u>mV After</u>
1	878	824 mV
2	822	Cross leak and cavity leak

Conclusion

The probability is quite high that the performance of a cell will be drastically affected subsequent to an automatic shutdown if the cell is operating on the dry side of optimum.

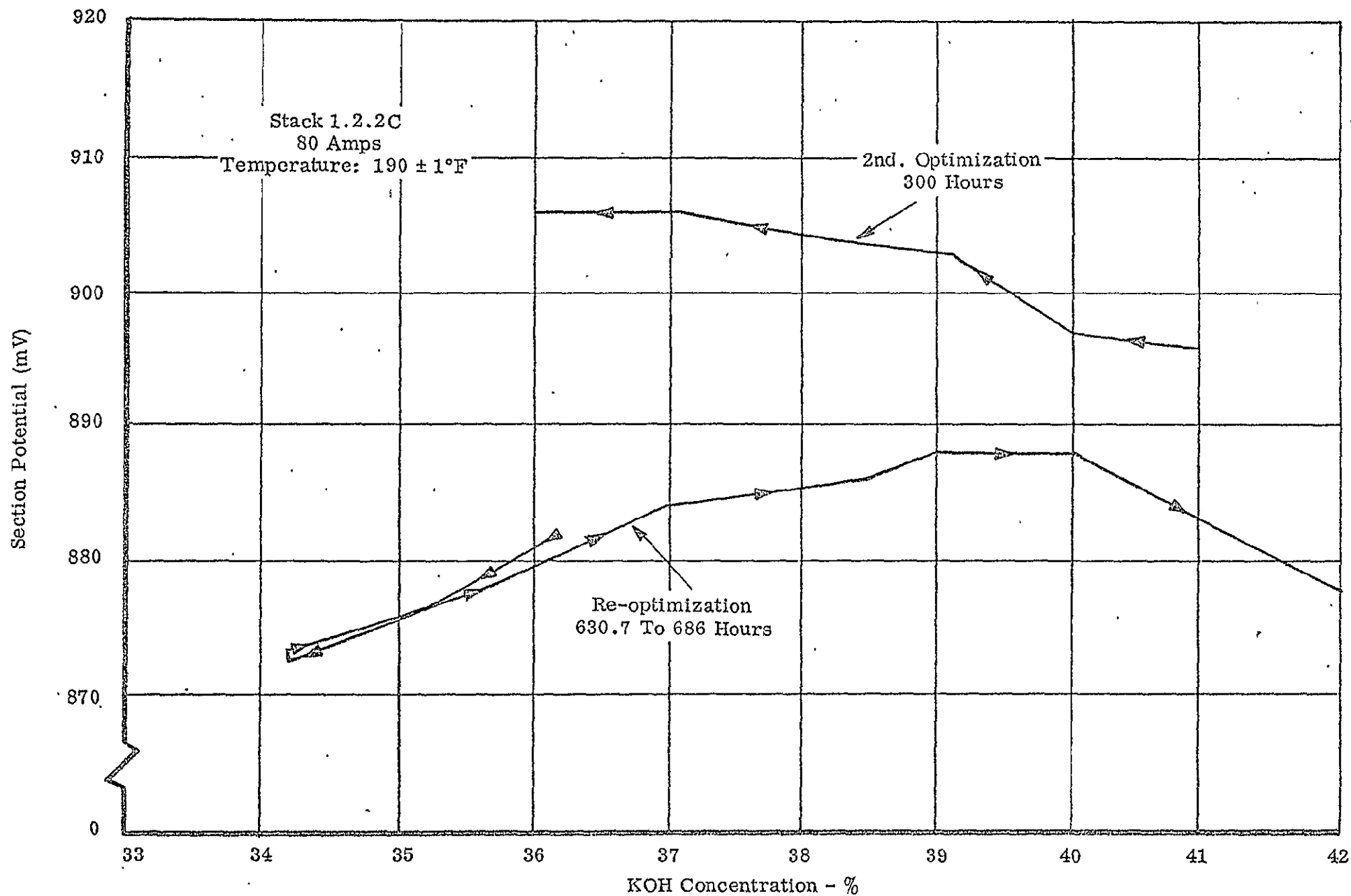


Figure 3.1-3. Results of Stack 1.2.2.C Reoptimization

STACK 1.2.2D

Objective

To make a direct performance comparison of two identically constructed cells, one flush loaded and this one EMA loaded.

Construction.

Number of cell sections	Two
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J.M.
% KOH Loaded	31%
KOH Loading Method	EMA

Test Results

This was operated for 21.1 hours at 38% KOH cavity setting at which time the test was terminated in order to direct the remaining contract funds and manpower to fuel cell tests of higher priority.

3.1.2.6 Conclusions and Recommendations Derived as a Result of the Effort Under Subtask 1.2

- Evaluation of the anode tests indicates that the initial performance of the AC XIV anode is slightly less than the AB40 anode - approximately 10 milli-volts lower capability at 200 ASF. Insufficient life test data has been obtained to compare the life capabilities of the two anodes.
- The contract expired before the AC XIV electrode could be evaluated sufficiently as a cathode.
- The reported performance levels of the Gold-Copper catalyst makes this catalyst worth further investigation. Effort must be made to reduce the cost of this catalyst.
- Loading the fuel cell components via the EMA technique has proved to be very beneficial.
 - Extremely uniform cell voltages have been attained across a full stack incorporating EMA's.
 - The optimization point of a stack can be more precisely and reliably predetermined because of the ability to fully load each cell component with electrolyte - every time.
 - Uniform performance of a stack can practically be insured by pre-selecting the EMA's for a stack based on electrolyte quantity.
 - EMA's can be fabricated and stored under refrigeration for an indefinite length of time; refrigerating the EMA's make them stiffer and easier to handle.
 - Greater confidence can be placed in the test results of experimental cell components if the components are "EMA loaded".
 - After an EMA is fabricated the option is available to give the EMA an initial performance test or to ascertain acceptability and to pre-condition the EMA prior to installation in a stack.

- Based on a small amount of data, indications are that once the initial operating cavity setting has been established and the corresponding internal resistance data has been obtained, maintaining this internal resistance by cavity setting adjustments will yield the most stable stack performance.
- The probability is quite high that the subsequent performance of a cell will be drastically affected by a shutdown if at the time of shutdown the cell has been operating on the dry side of the optimum water cavity setting.

3.1.3 Subtask 1.3 - Accelerated Test Techniques

The objective of this subtask is to develop a method for reducing the time and cost involved in life testing of fuel cells through the development of the relationship of degradation to elevated current densities and temperatures.

3.1.3.1 Accelerated Test Techniques

The approach taken to develop the relationships was to analyze fuel cell data by a statistically designed experiment known as the 2^n factorial with center points and the Path of Steepest Ascent (PSA)*. The PSA will aid in determining the linearity of the response surface and point toward the optimum operating values. This statistical analysis is described in more detail in the Monthly Report Number 3. The fuel cell data was obtained through the operation of four single-section stacks. The stacks were operated in test benches modified under this contract. Additional modifications were required for these particular tests because of the higher current densities and temperatures involved. The load bank and the power cables had to be modified for the higher currents and modifications to the stack "ovens" and coolant loops were made to handle the higher temperatures.

Two of the single-section stacks developed problems shortly after start-up primarily due to inadequate loading of the cell components with electrolyte. The next two stacks were loaded with electrolyte via the EMA technique. One of these stacks (1.3AR)

*Statistical Design for Pilot-Plant and Laboratory Experiments by A. C. Atkinson, Chemical Engineering - May 9, 1966, pp. 149

operated very well at higher current densities and the other stack (1.3BR) operated very well at higher temperatures. These two stacks were initially scheduled to be used to determine the operating parameters at the elevated conditions but since they operated so well testing was continued to establish the degradation relationships.

Descriptions of the stacks follow.

STACK 1.3A

Objective

To establish cell operating characteristics (procedures, optimum KOH percent, etc.) at 190°F and high current density.

Construction

Number of cell sections	One
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J.M.
% KOH Loaded	31%
KOH Loading Method	Flush

Test Results

This single-section stack was flush loaded with 31.1% electrolyte concentration. Less electrolyte was loaded into the cell on flushing, and an abnormal amount of KOH (30 cc as compared to 16 to 18 cc normally) was removed during the preconditioning operation. All attempts to optimize this stack were unsatisfactory; performance was low and unstable. The stack was obviously not typical and, therefore, not suitable for testing to meet our objectives.

STACK 1.3AR

Objective

To establish operating characteristics (procedures, optimum KOH percent, etc.) for fuel cell operation at 300 ASF and 400 ASF and 190°F.

Construction

Number of cell sections	One
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J.M.
% KOH Loaded	31%
KOH Loading Method	EMA

Test Results

This single-section stack was loaded with electrolyte via the EMA technique. Optimization was conducted with the stack operating at 200 ASF, 300 ASF, and 400 ASF. The results of the optimizations are:

<u>ASF</u>	<u>AMPS</u>	<u>VOLTS</u>	<u>OPTIMUM % KOH</u>
200	80	.912	38.5
300	120	.963	40.5
400	160	.790	42

This stack was operated for 430 hours and exhibited very stable performance. The stack was operated at 400 ASF the last 170 hours of the test with no apparent degradation. The test was terminated due to an expiration of contract time and funds.

STACK 1.3B

Objective

To establish cell operating characteristics (procedures, optimum KOH percent, etc.) at 200 ASF and elevated temperature.

Construction

Number of cell sections	One
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J. M.
% KOH Loaded	31%
KOH Loading Method	Flush

Results

This single-section stack was flushloaded with 31.1% electrolyte concentration and was nominal in every respect. The stack optimization was initiated, and all data appeared normal. The concentration was set at 43% KOH and the voltage was 0.912 V at 80 amps (200 ASF) for weekend operation. An automatic shutdown occurred at E. T. (Elapsed Time) 94 hours due to low temperature; subsequent testing indicated the cell had developed a leak in the water removal matrix.

STACK 1.3BR

Objective

To establish operating characteristics (procedures, optimum KOH percent, etc.) for fuel cell operation at 215°F and 230°F and at 200 ASF.

Construction

Number of cell sections	One
Anode Type	AC XIV
Cathode Type	HYSAC 4a
Matrix	30 Mil J. M.
% KOH Loaded	31%
KOH Loading Method	EMA

Test Results

This single-section stack was loaded with electrolyte via the EMA technique. Optimization was conducted with the stack operating at 190°F, 215°F, and 230°F (200 ASF load). The results of the optimizations are as follows:

<u>TEMPERATURE</u>	<u>VOLTS</u>	<u>OPTIMUM KOH %</u>
190°F	.910	39 - 40
215°F	.920	39 - 40
230°F	.923	38

This stack was operated for 280 hours and exhibited very stable performance. The stack was operated at 230°F the last 150 hours of the test with practically no degradation. The test was terminated due to exhaustion of contract time and funds.

3.1.3.2 Conclusions and Recommendations Derived as a Result of the Effort Under Subtask 1.3

- Stable operation can be sustained at 400 ASF for an indefinite length of time using static moisture removal.
- From the small amount of data acquired there is no indication that accelerated cell voltage degradation will occur due to operation at current densities up to 400 ASF.
- The results of optimizations at various current densities substantiate the theory that a higher % KOH equivalent cavity setting is required for operation at higher ASF to facilitate a higher rate of water removal.
- The results of optimizations at various temperatures indicate that a reduced % KOH equivalent cavity setting is required for operation at higher temperatures.
- The quantity of data gathered was insufficient to detect or predict any accelerated voltage degradation due to higher temperature cell operation.

3.1.4 Subtask 1.4 - Reactant Flow and Water Removal

The objectives of this subtask are to:

- Study various approaches to removing water from fuel cells
- Study the reactant flow distribution through the NASA type fuel cell plate
- Study methods of humidifying reactants external to the fuel cell
- Investigate diffusion membranes as a means of preventing KOH loss from the fuel cell into the by-product water.

3.1.4.1 Water Removal Methods

One of the most critical problems in obtaining sustained high performance levels from a hydrogen/oxygen fuel cell is the controlled removal of the by-product water from the cell. This is particularly true for cells in which a fixed supply of electrolyte is held in a

matrix. If the rate of water removal is less than the rate of production, the volume of electrolyte will increase and tend to flood the electrode pores; if the rate of water removal is greater than the rate of production, the volume of electrolyte will decrease and tend to drain the electrode pores. In either case, the result is a loss of cell performance capability.

Control of by-product water removal from matrix-type cells has been accomplished through three basic means:

1. Circulation of the electrolyte to continuously (or periodically) replenish the electrolyte supply. The product water is then separated from the electrolyte in an external evaporator.
2. Evaporation of product water from the cell electrolyte into a circulating reactant gas stream. The water is subsequently removed from the gas stream by condensation and mechanical separation of the condensate from the gas stream.
3. Evaporation of product water from the cell electrolyte and separation of the water vapor from the reactant gas (within the cell) by means of a selective-permeability membrane. The product water leaves the cell in the form of a nearly-pure vapor, and can be recovered by condensation.

The first method has the advantage of being relatively insensitive to the electrolyte concentration since the volume of electrolyte in the cell is not fixed. However, the space between electrodes must be great enough to provide for the circulating electrolyte, and this results in additional internal resistance and lower cell performance. In addition, special precautions must be taken to minimize circulating currents through the electrolyte manifolds; otherwise, electrolysis of water in the electrolyte will result in the generation of hydrogen and oxygen together in the electrolyte loop.

The most effective means of preventing electrolyte bridging from cell to cell employs a weir for each cell which controls the level of electrolyte in the cell. Electrolyte which flows over the weir falls by gravity to a sump. This approach if, of course, unsuitable for zero-gravity operation. There is no practical means of completely

eliminating circulating currents in the electrolyte loop for a system which must operate in zero-gravity. For this reason, and because of the major impact on cell design (to provide electrolyte circulation space between electrodes) the use of circulating electrolyte for cell water removal was not considered further in this study.

Water removal by means of a circulating stream of reactant gas is a well established technique for aerospace applications. This was the method employed in the Apollo fuel cell system. The method is equally applicable to water removal from matrix-type cells. A breadboard fuel cell system using a circulating hydrogen loop for water removal was constructed and successfully tested by Allis-Chalmers as early as 1962.

The circulating-hydrogen technique for water removal from fuel cells was abandoned by Allis-Chalmers after a practical means was developed for implementing the third type of water removal system. In this system, known as Static Moisture Removal, an asbestos matrix (similar to that used to hold the cell electrolyte) is impregnated with a KOH solution and located adjacent to the hydrogen distribution compartment. The matrix forms one wall of the hydrogen compartment. It freely absorbs water vapor, but is relatively impervious to the hydrogen. The absorbed water vapor is evaporated from the side of the matrix opposite to the hydrogen compartment, and the nearly-pure water vapor is removed from the cell by maintaining a lower-pressure sink outside of the cell.

The purpose of the trade studies reported in this memorandum was to re-examine the merits of the alternate methods of water removal and determine the optimum approach for light-weight fuel cell power systems. The following discussion first establishes the mechanisms involved in the water transport processes from a theoretical standpoint. Then the impact of the alternative water removal methods on system performance, weight, volume, reliability, and operational flexibility is briefly assessed.

• Circulating Hydrogen Analysis

Fuel cell reactions occur within the porous structure of the electrodes. The hydrogen and oxygen reactants are transported to (and by-product water is transported from) the reaction sites by mass diffusion. The driving

force for diffusional processes is a difference in mass concentration of the substance. The physical dimension of fuel cells, the diffusional properties of hydrogen and water vapor and the rates of water removal are such that only small differences in concentration are required to transfer the water from the electrode into the main hydrogen stream. For the present purpose, the concentration of water vapor in the main hydrogen stream can be considered equal to that in the electrode pores.

The concentration of water vapor in hydrogen can be conveniently expressed in terms of the partial pressures of water vapor and hydrogen:

$$F_v = \frac{1}{\frac{M_H}{M_v} \frac{P-P_v}{P_v} + 1} \quad (1)$$

where M_H = molecular weight of hydrogen

M_v = molecular weight of water

P = total pressure in reactant cavity, psia

P_v = vapor pressure of water, psia

The specific humidity of the hydrogen (pounds of water vapor per pound of dry hydrogen) is:

$$M = \frac{M_v}{M_H} \frac{P_v}{P-P_v} \quad (2)$$

Then the mass flow rate of water vapor in the hydrogen stream is given by:

$$\dot{W}_v = \frac{M_v}{M_H} \frac{P_v}{P-P_v} \dot{W}_H \quad (3)$$

where $\dot{W}_H$ = hydrogen flow rate, lb/hr

The hydrogen stream entering the cell can be considered to be made up of two components: the hydrogen which is recirculated, and that which is consumed in the cell, $\dot{W}_{H_R}$ and $\dot{W}_{H_C}$, respectively. The rate of water

removal from a cell is given by the difference between the flow rate of water into and out of the cell:

$$\dot{W}_w = \frac{M_v}{M_H} \frac{(P_v)}{(P-P_v)_f} \dot{W}_{H_R} - \frac{M_v}{M_H} \frac{(P_v)}{(P-P_v)_o} (\dot{W}_{H_R} + \dot{W}_{H_c}) \quad (4)$$

where the subscripts f and o designate cell outlet and cell inlet conditions, respectively. For steady-state condition, the water removal rate must equal the rate of water production:

$$\dot{W}_w = \frac{M_v}{M_H} \dot{W}_{H_c} \quad (5)$$

Combining and rearranging the last two equations gives:

$$P_{v_f} = \frac{P + \mu P_{v_o}}{1 + \mu} \quad (6)$$

The water vapor pressure of the electrolyte is dependent on the temperature and concentration of the solution, as shown in Figure 3.1-4. The required rise in water vapor pressure from inlet to outlet of the hydrogen stream can be accomplished by a decrease in electrolyte concentration, an increase in temperature, or a combination of these two. For the edge-cooled cell configuration used in the 2 kW system, the cell temperature is independent of position relative to the hydrogen flow, and removal of water by means of circulating hydrogen will establish an electrolyte concentration gradient with concentration decreasing in the direction of hydrogen flow. If the cells are cooled by a fluid circulated through the cell stack, it is possible to establish temperature gradients which increase in the direction of flow. If this method of cooling is used, it is possible to virtually eliminate concentration gradients in the cells.

Consider first the condition of edge-cooled cells. The stack temperature which is controlled, is sensed at the edge of the cells. The interior of the cell stack is at a higher temperature. The temperature difference between

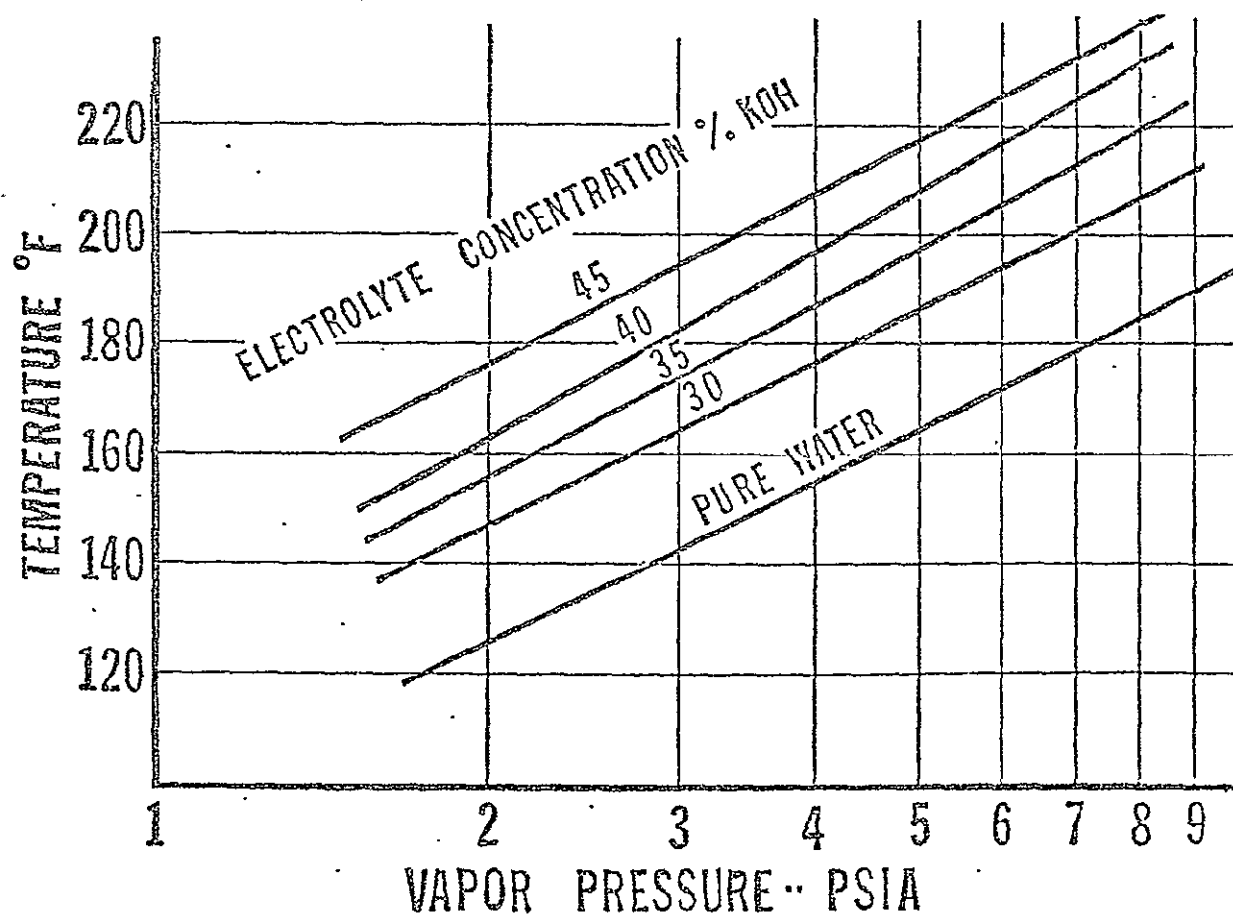


Figure 3.1-4. Electrolyte Vapor Pressure/Temperature Relationship

the center of the cell and the border is given by:

$$\Delta T = \frac{qa^2}{2KS} \quad (7)$$

where q = heat flux over electrode area, Btu/hr ft²

a = distance from center of cell to edge of electrode, ft

K = thermal conductivity of cell plates, Btu/hr ft²(°F/ft)

S = thickness of cell plates, ft

For a 2 kW cell reconfigured to eliminate the static moisture removal components, the physical properties result in:

$$\Delta T = .0240 q$$

Since the temperature distribution across the face of the electrodes is parabolic, the mean cell temperature is given by:

$$T_m = T_c + \frac{2}{3} \Delta T = T_c + .0160 q \quad (8)$$

where T_c = controlled (border) temperature, °F.

The above relationships were used to calculate the electrolyte concentration distribution in an operating cell using a circulating hydrogen stream for water removal and with edge cooling. Typical results are shown in Figure 3.1-5, for a hydrogen input to the cell of 0.0435 lb/hr ($\mu = 12$ at 40 amp). The electrolyte concentration variation with load at the hydrogen inlet end of the cell is due to the corresponding cell mean temperature variation.

Although the change in electrolyte concentration with load appears to be large in Figure 3.1-5, the average concentration ranges between 42.5% and 43.7% over the loads shown. This is because of the concentration gradient which exists between the hydrogen and oxygen sides of the cell. This gradient increases with load, and tends to offset the effects of load on hydrogen-side concentration.

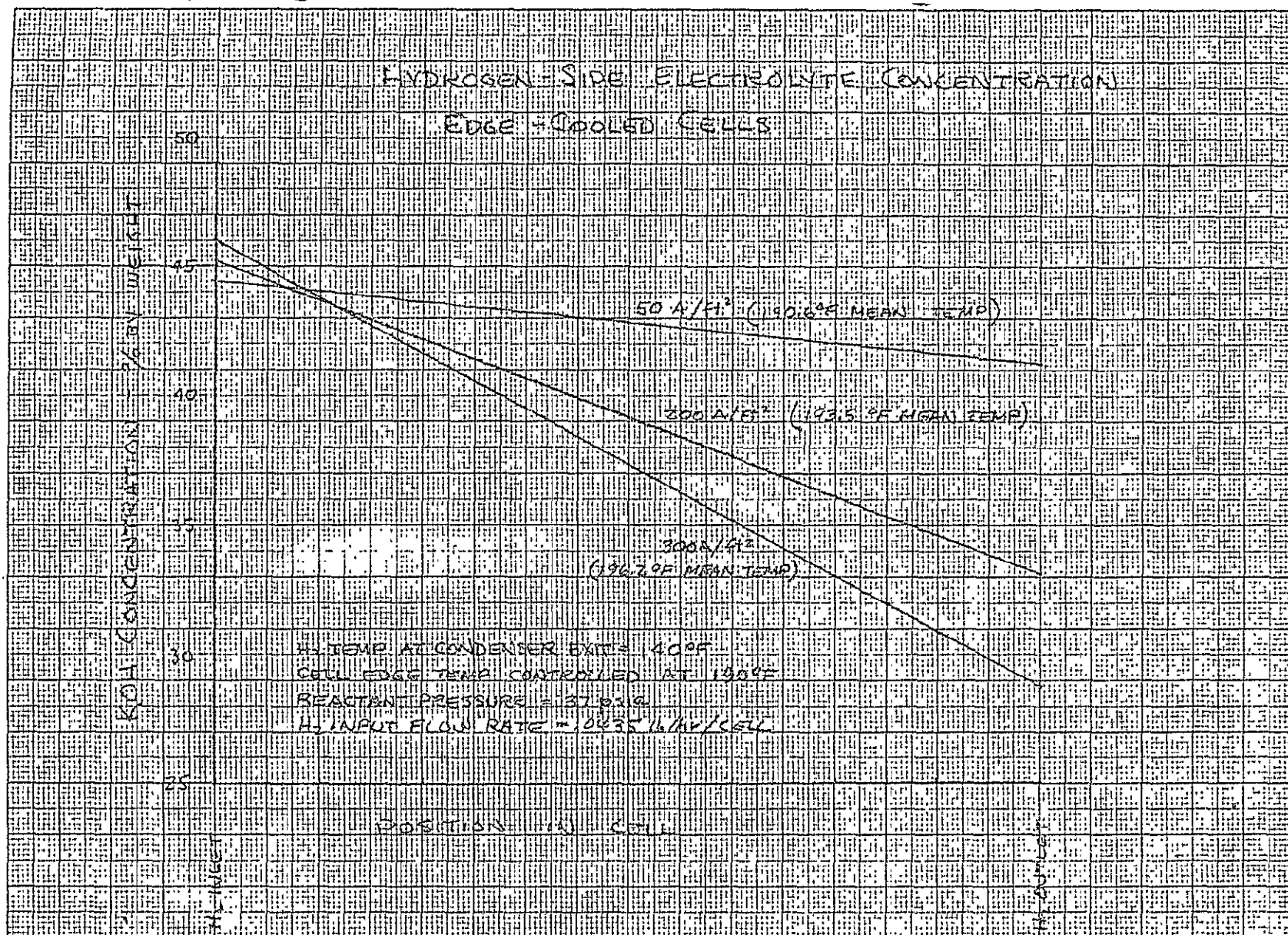


Figure 3.1-5. Hydrogen-Side Electrolyte Concentration Edge-Cooled Cells

Similar results for the internally-cooled cell are shown in Figure 3.1-6. A relatively small variation of KOH concentration across the face of the cell results in this system, due to the temperature rise of coolant (and, hence, electrolyte) as shown.

• Static Moisture Removal Analysis

Fuel cell by-product water is removed from the cell electrolyte by the same mechanism for both Static Moisture Removal and the circulating hydrogen method. The water is evaporated from the electrolyte within the porous electrode and diffuses into the hydrogen stream. With Static Moisture Removal, however, the electrolyte concentration is controlled by maintaining the appropriate KOH concentration in a matrix adjacent to the cell. The water diffused from the hydrogen electrode into the hydrogen compartment of the cell is then absorbed by the second matrix, and transported by diffusion to the opposite side of the water transport matrix.

As discussed for the circulating hydrogen system, the diffusional transport of water vapor through the hydrogen is accomplished with very little concentration difference. As a result, the concentration of KOH at the hydrogen face of the water transport matrix and the concentration in the hydrogen electrode will be nearly equal. Concentration gradients will, of course, be present between the hydrogen and oxygen electrodes, and between the faces of the water transport matrix. The magnitude of this concentration gradient is given by:

$$\Delta(pc) = \frac{\dot{W}_w t}{DA} \quad (9)$$

where p = local density of the KOH solution, lb/ft³

c = local concentration of the KOH solution, percent water by weight

$\dot{W}_w$ = rate of water transport, lb/hr

t = distance through which diffusion takes place, beet

D = diffusion coefficient for water in a KOH solution, ft²/hr

A = cross-sectional area available for diffusion, ft²

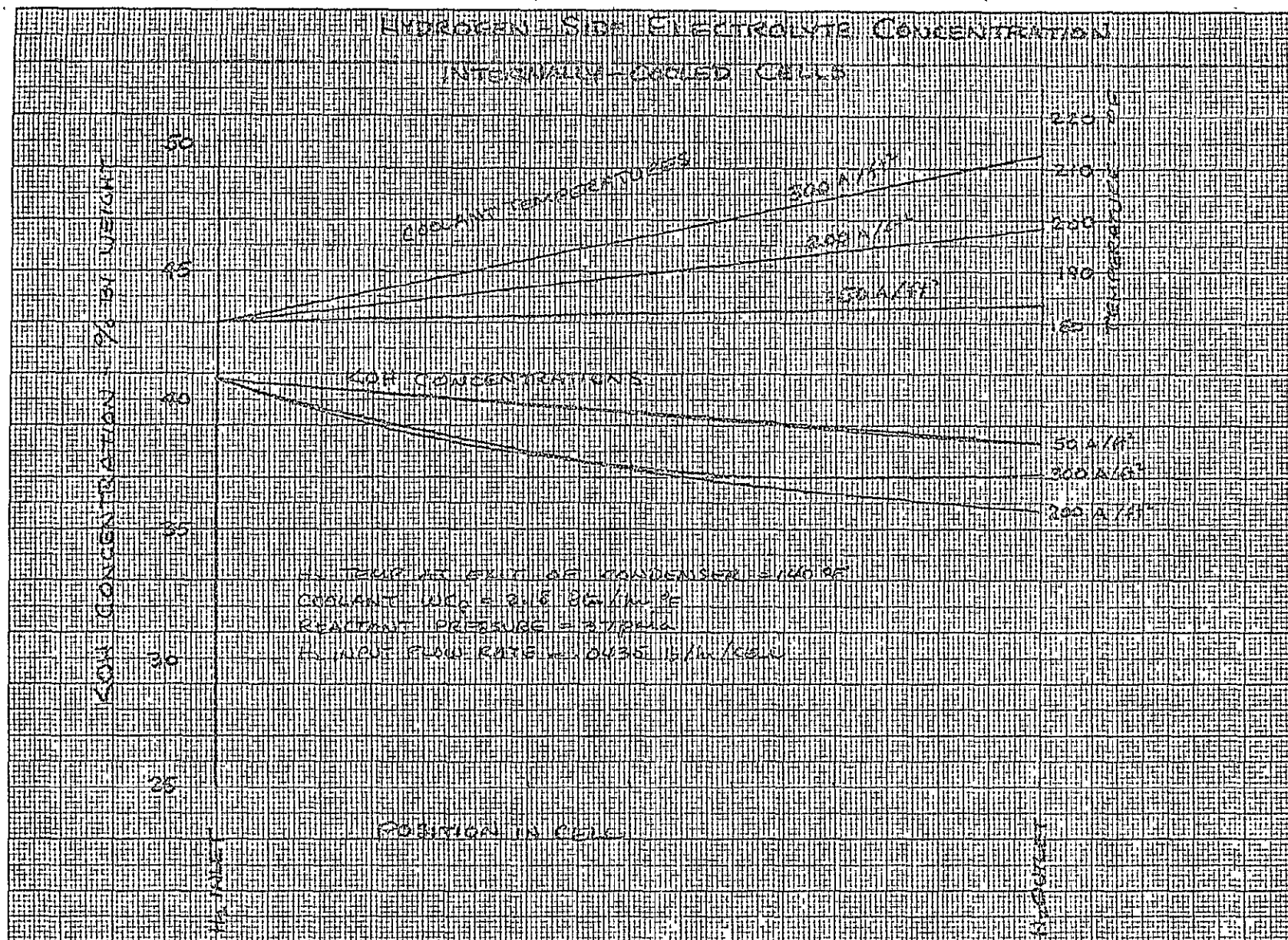


Figure 3.1-6. Hydrogen-Side Electrolyte Concentration Internally-Cooled Cells

The value of the diffusion coefficient for KOH not contained in a matrix is shown in Figure 3.1-7. These data were calculated by R. Iczkowski (Allis-Chalmers Research Division) from the fundamental properties of the solutions. The effect of entrapment in a porous matrix on the diffusion coefficient is reported to be analogous to the effect on electrical conductivity of the electrolyte.* The electrical conductivity of a KOH solution in an asbestos matrix has been measured as being 1/6 of the conductivity of free electrolyte.** Based on this information, the diffusion coefficient for a 35% KOH solution is:

$$D = 1.9 \times 10^{-4} \text{ ft}^2/\text{hr} \quad (10)$$

Then, for an area of 0.2 ft^2 and a compressed matrix thickness of 0.040 inches:

$$\Delta(\text{pc}) = 87.6 \dot{W}_w \quad (11)$$

The results predicted by this analysis are shown in Figure 3.1-8. Although the controlled cell temperature (sensed at the edge of the cell) is a constant 190°F, the mean temperature varies upward to 218.5°F. This is because of the temperature gradients defined by Equation (7). The existence of this gradient actually tends to stabilize the cell average concentration because the effective concentration in the water removal cavity increases with mean temperature if the water cavity pressure is held constant.

The limiting current density for a 50-mil water matrix with the above operating parameters is 800 amp/ft^2 . If the water removal matrix were made of 30 mil reconstituted asbestos, the limiting current density would be 1300 amp/ft^2 .

* R. E. Meredith and C. W. Tobia, Journal of the Electrochemical Society, V110, P1257, 1963.

** Holdervan, R. G., "Research and Development of High Performance Light-Weight Fuel Cell Electrodes", NASA CR 54436, American Cyanamid, 1965.

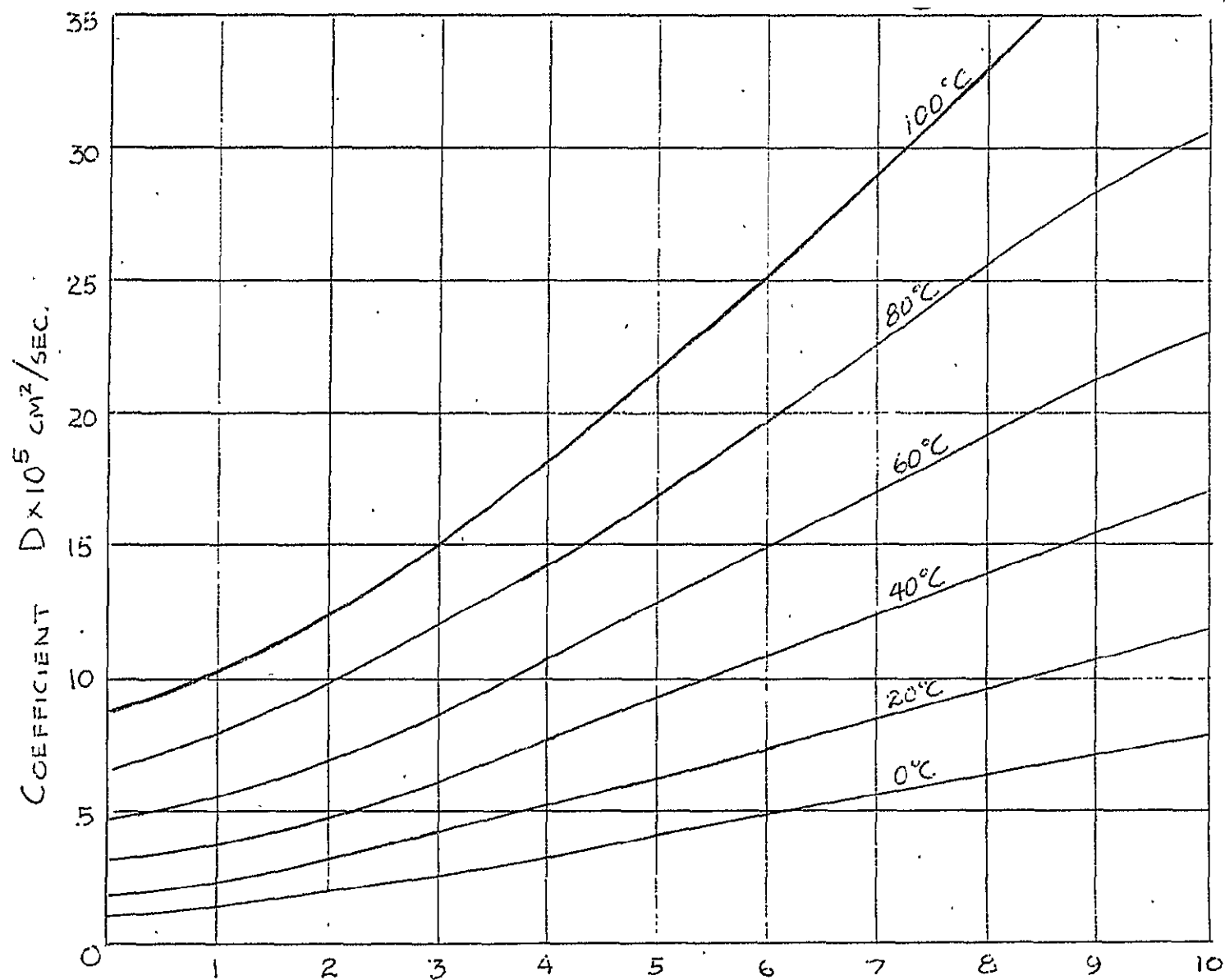


Figure 3.1-7. Diffusion Coefficient of KOH

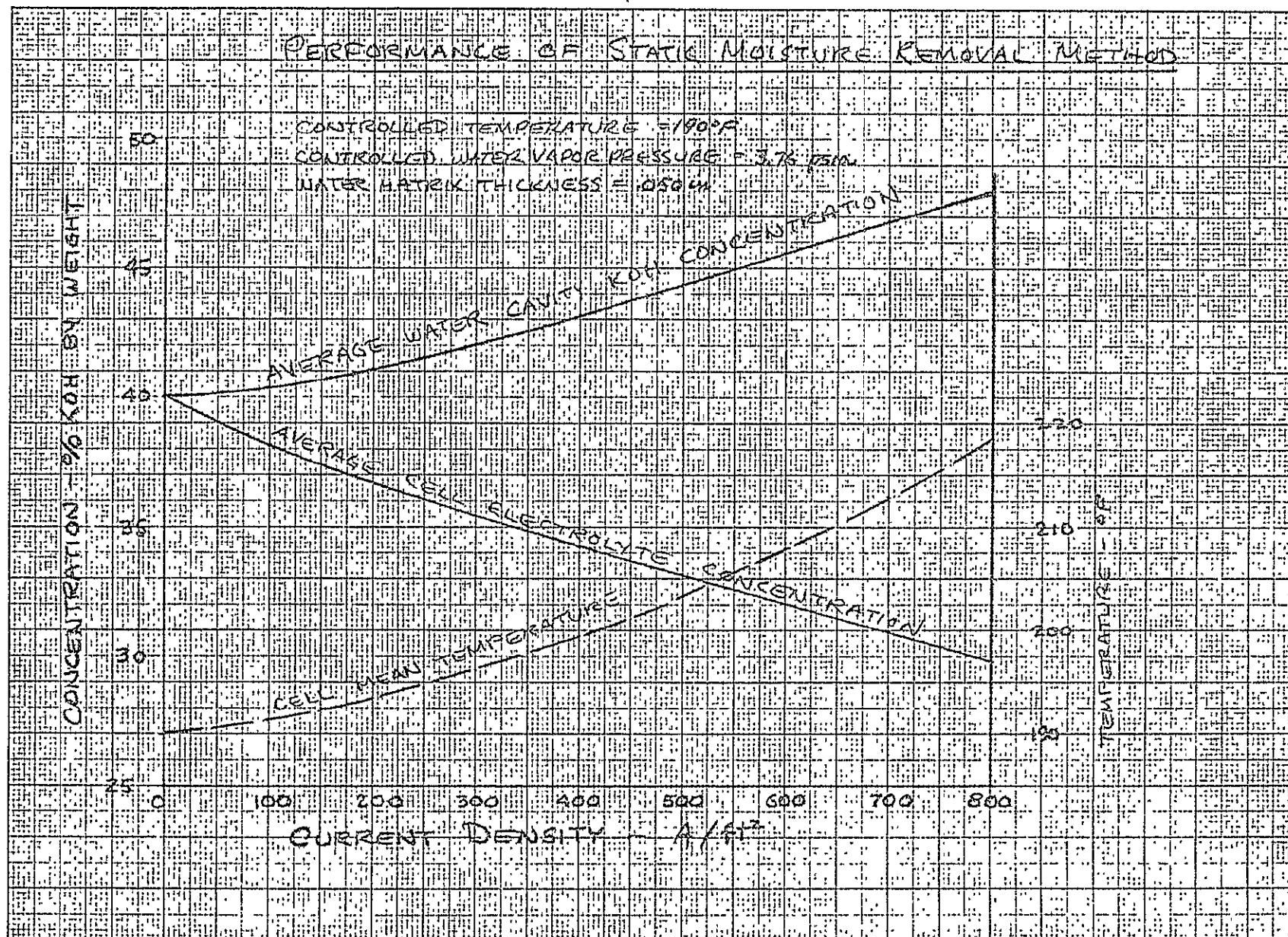


Figure 3.1-8. Performance of Static Moisture Removal Method

- o System Comparison

In evaluating the system alternatives, factors which were considered included:

- o Sensitivity of control technique
- o Weight
- o Parasitic power requirements
- o Reliability and maintainability
- o Operational flexibility
- o Cost

Each of these factors is discussed in the following paragraphs.

- o Control Sensitivity

Any of the moisture removal techniques previously identified have as their aim the maintenance of a near-constant concentration (or, equivalently, a near-constant volume) of electrolyte in the cell. To accomplish this, it is necessary to control certain operating parameters of the cells, such as temperature, pressure, or flow rate. The analytical models, derived as described in the preceeding sections, were used to evaluate the stability of the control techniques when subjected to upsets or control variabilities which affect the controlled parameters.

The results of the control sensitivity analysis are displayed in matrix form in Table 3.1-3. The values shown are the normalized partial differences for the response of cell electrolyte concentration to variations in the controlled parameter. The normalized partial difference is defined by: $\frac{(\Delta C)}{(C)} / \frac{(\Delta X)}{(X)}$

where X represents the controlled parameter. The larger the normalized partial difference, the greater the influence of that parameter on electrolyte concentration control.

The moisture removal technique which is sensitive to the greatest number

Parameter	Circulating H ₂ - Temperature Rise in Cell	Circulating H ₂ Concentration Decrease in Cell	SMR - 50-Mil Matrix	SMR - 30-Mil Matrix
Current	-.092	-.034	-.078	-.0082
Coolant/Cell Temperature	1.93	1.83	2.34	2.08
Condenser Temperature	-1.23	-1.08	0	0
H ₂ Flow Rate	.146	.140	0	0
Coolant Flow Rate	-.107	N/A	N/A	N/A
Reactant Pressure	-.157	-.146	0	0
Water Cavity Pressure	N/A	N/A	-.535	-.453

Table 3.1-3. Control Sensitivity Matrix

of parameters is the circulating hydrogen system with temperature rise in the cell. The concentration of electrolyte in the cell is affected to some degree by six cell operating parameters; however, only two of these parameters (coolant temperature at the inlet to the cell, and hydrogen temperature at the condenser exit) have a major impact. The sensitivity of the control to hydrogen flow rate indicates that care must be taken in the cell stack design to assure adequately uniform hydrogen flow distribution among the cells.

The circulating hydrogen system with a concentration decrease in the direction of hydrogen flow (cell edge cooling) responds to the cell operating parameters in much the same way as the previous system. Because of the edge cooling arrangement, however, this system is not sensitive to the flow rate of coolant, except as it may affect cell temperature.

Two alternates are shown for the Static Moisture Removal system; one uses a 50-mil matrix (present standard construction), and the other uses a 30-mil reconstituted asbestos matrix. Both of the alternates are sensitive to the same three parameters, but the 30-mil matrix is significantly less sensitive to all three. Only one parameter, cell temperature, has a major impact on electrolyte concentration control. This indicates the importance of incorporating a temperature-compensating feature in the water cavity pressure control, and of maintaining uniform temperature among the cells in the stack.

e Weight

System weights were estimated in terms of changes to the present 2 kW design. Weight improvements which have been previously identified were incorporated in the estimates as individually tabulated below. Weight reduction of cell plates was not included except when other changes made redesign of the plates necessary.

For the circulating hydrogen system with internal cooling, the following

weight changes would occur for a 32-cell stack:

<u>Design Change</u>	<u>Weight Change (lb)</u>
• Eliminate water removal plate and matrix assembly	-23.3
• Eliminate one of two H ₂ plates/section*	- 8.22
• Incorporate liquid cooled O ₂ plates with electrical insulation between plates*	+ 2.5
• Reduce stud weight for shorter stack	- 1.85
• Eliminate canister, dome, end plate, and heat exchanger	-16.8
• Eliminate fans, ducts, baffler	- 5.5
• Increase pump size for FC-75 circulation	+ 1.8
• Eliminate present H ₂ O recovery system	-22.38
• Add H ₂ pump/separatro**	+ 9.6
• Add condenser**	+ 3.4
• Add coolant control valve for condenser	+ 0.8
• Add protective cover for stack	<u>+ 1.0</u>
Net Change	-58.95 lb

* Requires redesign of stack for parallel connection of H₂, rather than O₂, plates.

** Based on Apollo fuel cell system component weights.

A circulating hydrogen system with cold plate (edge) cooling would permit the following weight reduction:

<u>Design Change</u>	<u>Weight Change (lb)</u>
• Eliminate water removal plate and matrix assembly	-23.3
• Add polysulfone spacer between the plates for electrical isolation	+ .67
• Reduce stud weight for shorter stack	- 1.66
• Eliminate canister, dome, end plate, and heat exchanger	-16.8
• Eliminate fans, ducts, baffles	- 5.5
• Add cold plates on each side of stack	+ 6.0
• Eliminate present H ₂ O recovery system	-23.38
• Add H ₂ pump/separator	+ 9.6
• Add condenser	+ 3.4
• Add coolant control valve for condenser	<u>+ 0.8</u>
Net Change	-49.17

The following weight changes would be incorporated in a Static Moisture Removal system using a 30-mil water removal matrix and cold plate cooling:

<u>Design Change</u>	<u>Weight Change (lb)</u>
• Reduce water removal matrix to 30-mil thickness	- 3.26
• Replace water cavity plate with .060 inch thick polysulfone	- 8.1
• Reduce stud weight for shorter stack	- 0.42
• Eliminate canister, dome, and plate, and heat exchanger	-16.8
• Eliminate fans, ducts, baffles	- 5.5
• Add cell plates to each side of stack	+ 6.0
• Incorporate Dynatherm design for condenser/separator	- 7.9
• Incorporate light weight water pump	<u>- 2.4</u>
Net Change	-38.38

• Parasitic Power

The systems which employ a recirculating hydrogen stream will require a hydrogen pump. The parasitic power required to operate the pump was estimated as follows:

From flow/pressure drop data on oxygen cell plates, it is known that at a flow rate equivalent to 250 amp consumption (.164 lb/hr) an average pressure drop of 0.05 psi results. Assuming Darcy's Law applies*, pressure drop is related to flow rate by the relationship:

$$\Delta p \propto \frac{\dot{W}}{\rho} \mu$$

* Electrochemical Systems Heat and Mass Transfer, NAS8-21159-QPR-005, Institute of Gas Technology, 1968.

where W = mass flow rate lb/hr
 ρ = fluid density, lb/ft³
 μ = fluid viscosity, lb/hr ft

Since the hydrogen and oxygen flow paths are nearly identical,

$$\frac{\Delta P_H}{\Delta P_O} = \frac{W_H}{W_O} \frac{\mu_H}{\mu_O} \frac{\rho_O}{\rho_H}$$

Substituting numerical values from test data and the known physical properties of the gases gives:

$$\Delta P_H = 1.12 \dot{W}_H \quad (\text{pressure drop in psi})$$

For a nominal circulation rate of 0.0435 lb/hr of hydrogen, $\Delta P = .0486$ psi.

In order to achieve satisfactory distribution of hydrogen flow among the cells in the stack, it will be necessary to insert orifices in each cell with carefully controlled dimensions. This is because the flow resistance varies from cell-to-cell, and tends to increase with time due to buildup of corrosion products, electrode swelling, etc. Based on past experience, a variation of at least $\pm 50\%$ in the flow resistance of cells in a stack should be allowed for. If, in addition, a tolerance of $\pm 10\%$ in the flow resistance of the orifices is allowed, the pressure drop needed to obtain proper flow uniformity can be calculated using the control sensitivity results presented in an earlier section.

Generally, a variation of $\pm 2\%$ KOH about the optimum setting is allowable. Assume this as a limit for maximum variation due to maldistribution of hydrogen and coolant flow among the cells; then, from Figure 3.1-8, the variation of concentration due to hydrogen flow maldistribution is given by:

$$\frac{\Delta C}{C} = .146 \frac{\Delta \dot{W}_H}{\dot{W}_H}$$

Similarly, for coolant maldistribution:

$$\frac{\Delta C}{C} = .107 \frac{\Delta \dot{W}_e}{\dot{W}_e}$$

Then, to limit concentration variation to a 2% KOH tolerance with a 40% KOH nominal setting:

$$\frac{.02}{.4} = .146 \frac{\Delta \dot{W}_H}{\dot{W}_H} + .107 \frac{\Delta \dot{W}_c}{\dot{W}_c} = .05$$

If the allowable maldistributions of hydrogen and coolant flow are taken equal:

$$\frac{\Delta \dot{W}_H}{\dot{W}_H} = \frac{\Delta \dot{W}_c}{\dot{W}_c} = 0.198$$

Now, with the assumed tolerance on flow impedances of $\pm 10\%$ for the control orifices and $\pm 50\%$ for the cells:

$$\frac{.1 \Delta P_c + .5 (.0486)}{\Delta P_c + .0486} = .198$$

and $\Delta P_c = 0.15$ psi.

This is the minimum pressure drop through the cell flow-control orifice which will provide adequate flow distribution under the stated conditions. The overall pressure drop in the system includes stack manifold losses, external line losses, and the condenser loss. An overall pressure drop of 0.4 psi would appear to be a reasonable minimum value.

Hydrogen pump power is calculated from the relationship:

$$P = Q\Delta P$$

where Q is the volumetric flow rate through the pump, and ΔP is the total system pressure drop. For a 32-cell stack operating under the condition indicated previously, and with the pump located downstream of the condenser, the pump power is:

$$P = \frac{32 (.0435)}{.0108} (.4) (144) = 7420 \text{ ft lb/hr}$$

$$P = 2.79 \text{ watts}$$

The overall efficiency of the hydrogen pump, from electrical input to flow energy output, is unlikely to exceed 5%. Then the total parasitic power required for the hydrogen pump is about 46 watts.

Parasitic power for the coolant pump was based on analyses performed for the High Performance Fuel Cell program (AF 33(615) - 3790). The analysis indicates a pressure drop of about 7.5 psi in the FC-75 coolant loop. Using an overall efficiency of 10% for the pump/motor combination, the required parasitic power is 23 watts.

The parasitic power for the recirculating system using heat pipe cooled cold plates is limited to that required for circulation of the hydrogen. This system is less sensitive to hydrogen flow rate variations and has no coolant flow maldistribution to provide for. The hydrogen pumping power can be calculated by the method described above. This value of this parasitic power is 43 watts.

The Static Moisture Removal system with heat pipe cooled cold plates has a very low parasitic power requirement. If a mechanical moisture removal valve is used, no parasitic power is required for water and heat removal. Even with an electronic controller, the average power consumption will be only about 10 watts.

• Reliability/Maintainability

A reasonable estimate of the relative reliabilities of alternate system approaches

can be obtained by comparing the number of critical components required in the alternate systems. Such a comparison is shown in Table 3.1-4. The circulating hydrogen system with internal liquid cooling has the greatest number (six) of critical components. If circulating hydrogen is combined with a heat pipe cold-plate cooled stack, the number of critical components is reduced to four.

In a system employing Static Moisture Removal with a mechanical temperature-compensated back pressure regulator for the water removal valve, this valve is the single critical component. Condenser temperature is not important, because the system has the capability of automatically switching to open-loop operation. Moderate variations in stack temperature are also unimportant because the water removal valve is capable of adjusting the controlled pressure to maintain a constant KOH concentration regardless of cell temperature. Furthermore, variations of reactant pressure have no effect on the Static Moisture Removal process.

Maintenance requirements for the system are also compared in the figure in terms of the components affecting water removal which are subject to wearout and replacement, the circulating hydrogen system with internal liquid cooling has one additional pump which is subject to wearout.

• Operational Versatility

Factors considered in evaluating the operational versatility of the alternate water removal methods are:

- Overload capability
- Growth potential
- Orientation requirements
- Environmental constraints

	Circulating H ₂ - Temperature Rise in Cell	Circulating H ₂ - Concentration Decrease in Cell	Static Moisture Removal
<u>Critical Control Functions</u>			
• Primary	• H₂ temperature at condenser exit • Coolant temp at stack inlet	• H₂ temperature at condenser exit • Cell temperature	• Cell temperature
• Secondary	• H₂ flow rate • Coolant flow rate • H₂ pressure	• H₂ flow rate • H₂ pressure	• Water cavity pressure
<u>Critical Water Removal Components</u>	• H₂ pump • Coolant pump • Condenser coolant control valve • Stack coolant control valve • Condenser • H₂ pressure regulator	• H₂ pump • Condenser coolant control valve • Condenser • H₂ pressure regulator	• Moisture removal valve
<u>Wearout Items</u>	• H₂ pump • Coolant pump • Deionizer	• H₂ pump • Deionizer	• H₂O pump • Deionizer

Table 3.1-4. Reliability/Maintainability Comparison

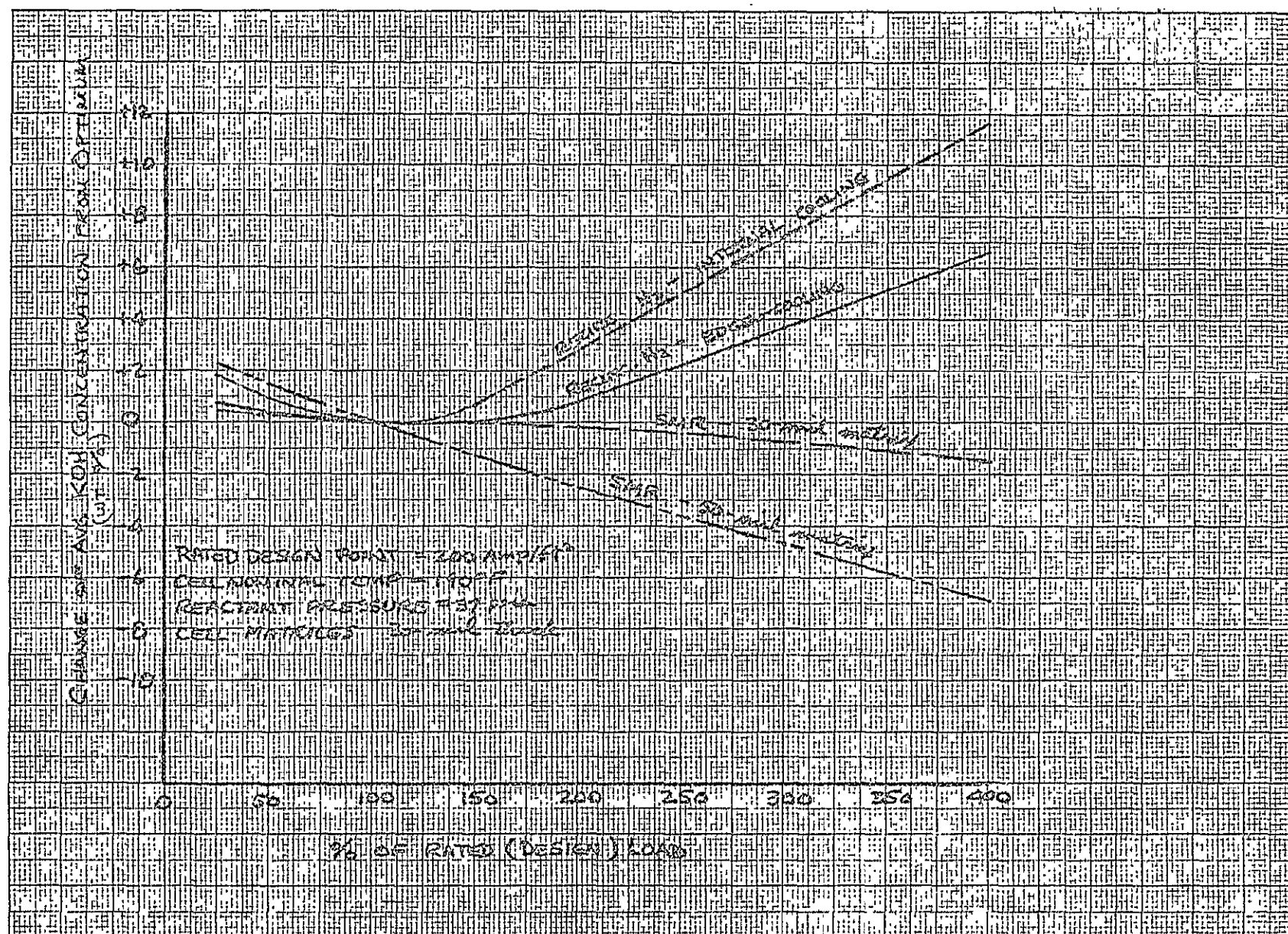


Figure 3.1-9. Comparison of Electrolyte Concentration Change with Load

of this limiting current will not greatly exceed 1300 amp/ft².

However, if a thinner cell matrix is employed, the limiting current can be increased at least a factor of two for the circulating hydrogen systems. In order to achieve this improvement with SMR, it would be necessary to decrease the water removal matrix to the thickness of the cell matrix. This is probably not feasible because of the danger of blow-through of the pores of a thin matrix; hence, the circulating hydrogen systems have an advantage in growth potential to very high current densities.

• Orientation Requirements

Both the circulating hydrogen system and the Static Moisture Removal System (SMR) are suitable for operation in zero-gravity. In a gravity the circulating hydrogen system will have a preferred orientation for the condenser relative to the pump/separator. Because of the high flow rate of hydrogen through the condenser, condensate will tend to be swept along the walls against the pull of gravity and decrease the effect of gravity.

The static moisture removal system is essentially insensitive to gravity as long as tubing containing water vapor is well insulated.

• Environmental Constraints

One of the major constraints of the Static Moisture Removal system has been the need to supply a vacuum at the condenser interface to enable venting of non-condensibles. This requirement has presented little problem in the past because the vacuum is readily available during a space mission. Operation under terrestrial conditions up to approximately 50,000 feet altitude complicates matters.

The non-condensibles in the condenser are virtually all hydrogen which has diffused through the water removal matrices. It is possible to provide a hydrogen "window" made of a silver-palladium alloy which has high permeability

to hydrogen, but is relatively impervious to other gases. With such a device (which is commercially available) it will only be necessary to periodically evacuate the condenser and lines to remove accumulation of trace quantities of gases other than hydrogen.

o Cost

Cost estimates have been limited to consideration of development cost only. Gross estimates have been based on the development necessary to reach the status of an engineering demonstration model. Documentation level included would be sufficient to insure duplication of the design. These estimates are as follows (values in millions of dollars):

o Static Moisture Removal	1
o Circulating hydrogen with heat pipe cold plate cooling	2
o Circulating hydrogen with internal liquid cooling	5

The cost of developing the improved Static Moisture Removal system is based on our recent proposal to NASA. It includes incorporation of heat pipe cooled cold plates, an improved condenser design, and incorporation of polysulfone water removal plates and thinner water removal matrices.

The circulating hydrogen system with edge cooling would require nearly all of the activity associated with the improved Static Moisture Removal method. In addition, a completely new water removal system would have to be designed and developed. A substantial amount of single section and small stack testing would be required to verify the design; this would, in turn, require extensive modification of the existing test benches. Additional test verification of the design would be required at the full size stack level.

The circulating hydrogen system with internal cooling requires a complete redesign of the fuel cell stack. It also requires development of a new water

removal system and thermal control system. The substantial amount of development testing, the large number of new drawings and specifications, and the need for a number of new system components results in the relatively large development cost estimate.

• Summary and Conclusions of Water Removal Methods

The factors considered in the comparison of the alternative water removal systems are summarized in matrix form in Table 3.1-5.

The system with greatest potential for hardware weight reduction (based on the present 2 kW design) employs circulating hydrogen with internal liquid cooling of the stack. This system also requires the greatest parasitic power. To make a proper weight comparison, the total system weight, including reactants consumed, must be considered. A normal average reactant consumption rate is about 0.8 lb/hr/kW. Then the mission duration for which the total system weights of the recirculating hydrogen system and Static Moisture Removal system are equal is given by:

$$T = \frac{58.95 - 38.38}{.8 (69-10) (1000)} = 435 \text{ hours}$$

Similarly, the break-even time for the recirculating hydrogen system with edge cooling is:

$$T = \frac{4917 - 38.38}{.8 (46-10) (1000)} = 375 \text{ hours}$$

If the weight of reactant tankage is included at the rate of 1.7 lb tank/lb H₂ and 0.27 lb tank/lb O₂, the break-even times become 304 hours and 262 hours, respectively. For the 200-hour mission duration envisioned for a 5 kW space shuttle power system, the weight advantages for the circulating hydrogen systems over Static Moisture Removal are 7.74 lb and 0.98lb, respectively. Thus, only an insignificant weight advantage exists for the circulating hydrogen systems.

	Circulating H ₂ Temp. Rise in Cell	Circulating H ₂ Concentration Decrease in Cell	Static Moisture Removal
Control Sensitivity (number of sensitive parameters)	6	5	3
Weight change from present 2 kW design , lb)	-58.95	-49.17	-38.38
Parasitic power (for water removal and cooling, watts)	69	46	10
Reliability (number of critical components)	6	4	1
Maintenance (number of wearout items)	3	2	2
Operational versatility (relative ranking from best (1) to worst (31)	2	1	3
Cost (development cost to status of engineering model \$M)	5	2	1

Table 3.1-5. Trade-off Matrix

Moisture Removal are 7.74 lb and 0.98 lb, respectively. Thus, only an insignificant weight advantage exists for the circulating hydrogen systems.

The inherent reliability of the Static Moisture Removal system is considerably higher than for the circulating hydrogen systems. This is due to the lack of rotating elements in the system and to the excellent stability of the control method. Maintenance requirements for any of the systems are nearly equal.

The operational versatility of the circulating hydrogen systems is greater than for Static Moisture Removal. This is primarily because of the greater potential for higher power density operation. Development cost of the circulating hydrogen systems is substantially greater than for Static Moisture Removal. This fact reflects the advanced state of development of the 2 kW system, and the relatively modest design improvements identified for weight reduction.

Based on the preceeding analyses and rationale, the following conclusions have been drawn:

- (1) Static Moisture Removal is the optimum method for controlled removal of by-product water from the space shuttle fuel cell power system.
- (2) Thinner water removal matrices (~ 30 -mil) should be incorporated in the cell design.
- (3) The circulating hydrogen system with edge cooling of the stack is the second choice for water removal method.

3.1.4.2 Reactant Prehumidification

In the A-C Fuel Cell System, dry reactants are fed to the cell cavities. Consequently, the electrode areas immediately adjacent to the reactant inlet tends to dry out and the KOH crystalizes. This local drying contributes to cell voltage degradation. The problem has been handled in the past by using drying shields at the reactant inlet.

This local drying can be overcome by reactant prehumidification, and several methods of prehumidification were studied.

Preliminary analysis of several prehumidification methods were made using equivalent saturation at 39% KOH at 190°F as the target for both reactants. Following discussion summarizes each method.

- o Prehumidification Cells

The reactants will pick up the moisture generated and become humidified when by-passed through the moisture removal cavity of several operating cells. The prehumidification will be self-regulating with power level, because both the reactant flow and the moisture removed is proportional to power level. The reactants would also be preheated to essentially the operating temperature of the cell, eliminating the temperature gradient in the stack caused by cold reactant feed. The number of cells required to prehumidify the reactants is not a function of current. Three water removal cavities would be required to prehumidify the hydrogen and 1.5 cavities, one plus an end one, to prehumidify the oxygen. See Figure 3.1-10.

- o Vapor Exchanger

By-passing the water vapor from the Static Moisture Removal System through a cell cavity with capillary matrix walls and the reactant on the other side of the matrix, the reactant can be prehumidified. The prehumidification, however, could not reach the equivalent of 39% KOH at 190°F because the water vapor would be at that equivalent and there would be a concentration gradient across the matrix.

Using three cell cavities to pass the vapor through, see Figure 3.1-11, the hydrogen can be passed through the center two reactant cavities and the oxygen through the outer two reactant cavities. Using the experimental water vapor transmission rates obtained in moisture removal tests performed under NAS8-2696 in 1965, the reactants can be prehumidified to the equivalent

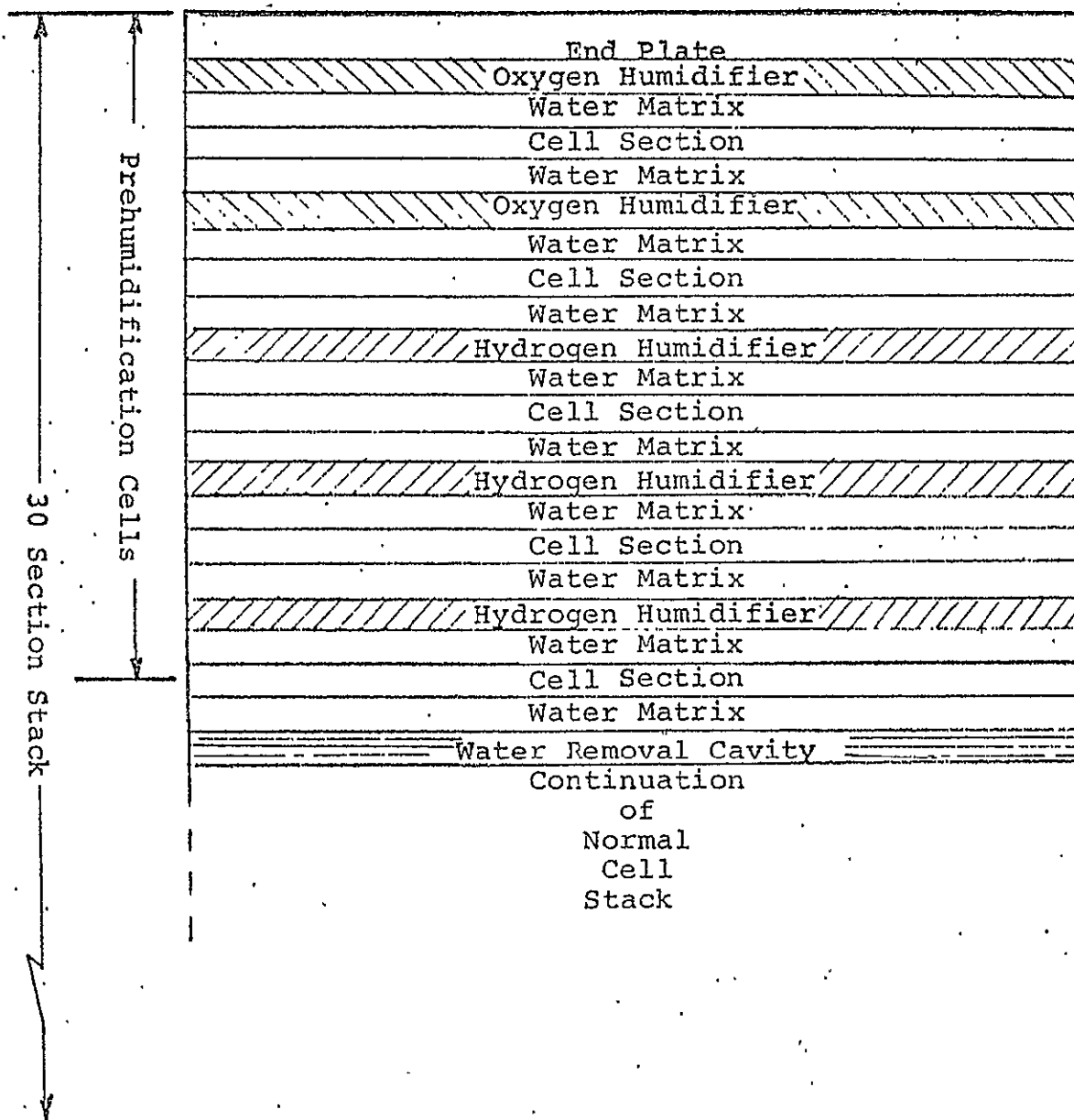
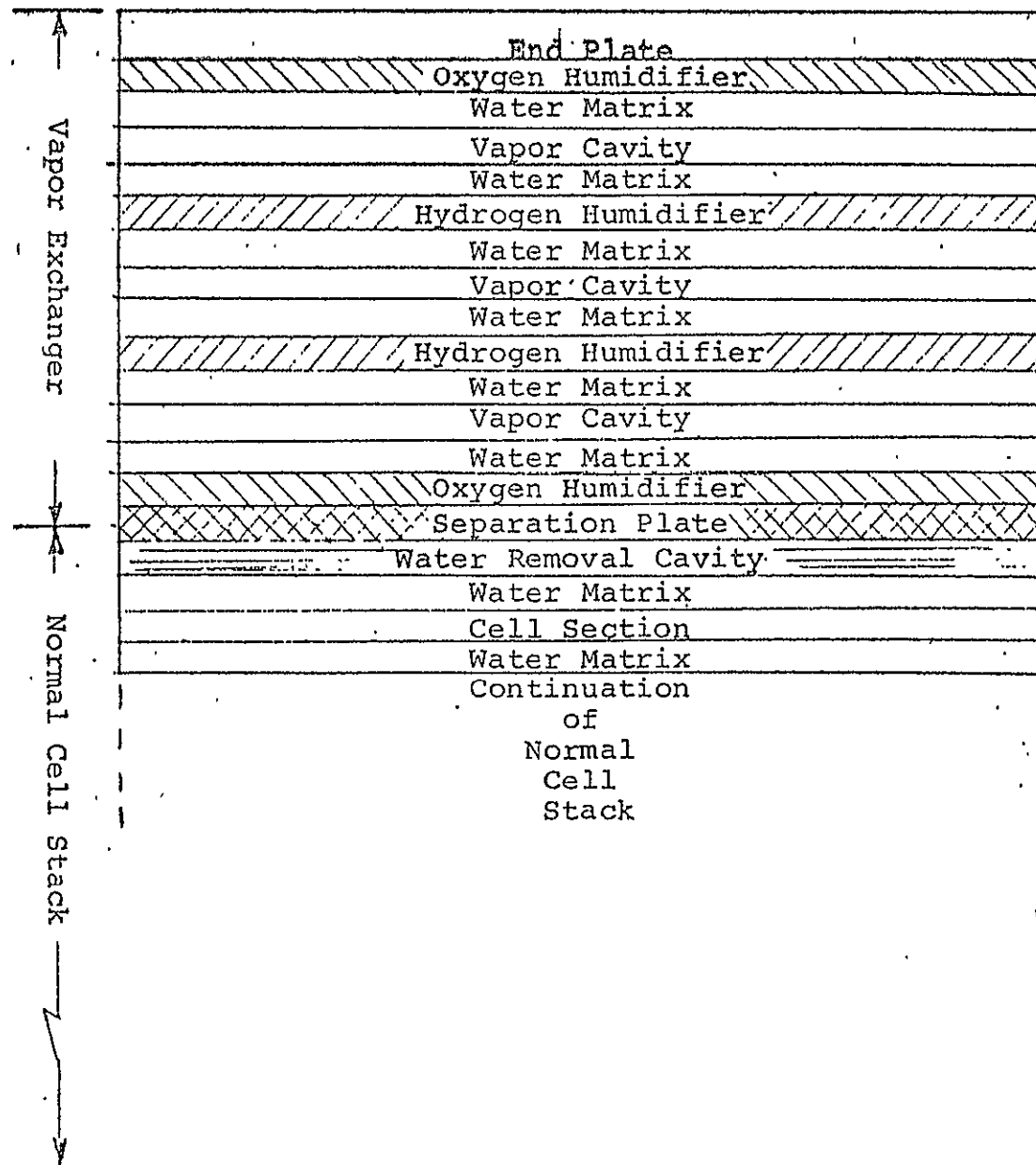


Figure 3.1-10. Prehumidification Cells

Figure 3.1-11. Vapor Exchanger



of 44% KOH at 190°F while operating 30-cell sections at 100 amps (250 ASF). The prehumidification level would be only slightly influenced by the power level, the prehumidification increasing toward the equivalent of 39% KOH at 190°F as power is decreased.

o Evaporator

The reactants can be humidified by various water evaporative methods. In each case, water and heat would have to be supplied in controlled manner. The simplest humidifier would perhaps be made by sparging of the reactants through a water bath. The level of humidification can be controlled by a temperature controller, and water addition by a level controller. This, however, would not work at zero gravity. Another would be a wick type evaporator. This would still require the temperature and the water addition controllers, although it would be independent of gravity. By placing this wick evaporator into the cell stack, the heater and the temperature controller could be eliminated because the cell would provide the heat stack temperature is already being controlled. However, since the operating temperature of the stack is considerably higher than that which would give the proper prehumidification with pure water, KOH would have to be introduced into the wick. This would tend to diffuse upstream via the water path, dilute the concentration in the wick and foul up the water flow control mechanism.

This evaporator would be sandwiched into the oxygen distribution plate; two cell sections could provide sufficient heat to evaporate the necessary water. However, three cell sections would have to be used, two for hydrogen and one for oxygen, to humidify both reactants to the same level.

o Reactant Recirculation

This method of reactant prehumidification has the potential of replacing the Static Moisture Removal System. Calculations were made with the assumption that both reactants are humidified while moisture is removed from the hydrogen stream only. The assumed KOH concentration was 32.8% KOH at

the anode and 37% KOH at the cathode. These are the values calculated in the concentration analysis using empirical diffusion coefficient.

To humidify the oxygen to the equivalent of 39% KOH at 190°F the required recirculation ratio* was calculated to be 13.1. If the prehumidification is only to the equivalent of 50% KOH the recirculation ratio reduces to .881.

The recirculation ratio for hydrogen with moisture removal and prehumidification to 39% KOH is 25. With prehumidification to 50%, it is 10.1.

If no moisture is removed from the hydrogen stream, the recirculation ratio is 3.3 at prehumidification to 39% KOH. It is .627 for prehumidification to 50% KOH.

Recirculation ratio that can be produced with a static system, i.e., jet pump, is usually less than one. Thus, only prehumidification to 50% KOH and without moisture removal could be handled by a jet pump. All other conditions would require a circulating fan or a blower.

● Conclusions

Using humidification cells appears to be a simple way of prehumidifying the reactants in the A-C fuel cell stack. The impact this modification would produce is the redesign of some moisture removal plates and rerouting of the reactants through them. The level of prehumidification using this method is narrowly limited to the equivalent of 39% KOH at 190°F. Since this is the target prehumidification level, it is not a detriment. Suitability of humidification cells is also dependent on the number of cells in the stack, and works out ideally for a 30-section stack. The humidification level is independent of current and would, therefore, require no controls.

* Recirculation ratio = $\frac{\text{Reactant recirculated}}{\text{Reactant utilized}}$

Vapor exchanger is another good way that the reactants can be prehumidified. It, itself, produces no impact on the fuel cell stack; however, it would be a separate unit which could be built into the stack. The level of prehumidification that a vapor exchanger would produce would be the equivalent to about 44% KOH at 190°F and would be somewhat dependent on the inverse of the current level. Unlike the humidification cells, it is insensitive to the number of cells and may be the better choice if the number of cells in the stack are changed from the present 30 sections. It also requires no controls.

It is felt that a wick type evaporator built into the oxygen plate using cell heat for evaporation would be the simplest of various water evaporator choices. It would eliminate a requirement for heating and for temperature controls. However, the need for KOH in the wick would tend to diffuse the KOH up the water inlet path, reduce the concentration in the wick and foul up the water flow control devices.

The main incentive for using reactant recirculation to prehumidify the reactants is that it be also used for moisture removal and thus, eliminate the static moisture removal sections of the stack. The analysis showed that in order to prehumidify the reactants to the equivalent of 39% KOH at 190°F, a mechanical blower would have to be used on both reactants. This is contrary to the aims of advanced design that moving parts be eliminated.

If the prehumidification is decreased to the equivalent of 50% KOH at 190°F and moisture is removed from the hydrogen stream only, then a static recirculator, jet pump, may be used on the oxygen stream. Mechanical recirculation will be required on the hydrogen stream as long as it is used for moisture removal.

Reactant recirculation would have a major impact on the A-C Fuel Cell System. The whole system as well as the stack would have to be redesigned. It is felt that this could be justified only if the Static Moisture Removal System was found to be inadequate.

From the above, it appears that either humidification cells or vapor exchanger are suitable methods of prehumidifying the reactants in the A-C Fuel Cell System. Humidification cells will not increase the number of components, whereas vapor exchanger will consist of an additional section added to the stack. Humidification cells are ideally suited to a 30-section stack and may not work out too well with 31 or 32 section. The vapor exchanger has no such cell limitations, but the humidification level attainable is somewhat lower. Using humidification cells will result in smaller and, therefore, a lighter system than with vapor exchangers, and it would be used as long as the stack remains with 30 sections. If the number of sections is changed, then vapor exchanger may be more suitable.

3.1.4.3 Cell Plate Study

This work item was initiated for the sole purpose of ascertaining the gas flow characteristics of the 2 kW fuel cell hydrogen and oxygen plates. Determination of the actual flow patterns associated with purge condition flow of a gaseous media would substantiate the design claims made for these plates.

It is held that during a six second purge at a gas flow rate equivalent to a 250 ampere gas demand, the total volume of a fuel cell plate is "swept" by the incoming gas.

The "sweeping" action is performed as movement of a plate wide front with an absence of preferential channeling or spikes.

In order to duplicate gas flow patterns using ammonia gas as a simulator of both hydrogen and oxygen, it was necessary to establish gas flow rates based on a Reynold's Number (R_e) equivalency. Resulting flow patterns simulate real life conditions but do not duplicate the actual gas volumes of hydrogen or oxygen passed through the plate in various discrete time intervals.

Gas flow rates under several pertinent temperatures and inlet pressures are itemized below.

1. Purge rates to satisfy electrochemical demands of 250 ampere load:

$$H_2 = 29.0 \text{ cc/sec. at } 0^\circ\text{C and 1 atm.}$$

$$O_2 = 14.5 \text{ cc/sec at } 0^\circ\text{C and 1 atm.}$$

2. Purge rates at flow test temperature (70°F):

$$H_2 = (29.0) \frac{(532)}{(492)} = 31.2 \text{ cc/sec}$$

$$O_2 = (14.5) \frac{(532)}{(492)} = 15.6 \text{ cc/sec}$$

3. Actual volume of gas through plate at fuel cell operating conditions:
190°F and 37 psia:

$$H_2 = (29) \frac{(14.7)}{37} \frac{(650)}{(492)} = 15.2 \text{ cc/sec}$$

$$O_2 = (14.5) \frac{(14.7)}{37} \frac{(650)}{(492)} = 7.6 \text{ cc/sec}$$

4. Actual volume of gas through plate at test conditions: 70°F and 52 psia

$$H_2 = (31.2) \frac{(14.7)}{52} = 9.0 \text{ cc/sec}$$

$$O_2 = (15.6) \frac{(14.7)}{52} = 4.5 \text{ cc/sec}$$

5. Actual volume of NH_3 through plate of test conditions: 70°F and 52 psia

$$Q_{NH_3} \text{ for } H_2 = (9.0) \frac{(102)}{128} = 7.1 \text{ cc/sec}$$

$$(R_{e_{NH_3}} = R_{e_{H_2}})$$

$$Q_{NH_3} \text{ for } O_2 = (4.5) \frac{(240)}{128} = 8.4 \text{ cc/sec}$$

$$(R_{e_{NH_3}} = R_{e_{O_2}})$$

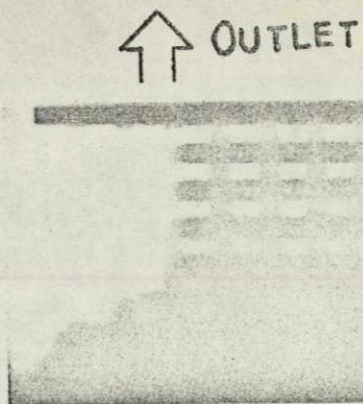
N.B. Test inlet pressure of 52 psia was selected to duplicate a fuel cell at 37 psia purging to a vacuum. Test purging was to ambient (14.7 psia).

Flow tests were performed using typical hydrogen and oxygen 2 kW fuel cell plates. A standard restrictor was afixed with seals in the inlet port and a standard ported film breaker afixed in the outlet port. Nitrogen and ammonia gas were plumbed to the inlet port and their separate delivery controlled by a three-way valve. The outlet port was plumbed to a flow-meter and hence, to a timer controlled solenoid valve.

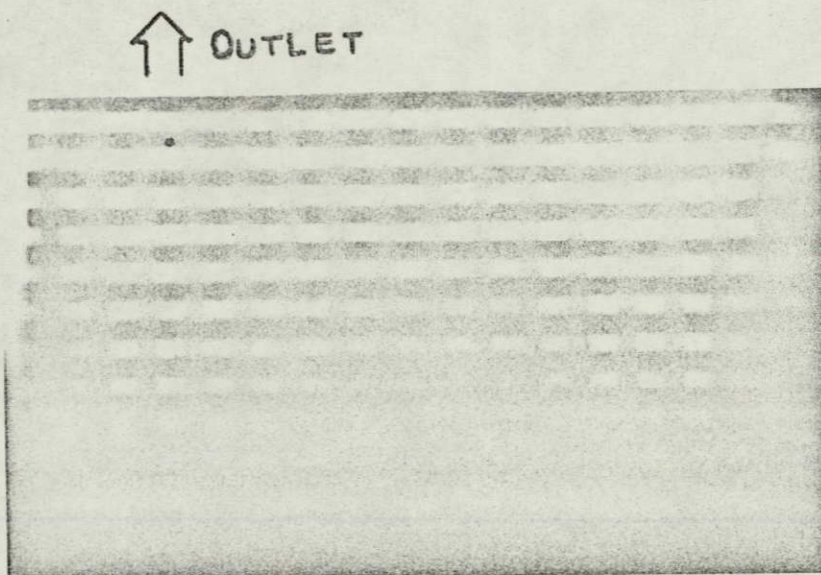
A normal test involved the following steps:

1. Blue-print paper was placed on both sides of a reactant plate.
2. The assemblage, complete with plexiglas cover and rubber gasketing was clamped securely in place.
3. Nitrogen at 52 psia was flushed through the plate and volume flow rate for N_2 was established. Accuracy of the flow-meter reading was verified by collecting the exhaust gas in a graduate over water and applying a pressure correction.
4. The three-way valve was turned to the ammonia side, and ammonia gas was permitted to flow through the plate for a preselected period of time.
5. After a two minute wait period, the plate was depressurized to ambient by flowing the ammonia back through the inlet port. The wait period of two minutes assured complete reaction of the blue-print paper with the gaseous ammonia.

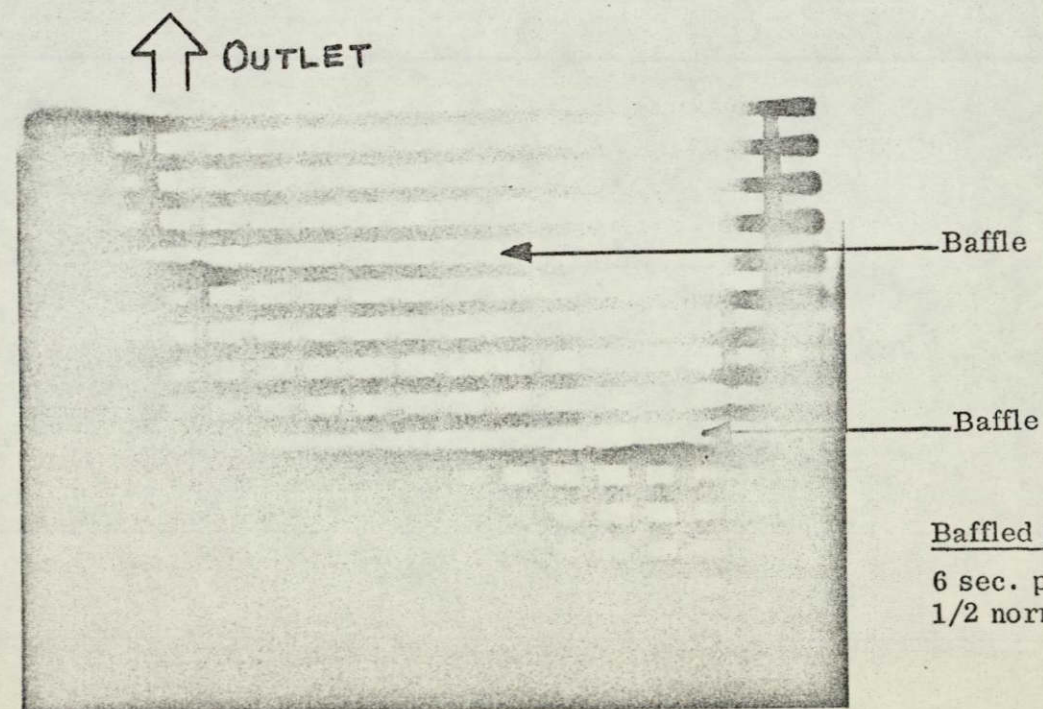
The resultant test paper samples show a large area of totally reacted paper, and a smaller area of delineation of the plate channels. Initial tests, at the calculated flow rate, resulted in complete darkening of the blue-print paper, obliterating passage through the plate channels. For this reason, the volumetric flow-rate was halved. Thus, tests performed for a period of six seconds actually reflect in a fuel cell proper, the flow conditions of a three second purge.



O₂ Plate
 6 sec. purge at
 1/2 normal purge rate



H₂ Plate
 6 sec. purge at
 1/2 normal purge rate



Baffled H₂ Plate
 6 sec. purge at
 1/2 normal purge rate

Full Scale

Figure 3.1-12. Purge Flow Test Results

Figure 3.1-12 illustrates typical results and verify the adequacy of the fuel plate design.

1. Flow occurs as a uniform plate-wide sweep with no preferential channeling.
2. The total volume of the plate is "swept" by the incoming purge flow with the apparent removal of collected inerts.
3. There is no need for baffling of the plate to accomplish the design requirements of inert purging. Baffling additions would probably produce undesirable flow channeling.

An additional investigation was made to determine if fuel cell performance could be optimized by varying the percent of land and border area in contact with the electrodes. It is apparent that fuel cell performance will be reduced if the percent of contact area becomes large enough to prevent the reactant gases from reaching the reaction sites in the electrodes. It is also apparent an extremely small percentage of contact area will not provide adequate support of the electrodes nor will it provide efficient current collection. The question then becomes how sensitive is performance to the contact area. A review of performance associated with a number of our fuel cell designs gave us the answer.

Table 3.1-6 describes the best initial performance associated with four different fuel cell designs. Each of the designs uses static moisture removal, Hysac silver electrodes, AB-40 or A-C Type XIV anodes and 0.030" asbestos. The only significant difference in the cell designs is their electrode area and the plate area in contact with the electrodes. The variations in cell area have been normalized by comparing the percentage of electrode in contact with the plate for each design. A review of the initial performance data indicates the percent contact area is not significant over the entire range (26.9 to 42.5%). No significant improvement in performance can be expected if the present NASA plate design is reduced to as low as 27% contact area. Any reduction below this would be undesirable.

The 4C-03 design actually posed problems due to the small land size. The 0.050" x 0.050" lands squeezed through the electrode support screen mesh and caused partial blockage of gas distribution grooves.

In summary, the past performance and design data show the electrode contact area is not a parameter which can be varied to improve performance at present current densities where current collection is not a consideration.

	<u>% Land and Border</u>	<u>100 ASF</u>	<u>150 ASF</u>	<u>200 ASF</u>
High Performance 4C-03	26.9	0.97	0.94	0.92
High Performance 4DR	39.75	0.97	0.93	0.91
NASA 196	42.50	0.97	0.94	0.92
RCFC 28A	36.60	0.97	0.94	0.91

Table 3.1-6. Fuel Cell Performance with Different Electrode Contact Areas

3.1.4.4 Diffusion Membranes

The Static Moisture Removal System of the A-C fuel depends on water vapor leaving a KOH soaked asbestos matrix. Inherent in the design of this system is a differential pressure across this matrix of up to 37 psi. It is understandable then that small amounts of KOH can be found in the by-product water. A deionizer will remove the KOH from the water rendering it potable, but a deionizer has a limited life and adds extra weight to the system. Also, a continuous loss of small amounts of KOH from the cell contributes to the voltage degradation of the cell. It was thought that a way of overcoming this loss of KOH would be a perm-selective membrane between the KOH soaked matrix and the water cavity.

Two diffusion membrane suppliers, DuPont and GE, were contacted concerning perm-selective membranes. DuPont declined to send us any samples because they do not yet have a perm-selective membrane compatible with KOH. Samples of two types of membranes were received from General Electric Company. They were an unbacked dimethyl silicone membrane and a silicone polycarbonate copolymer membrane (#MEM-213).

Two major requirements of the membranes is that they pass sufficient water vapor (per unit time) and that they do not react with KOH.

The permeability rates of the dimethyl silicone membrane were too low for our requirements. In addition, KOH compatability tests were conducted on the membranes and both types dissolved in 45% KOH, at 250°F, in 100 hours.

The published permeability rates of the Amicon polysulfone membrane indicates that this membrane would pass sufficient water vapor (per unit time) to meet our needs. The stability of this membrane in KOH has been demonstrated by compatability tests performed in other programs. Fuel cell tests would have to be conducted to determine the effect of this membrane of the performance of the fuel cell and on the by-product water. Expiration of the contract eliminated the possibility of any fuel cell tests on the membrane.

3.1.5 Subtask 1.5 - Fuel Cell Module Testing

The objectives of this subtask were:

- Engineering Definition

Definition of the fuel cell module to be tested under this task. Drawings would be prepared as required for fabrication. The first task to be performed would be the preparation of a list of improvements that would be included in the module. Basically, these improvements from Tasks 1.0 and 2.0 would be those having sufficient development to make incorporation at the module level practical.

- Fabrication

One of the MOL FCA's would be used for this task. A new stack would be incorporated having matrix, electrode, and restrictor improvements. Component improvements (purge valves, pressure regulators, etc.) would also be included on the module if available.

- Testing and Documentation

The improved fuel cell system would be operated at AEPD in a 'hands-off' condition for 500 hours. The MOL portable test console was to be used for the tests. A test plan would be prepared and submitted for NASA approval 30 days prior to the start of the test. It was expected that this test would be the first phase of a 10,000-hour test which would be continued in the Phase II effort.

3.1.5.1 Engineering Definition

As a means of expediting the available NASA hardware inventory, a preliminary assembly drawing of the stack definition minus restrictors and seals was prepared.

New restrictors and seals were being designed and tested as part of another contract.

As a part of the restrictor design activity, the reactant parts of MOL-EDCTU #2 stack (used to rebuild MSC stack) were borescope inspected. There were no hardened KOH deposits detected in any of the ports or EDM holes.

Decisions were reached regarding the configuration to be built to permit a final documentation of the design. The fuel cell built for MSC was an MOL EDCTU with the following changes:

- The fuel cell matrix material was reconstituted asbestos.
- The fuel cell electrodes consisted of A-C XIV anodes and Hysac cathodes.
- Restrictor and grommet improvements developed on the MSFC Program were incorporated.
- The vacuum impregnation techniques (out-of-stack) developed in Task 1.0 was used to load KOH into the fuel cell.
- Redesigned stack compression device.
- Addition of two cell sections for increased power.
- Four hundred (400) Hz power was supplied from a laboratory source. The fuel cell fan inverters were eliminated since the shuttle fuel cell would not require inverters.
- The regulator design used on the MSFC fuel cell was incorporated.
- Purge valves and moisture removal valves (MRV) with improved operational characteristics were incorporated.
- A proportional MRV was not included in the original fabrication. However, if the valve were developed, it was to be incorporated into the system test.
- The MOL test equipment was used for performing the life test.

In order to document all the changes for the MSC design, 53 new drawings and 11 drawing changes were necessary. The major changes are shown in Table 3.1-7.

Drawing Number	Title	Major Change from MSFC Design
49001042-503	Fuel Cell Powerplant	New powerplant subassembly New control cable assembly New electrical schematic Remove Fan #1 and Fan #2 cables Remove inverter assembly
49500371-503	Powerplant Assembly	New stack assembly
49500342-504	Stack Assembly	New hydrogen electrodes New matrix New KOH loading procedure Add two cell sections

Table 3.1-7.

The vacuum impregnation electrolyte loading technique was refined for production runs. It was used for both electrode/matrix assemblies (EMA) and water set assemblies (WSA). EMA and WSA drawings specified component tolerances, and data forms were established for EMA and WSA component matching. This was done to provide uniformity throughout the stack.

Stack compression investigations centered about those items which required immediate definition: 1) determination of total stack relaxation through a 10,000 hour design life; 2) the redesign of the Belleville washer assemblies to compensate for stack relaxation; and 3) establishment of a wet "fuel cell stack pressing specification". These items were completed as follows:

Total 10,000-hour stack relaxation was fixed at 0.134 inches. This is the aggregate of the fuel cell plate and insulation spacer creep (0.130 inches), and the thermal expansion difference of components and the stack studs from 70°F to 40°F (0.004 inches). Note: It was assumed that Belleville washer assembly

creep is insignificant due to reductions in the Teflon coating thickness on the spring washers, and/or assembly preconditioning.

The Belleville washer assembly redesign was attained by regrouping existing components into an array of two Belleville spring washers in parallel and twelve in series. This grouping nominally deflects 0.140 inch succeeding preconditioning with force variations from 375 to 1250 lb/assembly. Drawings were completed for the assembly.

A new "fuel cell stack stacking specification" was generated. This specification established the requirements for determining the dry stack height, and for pressing and bolt torquing the wet loaded MSC stack.

The two cell sections were added to the fuel cell stack to increase its power rating and make it more adaptable for the shuttle application. The change involved not only adding components to construct two more cell sections, but also included changes to wiring, positive terminal rod, and baffles.

As a result of MOL-EDCTU teardowns, the tubing passivation process was changed to provide increased protection in an oxygen atmosphere. Standard wall thickness tubing was substituted for all thin-walled tubes and flared tubing fittings were used instead of Aeroquip fittings on the O_2 and H_2 inlets.

To obtain more versatility and better control of the FCP, the moisture removal valve supervisory switch leads and spare platinum temperature sensor leads were brought to the interface and connected to readout in the test console.

Engineering also provided the necessary support for fabrication and test to ensure that the FCP was fabricated and tested on schedule.

3.1.5.2 Fabrication

A preliminary parts list was used to check on the availability of all hardware. After completion of the inventory all items not in stock, required to complete the MSC-FCA, were purchased. Included in these items were platinum catalyst, hydrogen electrodes,

bottom stack support plate, nickel plating stack length spacers, inlet restrictors, inlet restrictor seals, Teflon coated studs, and oxygen outlet manifold inserts.

A preliminary detail schedule was prepared, and Operations and Inspections (O&I's) plans were prepared for EDCTU #2 stack disassembly, reactant regulator rework, solenoid valve seats and modifications, and stack length spacers. Advance O&I's were released to Material Control for assembly kit preparation for the WRA and for the fuel cell stack.

A detailed PERT network was prepared for the system and included fabrication of the A-C XIV electrodes, reconstituted cell matrices, EMA's, WSA's, and fixtures for these items.

All major purchased components were acceptance tested before installation on the FCS or FCP.

The fuel cell stack was assembled, compressed, torqued and leak tested. The fuel cell stack and frame assembly was then completed and successfully leak checked. Stack acceptance testing was performed. After stack acceptance testing the temperature control thermistor which failed, was replaced. The stack was retorqued and again leak checked.

The MSC-FCP system was then completed and returned to the test group for leak and acceptance testing.

3.1.5.3 Testing and Documentation

At the start of the program the most critical test item was the completion of the number 2 MOL Portable Test Console. Authorization was given the test group to purchase the required material and complete the console. Then due to a delay in the MSFC fuel cell program, the Portable Test Console #1 was going to be available for the 500-hour MSC test. Therefore, the design and fabrication of Portable Test Console #2 was cancelled.

Accommodations for voltage readout of the two additional cell sections at the Portable Test Console were designed and the parts purchased. An automatic load programmer and a larger 0- to 10-ampere vernier load control to allow better load control were selected and purchased for the load bank console.

The 400 Hz control panel and a cable from a NASA-DVT bench were modified to function with the Portable Test Console and installed in the load bank console.

Gas break-through tests on all the reconstituted asbestos matrices were performed.

The following procedures were required to perform the in-process, stack, acceptance and life tests:

49156112	Inlet Restrictor Pressure Drop
49156113	Stack Proof Pressure and External Leak Test
49156114	FCS Cavity and Canister Leak Test
49156116	FCS Test Console, Leak Test
49156117	FCS Test Console, Operating
49156118	FCS Preconditioning and Conditioning Test
49156119	DATA Log for above
49156120	Oxygen and Hydrogen Plate Pressure Drop
49156121	Data Log for above
49156122	FCS Acceptance
49156123	FCS Acceptance, Data Log
49156124	FCS Canister Fill and Leak Test (Post-Retorque)
49156125	Frame Leak Test
49156128	FCP Acceptance Test
49156127	FCP Portable Test Console Operating Procedure
49156130	FCP Leak Test
49156132	FCP Calibration Test
80045-TA-0021	Test Plan (Development)

The completed stack was leak tested successfully. The fuel cell stack was then pre-conditioned, conditioned and an acceptance test was run. All these tests were passed with exceptional results. The unit had the lowest millivolt differential between cell sections and highest initial performance of any large stack ever tested by AEPD.

Figure 3.1-13 shows the V-A curve for the stack during both the conditioning and acceptance tests. The difference in voltage between the highest and lowest cells varied from 6 to 18 millivolts during all the tests. The MSC stack averaged about 3% better performance

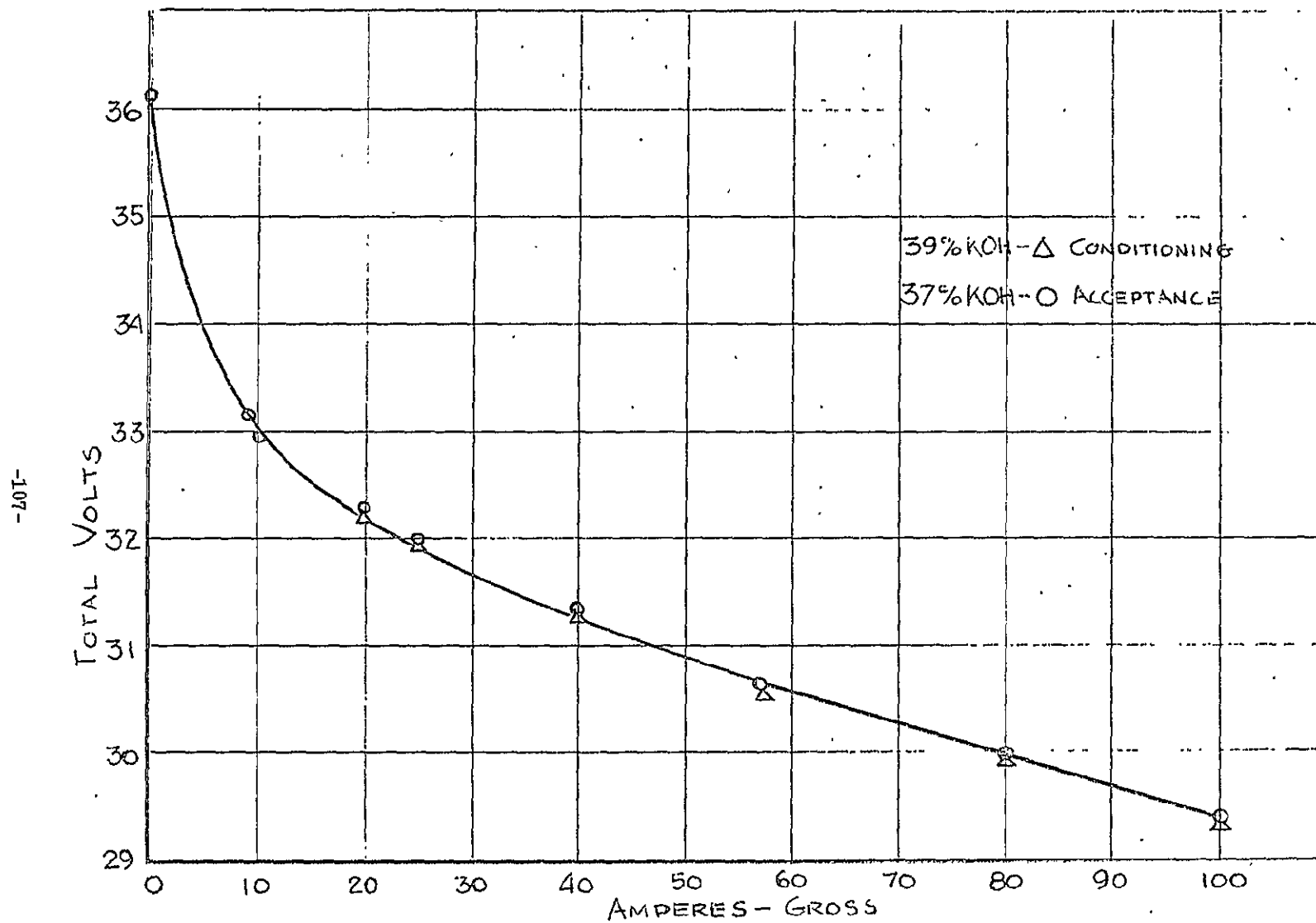


Figure 3.1-13. MSC Stack #1 Performance

(higher voltage for comparable current level) than EDS #1 during its initial testing (best previous stack).

The only nonconformance was an upward drifting of the stack temperature. Manual control was used to maintain the stack within range. An investigation at the conclusion of the test showed that the coolant control thermistor was faulty and drifting. The coolant temperature control thermistor, was examined and found to be defective.

3.1.5.4 FCP 500-Hour Test

Test Procedure

The test was conducted in accordance with Test Plan (Development) 80045-TA-0021, Section 1.3.9, including Supplements 1 and 2. After completion of the 20-hour acceptance test, the life test was started without a shutdown. The repetitive life load cycle profile shown in Figure 3.1-14 was run for a period of 150-hours. This was followed by a 9.5 hour period at a steady load of 40 amperes during which the load spike tests were run. Table 3.1-8 is a chronology of the high load spikes. At an Elapsed Time (E.T.) of 159.5 the repetitive life cycle load profile was resumed for 30-hours. At E.T. 189.5 a steady load of 40 amperes was applied until completion of the test at E.T. 195.2.

The unit was shutdown and restarted at E.T. 89.4 for a scheduled weekend shutdown during which the moisture removal valves were replaced because of excessive pull-in-voltage.

System operation parameters of percent KOH and the number of helium cooling fans in operation, were varied during the test. Table 3.1-9 lists the operating conditions during the test.

Test Results

The voltage-current characteristics of the FCP at the start of the test and near shutdown (E.T. 182 - 187) are shown in Figure 3.1-15. The voltage degradation of approximately 20 micro-volts per cell per hour.

E. T. - Hours	FAN ON		KOH %		
	1	2	36	37	38
0 - 30	X	X		X	
30 - 40.5	X			X	
40.5 - 60.7	X		X		
60.7 - 78.8	X	X		X	
78.8 - 89.4	X	X		X	
Shutdown	Replaced MRV's				
89.4 - 107	X	X		X	
107 - 114.5	X			X	
114.5 - 165.9		X		X	
165.9 - 175.8		X			X
175.8 - 195.2		X	X		
Shutdown					

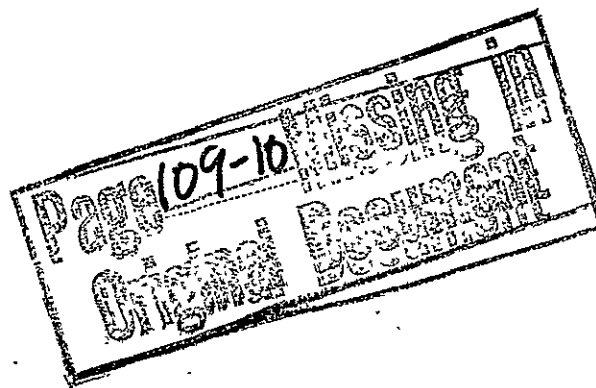


Table 3.1-9. MSC-FCP Test Operating Conditions

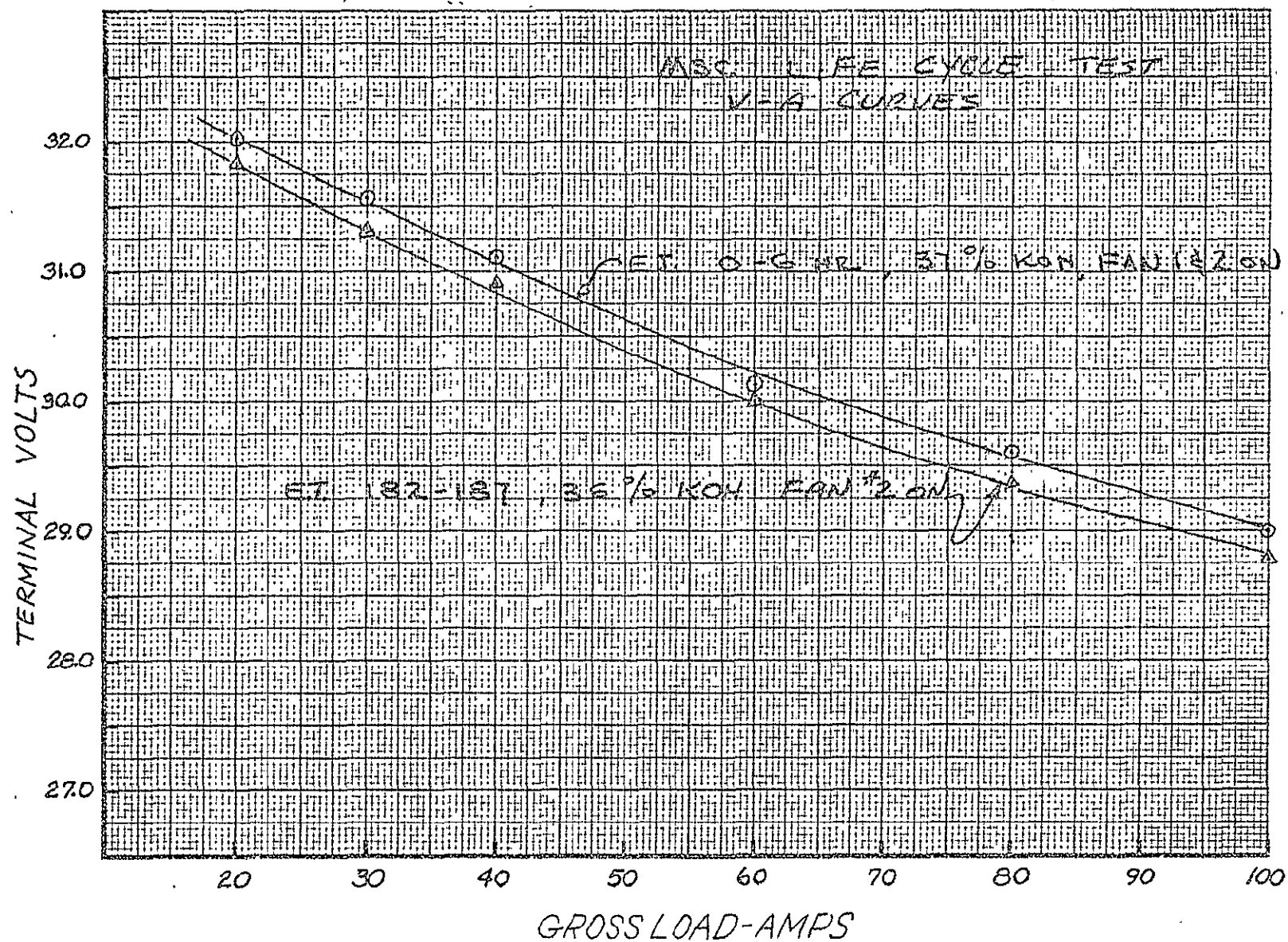


Figure 3.1-15. MSC Life Cycle Test V-A Curves

Cell Number 1 was generally the low cell throughout the test. Cell 1, 16, and 32 are plotted versus elapsed time in Figure 3.1-16. Cell 1 voltage dropped off with a decrease in KOH and improved with an increase in KOH indicating that it was operating on the "wet" side of optimum. The two other cells appeared to be unaffected at 40 ampere loads but at 80 ampere loads Cell 16 also appeared to be wet while Cell 32 appeared to be on the "dry" side.

Figure 3.1-17 is a plot of cell spread (m.V.) versus elapsed time for loads of 20, 40, 80, and 100 amperes. The spread is almost entirely due to the spread between Cell 1 and Cell 2, which were the lowest and highest cells and remained relatively constant through the test duration.

Figure 3.1-8 is a plot of the terminal voltage versus elapsed time for loads of 20, 40, 80, and 100 amperes. The curves indicate that the voltage degradation was relatively uniform over the life test.

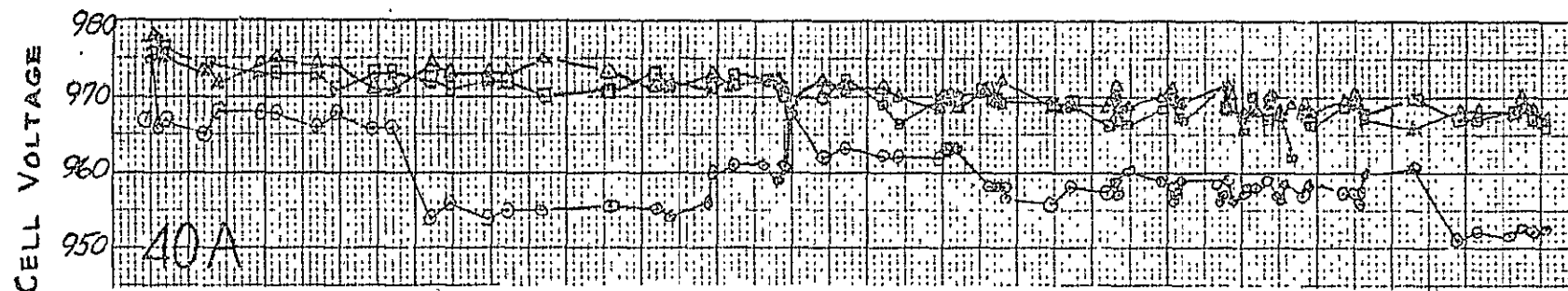
In general, the performance of the upper cells improved somewhat with a decrease in percent KOH and the lower cells improved somewhat with an increase in percent KOH, indicating that the upper cells were operating on the "dry" side and the lower cells were operating on the "wet" side of optimum. No discernible effect on cell performance was noted with either or both cooling fans operating.

The voltage-current characteristics of the unit during the load spike tests and the life cycling tests prior to and after the load spike tests, are shown in Figure 3.1-19.

The curves show that the load spike test had no apparent effect on the system performance. This is also verified by the performance parameter curves on Figures 3.1-16 to 3.1-18, showing no appreciable change after the load spike tests.

Although nominally rated at 2 kW output the MSC system demonstrated a capability of producing 5 kW at approximately 26 volts for a test period of six minutes.

The performance of the MSC unit was generally excellent compared with performance data for previous units, such as: DVT 15, DVT 16, and EDS #1, as shown in Figure 3.1-20. The improvement was most noticeable at the higher loads.



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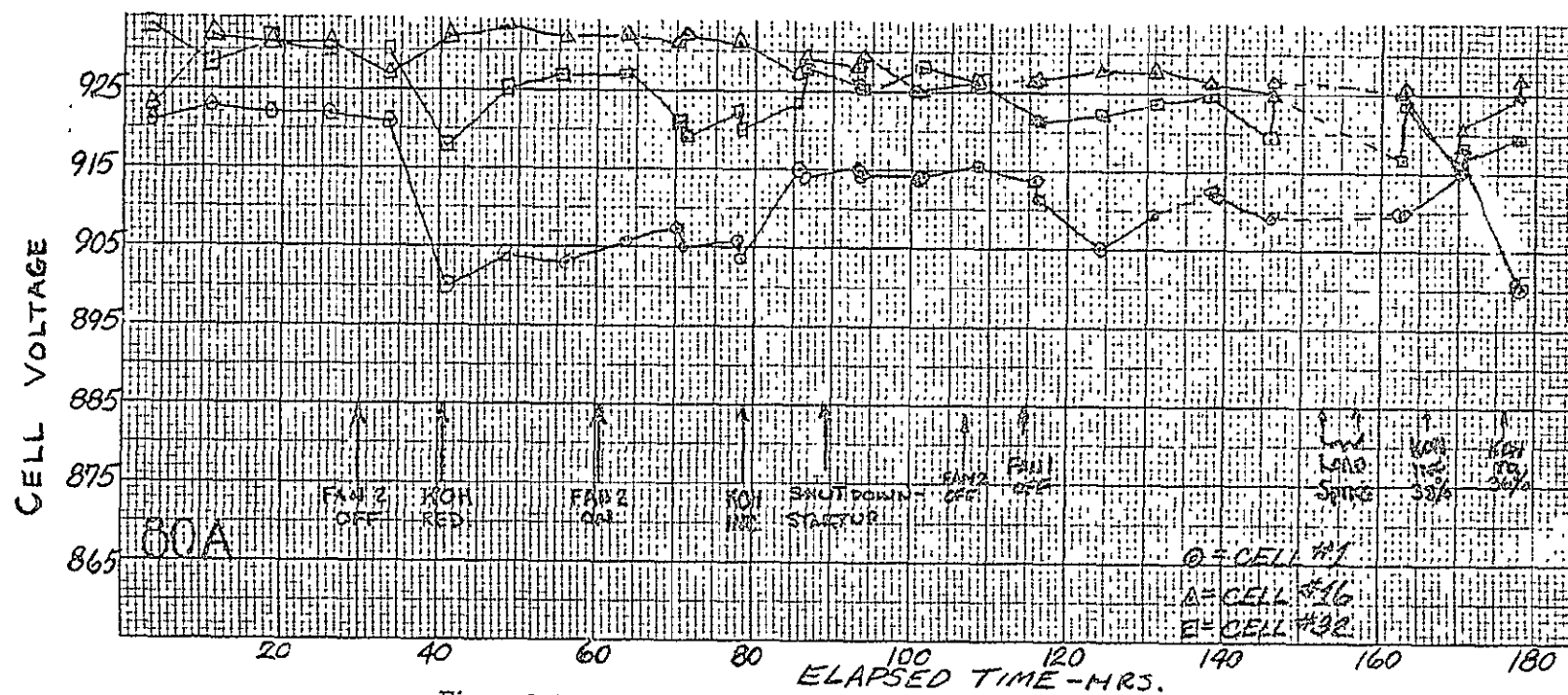
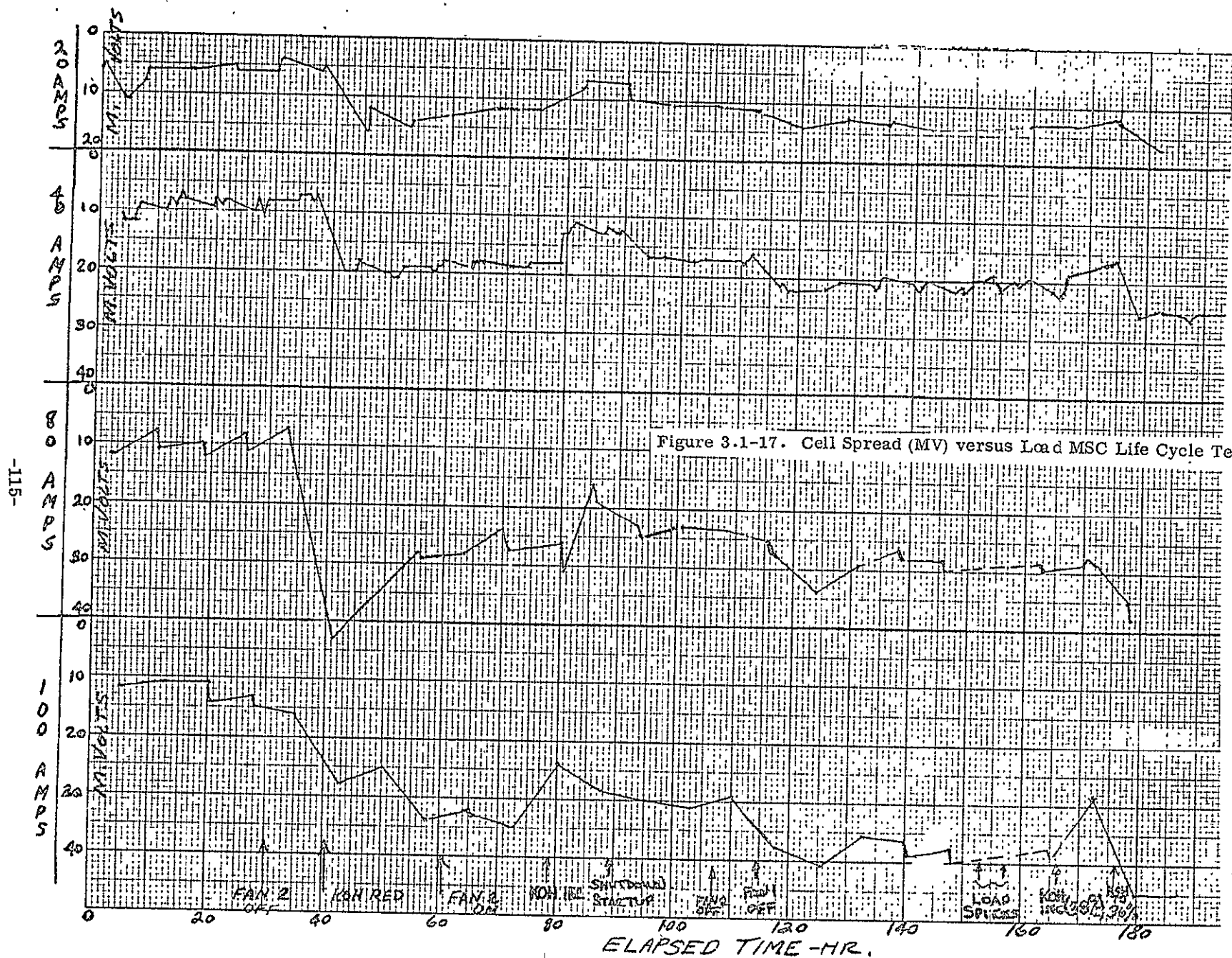
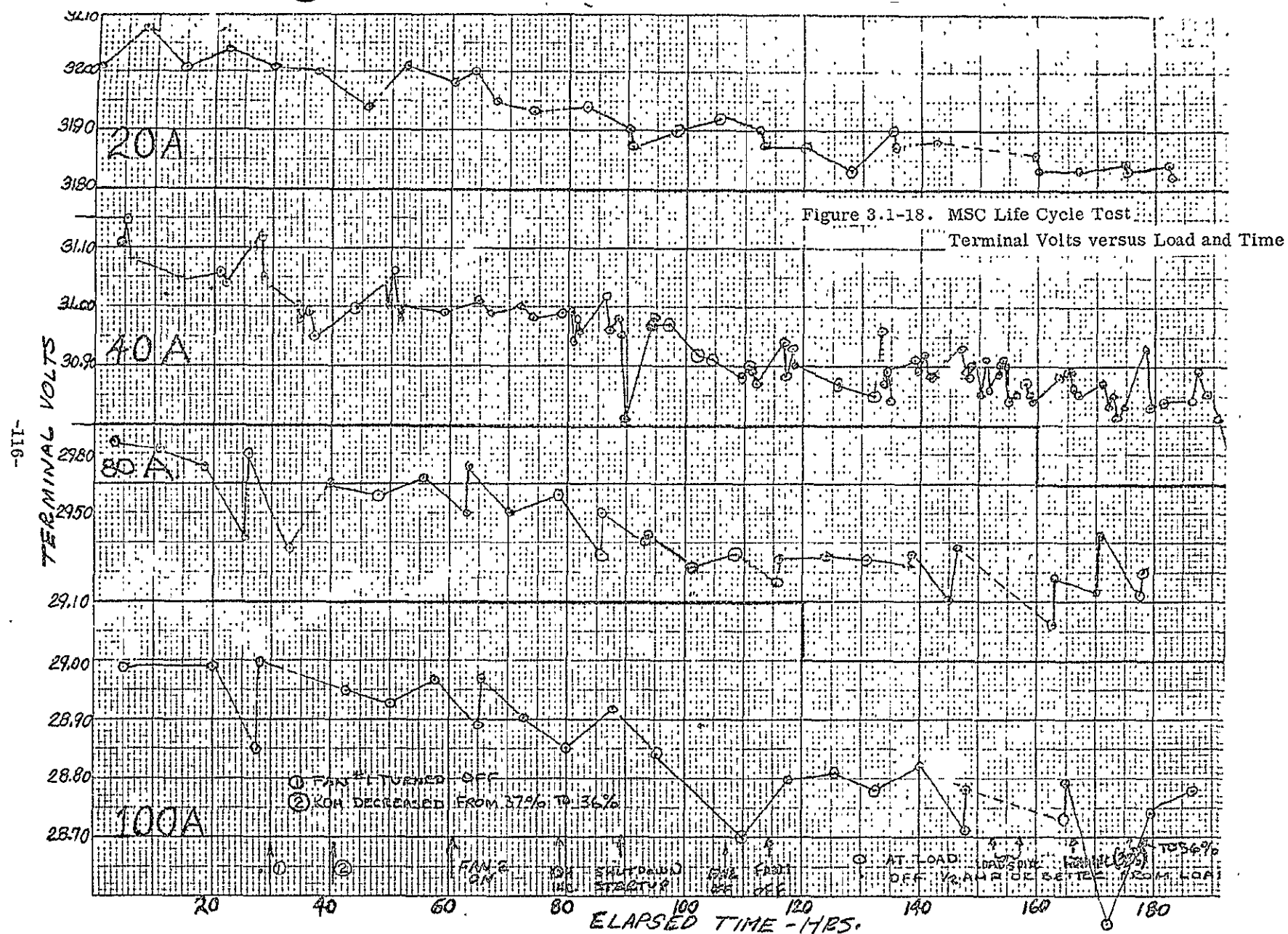


Figure 3.1-16. MSC Life Cycle Test Cell Voltage versus Load and Time





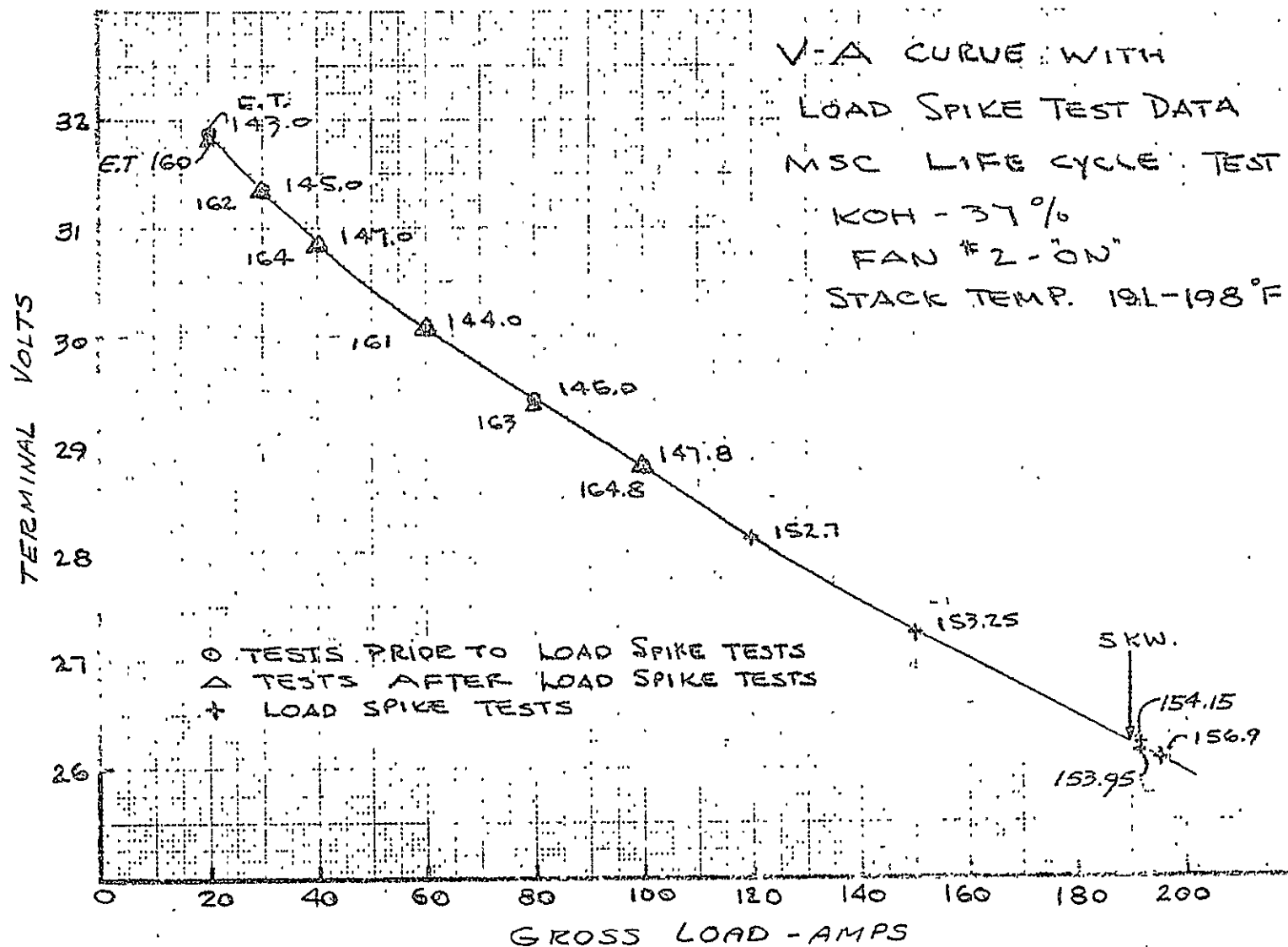


Figure 3.1-19. V-A Curve with Load Spike Test Data

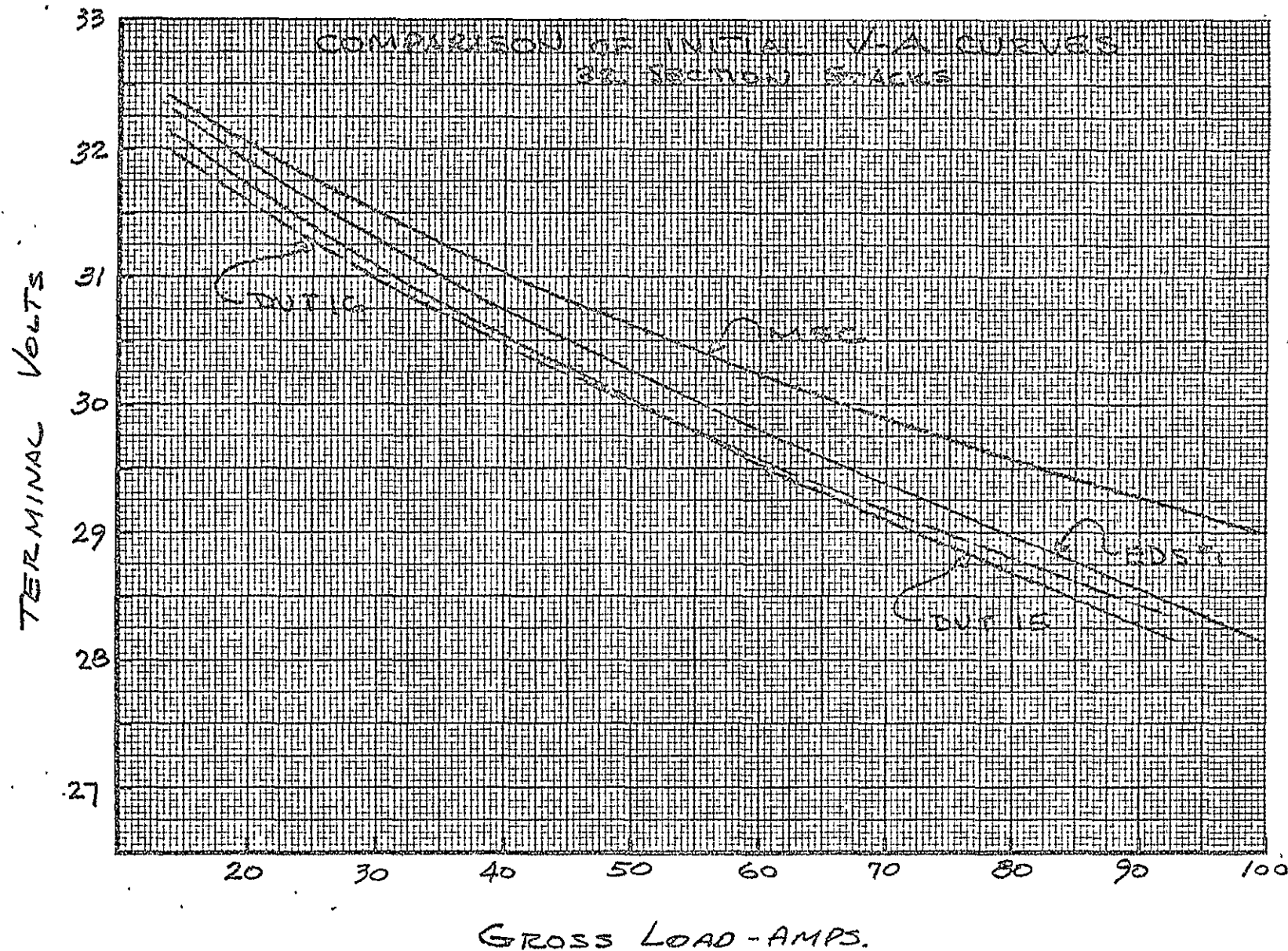


Figure 3.1-20. Comparison of Initial V-A Curves

Test Nonconformances

The FCP problems associated with the life test were documented and dispositioned in Test Nonconformance Report 45-10 which is summarized below.

1. The stack coolant inlet temperatures were over the specified limit of 100°F during the higher power runs.

Solution: Cooling water valves were adjusted to increase the water supply to the coolant heat exchanger. The Test Console operating procedure was modified to reflect these changes.

2. Unscheduled purges occurred at approximately 64 amp-hours.

Solution: The EMCA required a reset procedure which was added to the Test Console Operating Procedure.

3. Moisture Removal Valve #2 would not open intermittently.

Solution: The test console auxiliary power supply voltage was increased to 31 Vdc. Both moisture removal valves were replaced and they operated normally at 28 Vdc.

4. Gas stop valve supervisory contacts appeared to be intermittent at times.

Solution: No action was taken as they were functioning normally at the end of the test.

3.2 TASK 2.0 - ADVANCED SYSTEM ENGINEERING

3.2.1 Subtask 2.1 - Hardware Assessment

The objectives of the subtask were:

- To review and summarize the recent test history of Allis-Chalmers hydrogen/oxygen fuel cell systems
- To determine trends in failures, performance and life
- To isolate hardware problem areas
- To provide inputs to a hardware development plan

The effort involved the review of recent system test data and the review of nonconformance and corrective action reports.

The objectives of this effort were satisfied and are reported in full in topical report number 80045-147.

The failure reports written during the NASA, MOL, AAP and RCFC programs were reviewed in detail and grouped by defect code and responsibility. The summaries were then categorized by components in an effort to analyze the failure history and identify failure trends and problem areas (Figures 3.2-1 and 3.2-2). The grouping of the discrepancy into defect cause codes is an aid in design reviews and also points out those areas of previous malfunctions that have not been eliminated by a design change. The specific discrepancy details of each component are recorded and are available. The chart in Table 3.2-1 shows the component discrepancies listed in order of frequency. The five most frequently discrepant components (18% of the total) were responsible for 60% of the reported problems. Table 3.2-2 lists the Fuel Cell Module and Stack discrepancy causes in order of frequency of occurrence. Table 3.2-3 lists the total number of discrepancies against each major component.

Programs: NASA, RCFC, MOL, AAP		Responsibility																Defect Cause Code																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
		Discrepancy Reports		Quantity Discrepant		Quantity Tested		Vendor		Production		Procedure		Test		Quality Assurance		Correction		Output Out of Spec.		Handling		I.D. Error		Leakage		Vibration		Shock (Open/Closed)		Unstable		Calibration		Contamination		Visual (Barre, Flare)		Over Stressed		Documentation		Elec. Connector		Elec. Short		Elec. Open		Life Associated		Wear-Fracture		Temperature		Need Switch		Diaphragm																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										
Component		40	44	26	1	4	12	6	2	0	32	2	0	6	9	2	4	5	0	1	2	6	1	1	1	1	3																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									

Figure 3.2-1. Discrepancy Report Summary

Fuel Cell Module and Stack							Responsibility																						
							Discrepancy Reports					Leak (Pressure Cavity)															Ind. Cell % Lo		
							Design	Material	Test	Fabrication	% KOH	Output Lo - Total	Contamination	Test Equipment	Handling	Component	Restrictor	Purge	Vibration	Fracture	Workmanship	KOH	Temperature	Cable Conn.	EMCA	Elec. Control and O/P			
RCFC	33	27	0	2	6			2	8	7	0	1	3	1	15	2	2	6	0	2	4	4	4	0	3				
NASA	39	31	3	6	7			3	8	7	3	5	3	4	11	3	2	3	2	2	2	9	1	2					
Total	72	58	3	8	13			5	16	14	3	6	6	5	26	5	4	9	2	4	6	13	5	2	3				

Figure 3.2-2. Components Discrepancy Cause

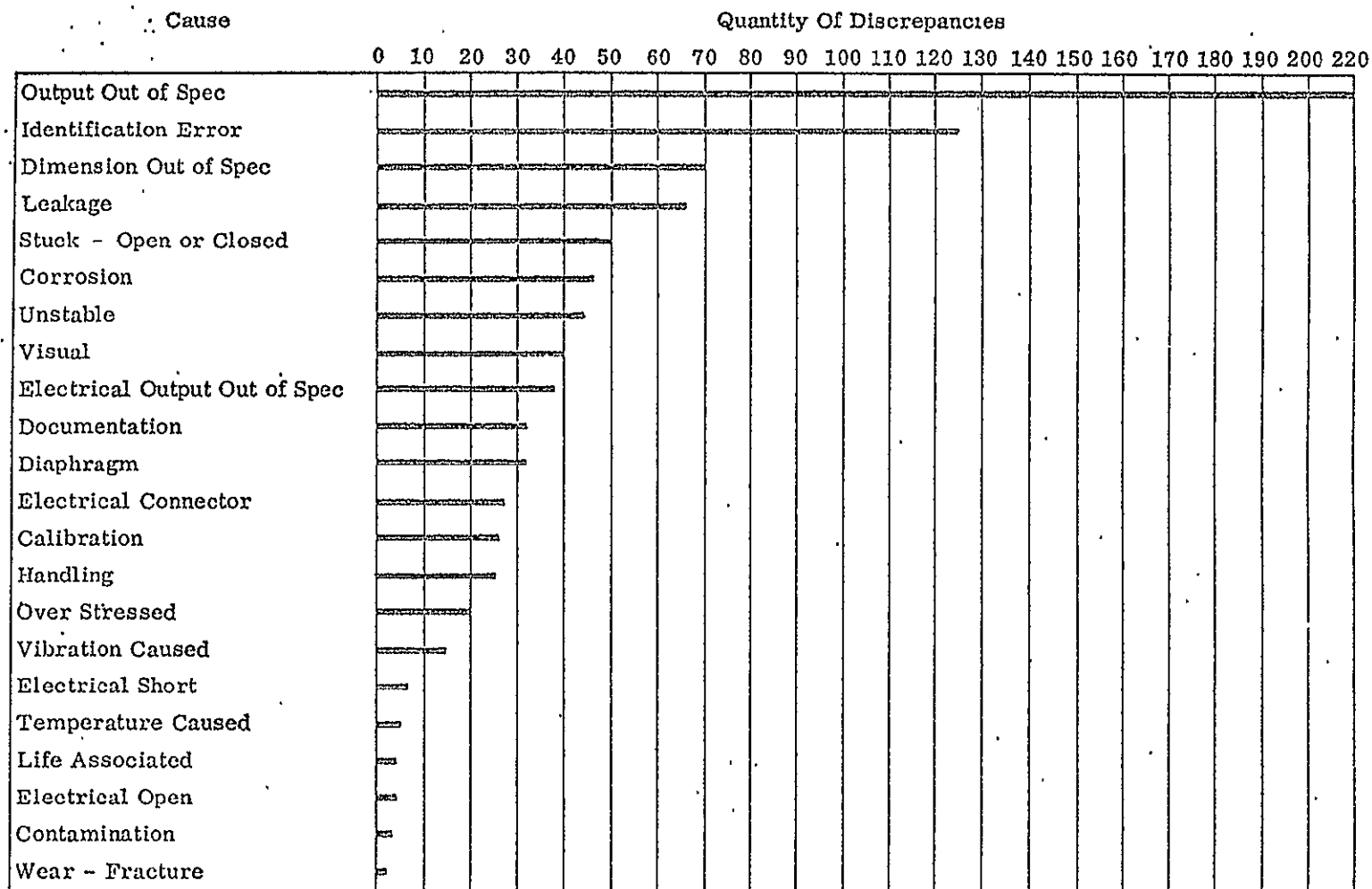


Table 3.2-1. Component Discrepancy Cause Comparison

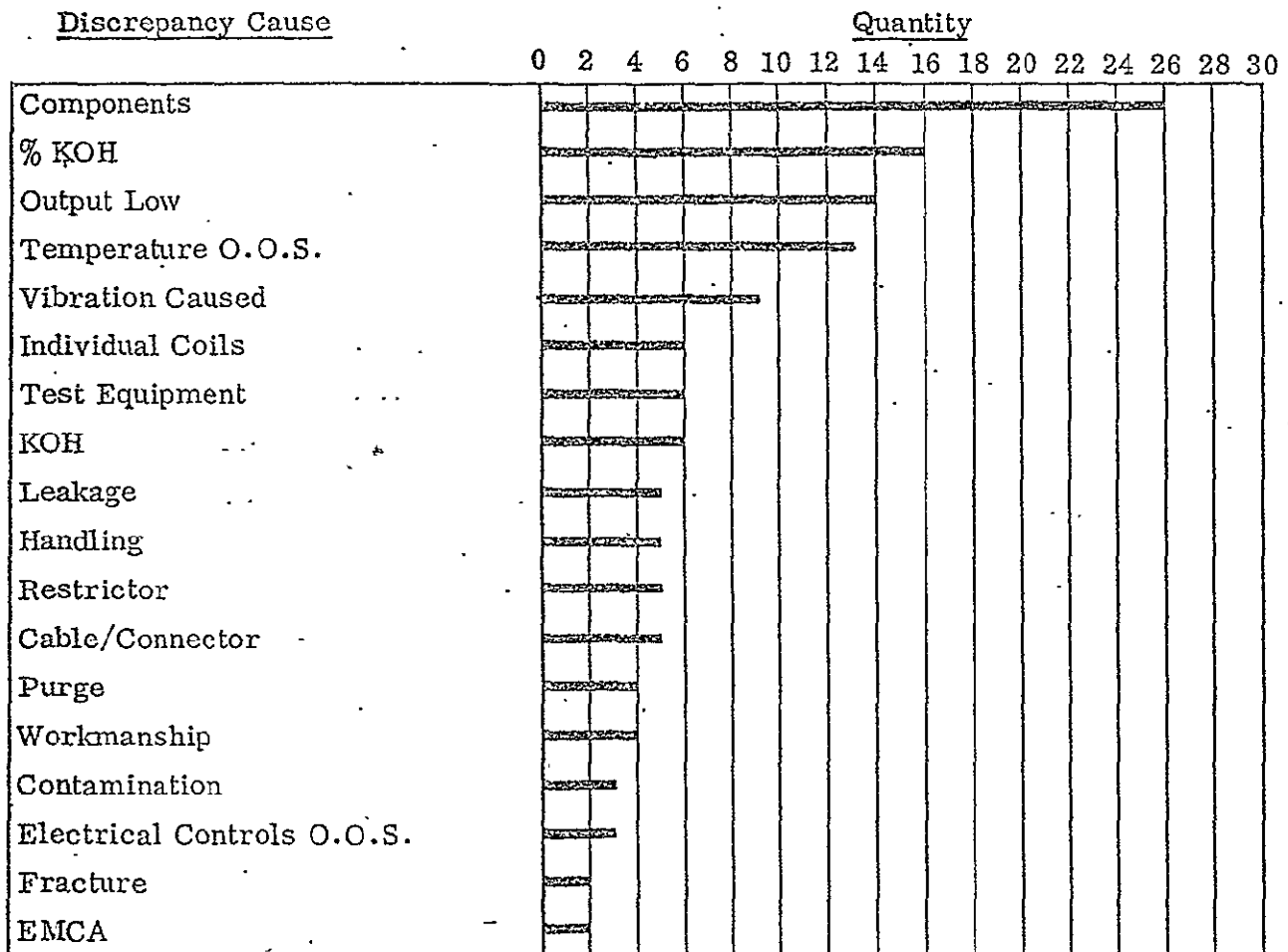


Table 3.2-2. Fuel Cell Module and Stack

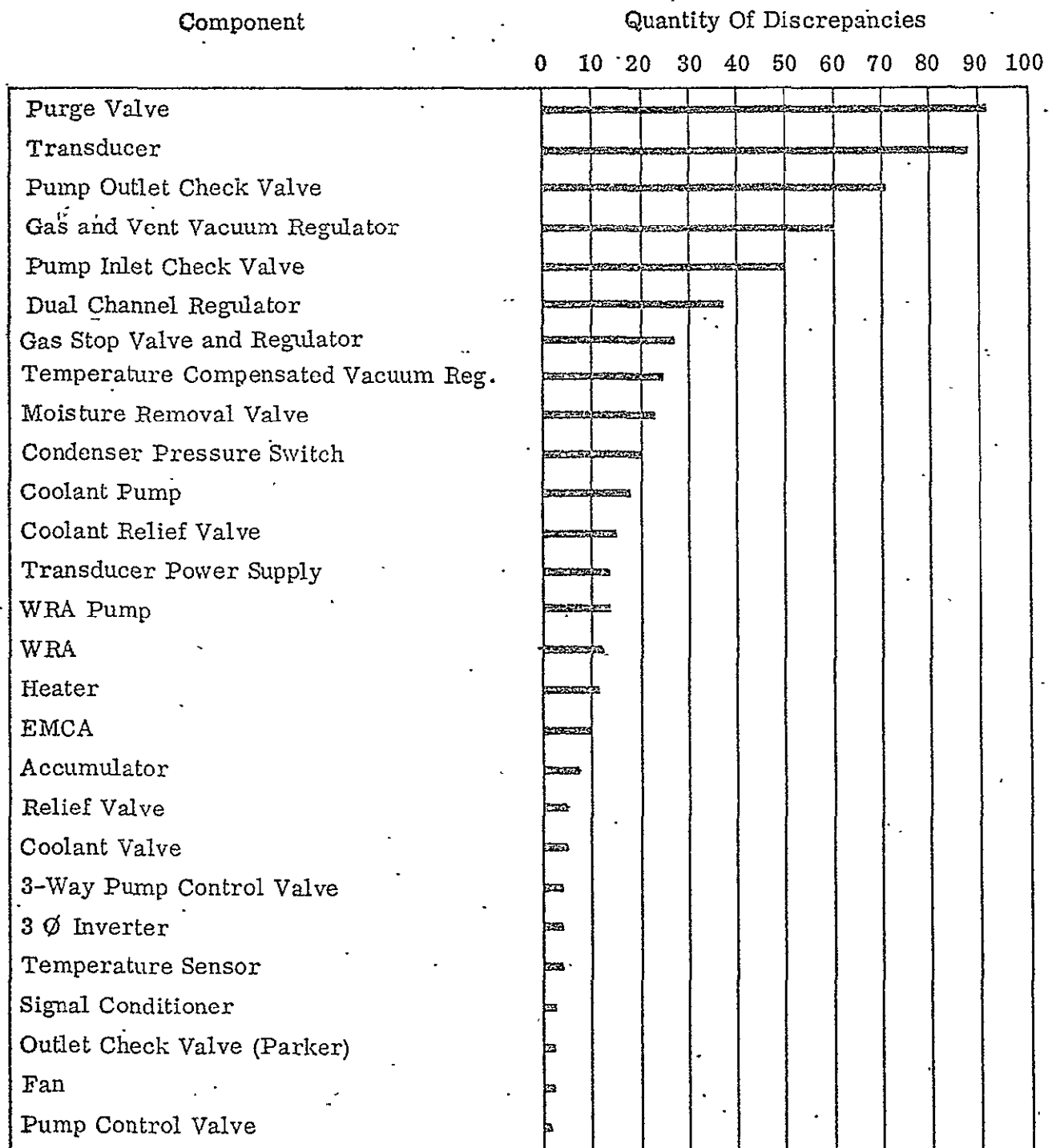


Table 3.2-3. Component Discrepancy Chart

TEST HISTORY

X Only DVT 15 & 16 test hours included * No reported failures	RECENT NASA TEST HISTORY											
	Quality Tested	System & Subsys- tem Operation (Ambient Condi- tions)	Thermal Vacuum 10-6 Temperature Variation	Vibration on System	NASA DVT Component Test	Average Test Time/Component	Average Test Time /Test Discrepancy	Test Discrepan- cies	Inspect. Discrep.	NASA DVT Test Time	Other Development Tests	Total Test Time
Component												
Dual Channel Regulator	2	1,430.3	852	7.2	X	1,145	64	36	1	2,289.5	2071.5	4,361
Power Supply	2	1,677.0	911	7.2	X	1,296	864	3	0	2,595.2	--	2,595.2
Single Conditioner	2	1,677.0	911	7.2	X	1,296	1298	2	0	2,595.2	4874.8	7,470
Warm-up Heater	6	3,366.0	1,822	14.4	X	870	5202	1	1	5,202.4	24,927.6	30,130
WRA Pump	15	4,774	1,391	12	240	425	534	12	1	6,417	8281	14,698
Coolant Pump	8	1,674	911	8.2	14,756	2,170	1580	11	1	17,349.2	8058.8	25,408
Coolant Relief Valve	5	1,674	911	7.2	232	565	707	4	2	2,824.2	--	2,824.2
MRV (Parker)	7	965	242		2,539	536	375	10	3	3,746	2460	28,346
Fan	4	3,354	1,822	14.4	X	1,295	5190	1	1	5,190.4	15,375.6	158,946
Pump Outlet Check Valve	7	3,193	1,372	7.2	172	676	1185	4	3	4,744.2	5807.8	10,552
Hz Fill Valve	3	1,674	1,360	8.2	0.3	1,015	3042	1	0	3,042.5	--	3,042.5
Over-Pressure Switch	4	3,354	1,822	14.4	X	1,295	5190*	0	0	5,190.4	55,749.6	60,940
Pump Control Valve	9	2,317	1,391	8.2	176	432	974	4	1	3,892.2	9167.8	3,060
Pump Inlet Check Valve	9	1,677	2,891	7.2	462	564	718	7	3	5,037.2	5807.8	10,845
Gas-Vacuum Regulator	5	3,316	1,391	7.2	307	1,004	836	6	2	5,021.2	16,076.8	21,098
Coolant Control Valve	4	1,889.5	911	7.2	X	702	2809	1	0	2,807.7	19,362.3	22,170
Pump Relief Valve	5	2,157	911	7.2	420	700	3495	1	1	3,495.2	--	3,495.2
Condenser By-pass Valve	12	5,192	911	11	151.5	522	895	7	0	6,265.5	5,484.5	11,750
Vent Vacuum Regulator	6	3,796	911	7.2	307	837	838	6	2	5,021.2	16,076.8	21,098
Cartridge Valve (Sterer)	27	4,376.3	1,977	28.8	151	242	126	52	9	6,533.1	59,406.9	65,940
Pressure Transducer	21	7,560	3,644	35	X	535	296	38	2	11,239	155,846	167,085
Gas Stop Valve	6	1,677	1,391	7.2	2.3	512	615	5	3	3,077.5	1,482.5	4,560
Condenser/Deionizer	7	3,174.3	1,391	7.2	4,231	1,260	4410	2	0	8,803.5	17,394.5	26,198

Figure 3.2-3. Test History

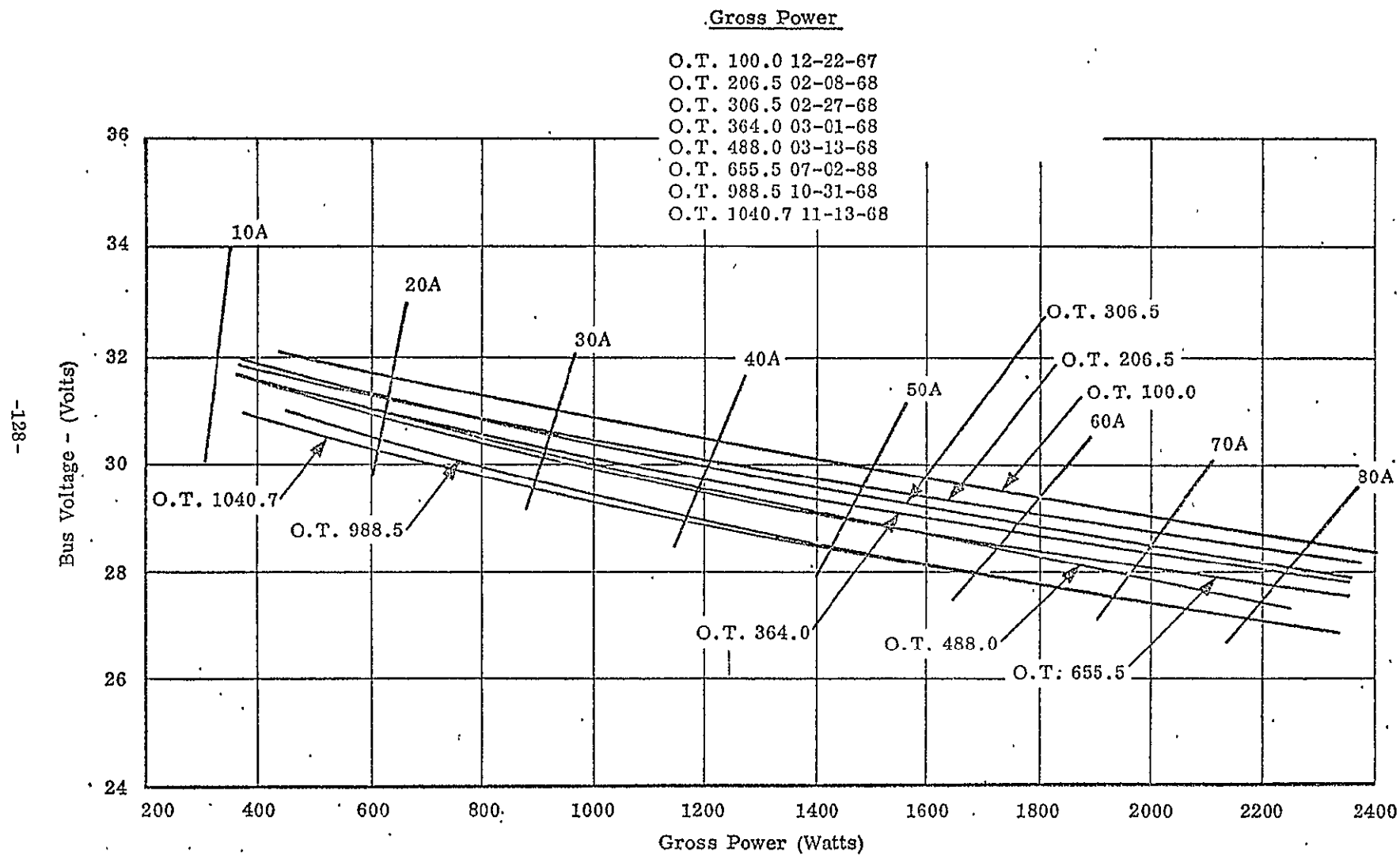


Figure 3.2-4. DVT 15 Performance Curve

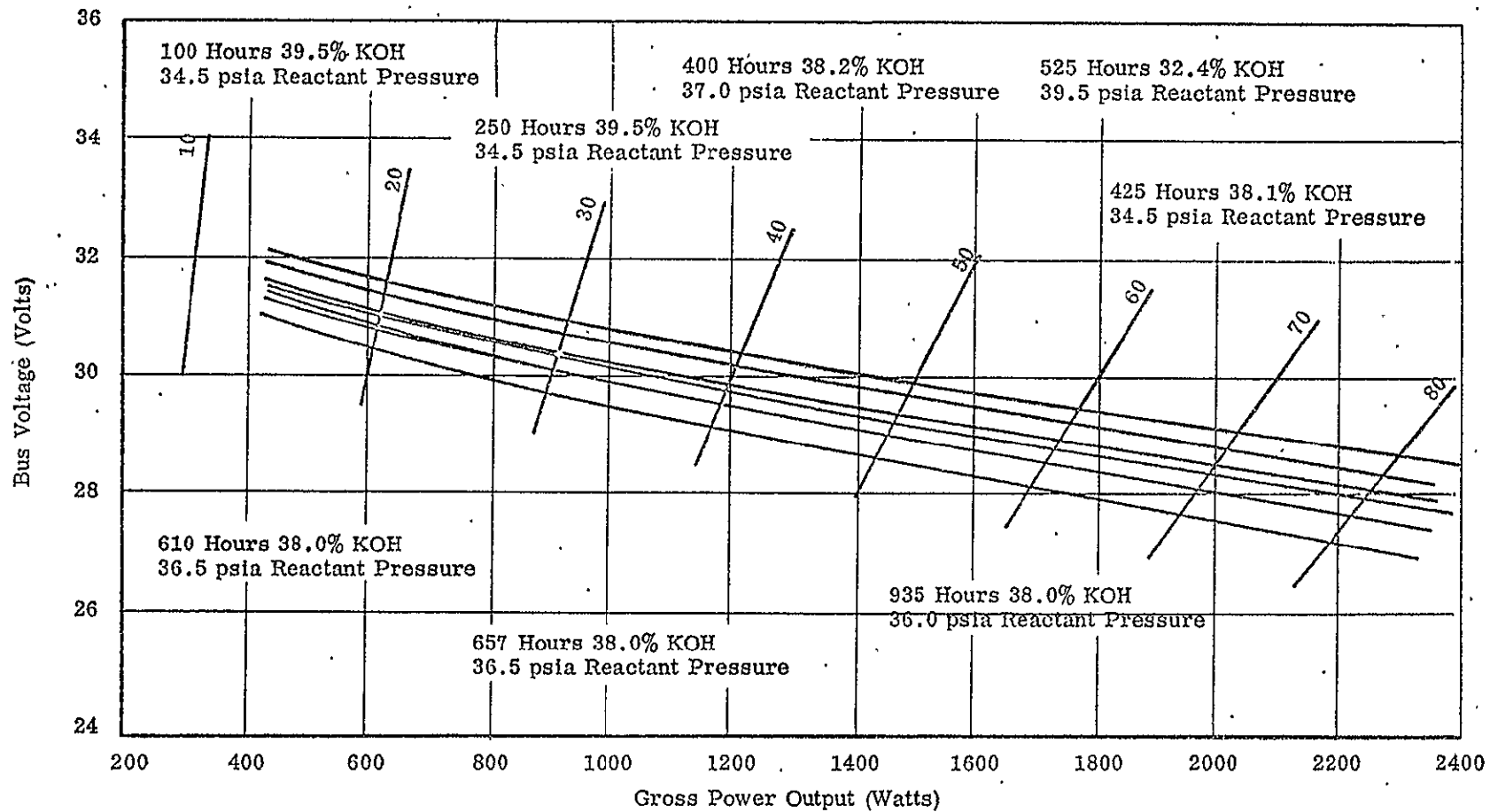


Figure 3.2-5. DVT 16 Performance Curve

Reactant over-pressure protection is provided by pressure switches which automatically close the reactant inlet lines on over pressure. Although this protective arrangement worked well on the DVT Systems, it does impose limitations on the length of tubing that can be tolerated between the reactant inlet valves and the module. To avoid placing any constraints of this nature on the vehicle, the Advanced System should incorporate relief valves to provide over-pressure protection to the fuel cell, or the reactant inlet valves should be closed-coupled to the dual channel regulator. Over-pressure switches should be provided to furnish a warning signal to the crew if an over-pressure condition occurs so that the reactant inlet valves to that fuel cell module could be closed.

The system was brought to operating temperature by application of external power to the system heaters, or through the use of the "bootstrap" technique where the system voltage is applied to its own heaters. During the bootstrap startup tests it was noted that the control system will normally hold the moisture removal valve open at low stack temperatures in an attempt to control the electrolyte concentration. This action, which tends to dry out the stack, is not tolerable. For test evaluation, the valve could be held closed through special provisions, however, in the Advanced System an automatic control should be provided to hold the moisture removal valve closed until a stack temperature of approximately 160°F is reached.

Control operation under load was stable, and response to transient loads proved to be well within specification limits. Load-sharing capability was successfully demonstrated and proved to be predictable in accordance with the individual performance curves. Instrumentation and readout equipment was more than adequate.

System shutdown was accomplished by closing the reactant inlet valves after dropping the load. The reactant cavities were purged of reactant gases and then inerted with helium for any shutdown exceeding 24 hours. The module was allowed to cool down either through natural heat loss or by

circulating coolant through the canister heat exchanger in a forced cool-down mode.

3.2.2 Subtask 2.2 - System Improvement Studies

The system improvement studies of Subtask 2.2 were conducted with the object of establishing an advanced fuel cell system concept. This report summarizes the study activities and defines the advanced system concept. These activities involve establishing system requirements, comparing existing technological capabilities to those requirements, identifying required or beneficial improvements and estimating cost and schedules for improvements.

Contact with potential shuttle vehicle contractors and NASA identified most of the basic future fuel cell requirements. Recently, a review of the NASA Request for Proposal #BG 731-50-0-229P for an advanced fuel cell technology program has produced a consolidated set of system guidelines. All of the obtained information was reviewed and an advanced system requirements document prepared. This document is in the form of the requirements section (Section 3) of a design specification. (Refer to Appendix B).

After the requirements were established, a review of the existing Allis-Chalmers fuel cell technological capabilities was made and assessed in terms of the advanced requirements. A comparison of the key performance requirements is shown in matrix form in Table 3.2-4.

The comparison of present capabilities and future requirements points out several discrepant areas:

- Weight
- Voltage Control
- Power/Life Requirement
- Life
- Maintainability
- Operational Flexability
- Weight to Power Ratio

KEY SHUTTLE REQUIREMENTS					
Parameter	Desired Value	Prior 2 kW NASA-AAP	Design Changes Required	Level Of Risk	Comments
Structural					
Configuration Weight Volume Mounting	Optional 10-60 lb/kW TBD Any Axis Hard Mount Component Minimum I/F Impact	Integral System at 2 kW 100 lb/kW 2.6 ft ³ /kW Any Axis Hard Mount Component Minimum I/F Impact	Repackage Two (2 kW) Stacks & One Sat Aux. Upgrading Stack 2.5 kW, Aux. 6.0 kW Flexible Design Two Stacks No Change	Low Very Low Very Low None	Direct Ext. of Present Frame & Mig. Exp. All Performance Requirements Demonstrated. Permits Freedom to Opt. Inif. & Maint. Feature. Req. Fully Demonstrated.
Reactants					
Fuel Oxidizer	H ₂ O ₂	H ₂ O ₂	No Change	None	Requirement Fully Demonstrated.
Source Pressure Propulsion O ₂ Propulsion H ₂ Cryo O ₂ Cryo H ₂	45 - 20 psia 45 - 20 psia 1000 - 800 psia 400 - 200 psia	N/A N/A 1000 - 100 psia 1000 - 100 psia	Develop New Reactant Conditioner No Change	Moderate None	Subject of Trade-off. (see subtask 2.3). Requirement Fully Demonstrated.
Purity Propulsion O ₂ Propulsion H ₂ Cryo O ₂ Cryo H ₂	0.995 0.99995 0.99995 0.99995	N/A N/A 0.99995 0.99995	Develop New Reactant Conditioner No Change	Moderate None	Subject of Trade-off. (see subtask 2.3) Requirement Fully Demonstrated.
Thermal					
General	TBD	Gas-Liquid Loop	Cold Plate Stack Cooling.	Low	(See Subtask 2.3)
Heat Rejection Mode Normal Other Coolant Fluid	S/C Radiators TBD TBD	S/C Radiators (Design) Water Venting Capability H ₂ O ~ Glycol	No Change Modify Control Per TBD No Change	None Low None	Requirement Fully Demonstrated. Features Desired Fully Demonstrated. Requirement Fully Demonstrated.
Electrical					
Voltage	28.0 ± 5% Vdc	28.0 ± 10% Vdc (No Regulator) N/A	Add Integral Stack Power Conditioner	Low	Prototype Dev. & Tested on Previous Contract
Power					
Rated Average Peak Spoke Power/Life	0-5 kW 2.5 kW TBD TBD 12,600 kWh	0-2 kW 1.6 kW 3 kW 4.5 kW 1500 kWh	Modest Upgrading of Stack to 2.5 kW No Change No Change No Change Incorporate Improvements Contract 10443	Low None None None Low	Demonstrated on Previous Contract. Requirement Fully Demonstrated. Transient Reserve of System Demonstrated. Increased Perf. & Life Potential Demo.
Parasitic Power	Minimum	77 Watts	Remove Fans	None	Not Needed With Cold Plate
Signal Conditioning, Transducers Degradation	TBD TBD	Integral With System Less Than 20 μ V/Cell Hour	Relocate & Substitute as Required. Incorporate Improvements	Low Low	Approach is Based On Proven Components. Increased Performance (see Task 1.0)
General					
Start/Stop Components and Control	Unlimited Minimum	Frequent Semi-automatic Flight Quality Fan and Pump Rotating Some Field Partial Diagnostics Instant at Temperature	Incorporate New Control Circuits Eliminate Fans, Evaluate Pump Requirements. Modular Packaging Incorporate Sensors	Very Low Low Low Low	Demonstrated With Bench Equipment. Fans Not Needed, Pump May Be Replaceable By Heat Pipes. Will Permit Rapid Field Maintenance.
Maintenance Checkout, Validation Start-up Time	Field In Place Instant	Instant (Manual Cooledown)	Incorporate New Control Circuits	Low	Demonstrated With Bench Equipment.
Shutdown	Instant	Instant (Manual Cooledown)			
By-product Water	C21-D + TBD	C21-D Automatic Delivery	No Change	None	Requirement Fully Demonstrated.
Life					
Design Operating	3,000 Hours	3,000 Hours Demonstration Stack	Incorporate Improvements Provide Prehumidification Reactants	Low	Demonstrated on Previous Contract.

Table 3.2-4. Comparison of Shuttle Goals and Present Technology

Means of advancing technology to meet the future requirements have been identified and evaluated and are presented in Tables 3.2-5 and 3.2-6. The following is a description of each improvement:

3.2.2.1 Life and Performance

Extension of life and improvement in performance are related closely in that both are aimed at the same end result: high end-of-life performance. Available techniques which reduce degradation generally tend to increase initial cell performance as well. Figure 3.2-6 shows a comparison of present AAP cell performance to a projected improved cell.

- Matrix Optimization

The electrolyte matrix plays a key role in the performance and life expectancy of the capillary fuel cell. An optimized matrix has minimum IR drop, maximum breakthrough strength and uniform distribution of electrolyte. Matrix optimization studies and tests were conducted under Subtask 1.1. The results of this effort are reported in the summary report of Work Task 1.

- Electrolyte Loading

A technique has recently been developed for the vacuum impregnation of fuel cell electrode/matrix "sandwiches" with electrolyte prior to assembly of the cell (refer to Subtask 1.1). This technique shows promise for improving cell performance and endurance characteristics. Benefits result from the ability to perform electrolyte loading under conditions of much "harder" vacuum. This eliminates entrapment of gases within the matrix pores, and results in higher resistance to cell cross-leaks, lower electrical resistance, and a larger inventory of electrolyte for the cell.

The full potential of "Electrode Matrix Assembly" technique requires further demonstration.

Areas of Advancement	Items to be Improved
Life and Performance	Matrix Optimization Electrolyte Loading Reactant Prehumidification Proportional MRV Variable Reactant Pressure Stack Electrolyte Replenishment High Power Density
Weight and Configuration	Weight Reduction Volume and Mounting
Reactant Management	Propellant Grade Reactant Usage Low Pressure Reactants Minimum Reactant Consumption
Thermal Control	Cold Plate Cooling Improved Water Removal
Operational Flexibility	High Voltage Output Power Conditioning Multiple Start/Stop

Table 3.2-5. Areas of Beneficial Improvement

Item	Advanced System	Means
<u>Stack Assembly</u> Consists of: - Cells - Top and bottom end plates - Compression device - Connections	138.0 (2 at 69.0 each)	- Plastic water plates - Modified end plates - Low-load compression device - Reduced plating - Use heat pipe techniques
<u>Thermal Control</u> Consists of: - Heat exchanger - Coolant valve - Heaters/insulation - Canister - Plumbing - Cooling fans	13.6	- Cold plates replace canister and heat exchanger - Fans eliminated - Use vehicle-supplied coolant
<u>Reactant Control</u> Consists of: - Purge valves - Regulator - Preheater - Transducers - Plumbing	5.0	- Improved packaging and layout - Simpler heaters - Modular unit supplying two 2.5 kW stacks
<u>Water Delivery</u> Consists of: - Removal valves - Condenser - Pump - Deionizer - Valves/regulators - Plumbing	18.8	- Proportional MRV - Improved Condenser/repackaging/heat pipes - Replaceable cartridge deionizer - Plumbing simplification - Modular unit supplying two 2.5 kW stacks
<u>Electrical Control</u> Consists of: - Inverter - Controllers - Signal conditioning - Cabling	33.2	- Add voltage regulator - Delete inverter - Controller packaging improvements - Modular unit supplying two 2.5 kW stacks
<u>Structures</u> Consists of: - Mounting frame - Thermal isolation - Mounting hardware	11.0	- Stack support integral with end plate - Components clustered on common structure
Total System Weight	219.6	
Power Rating	5.0 kW	
Weight-to-Power Ratio	44 lb/kW	

Table 3.2-6. Advanced System Weights

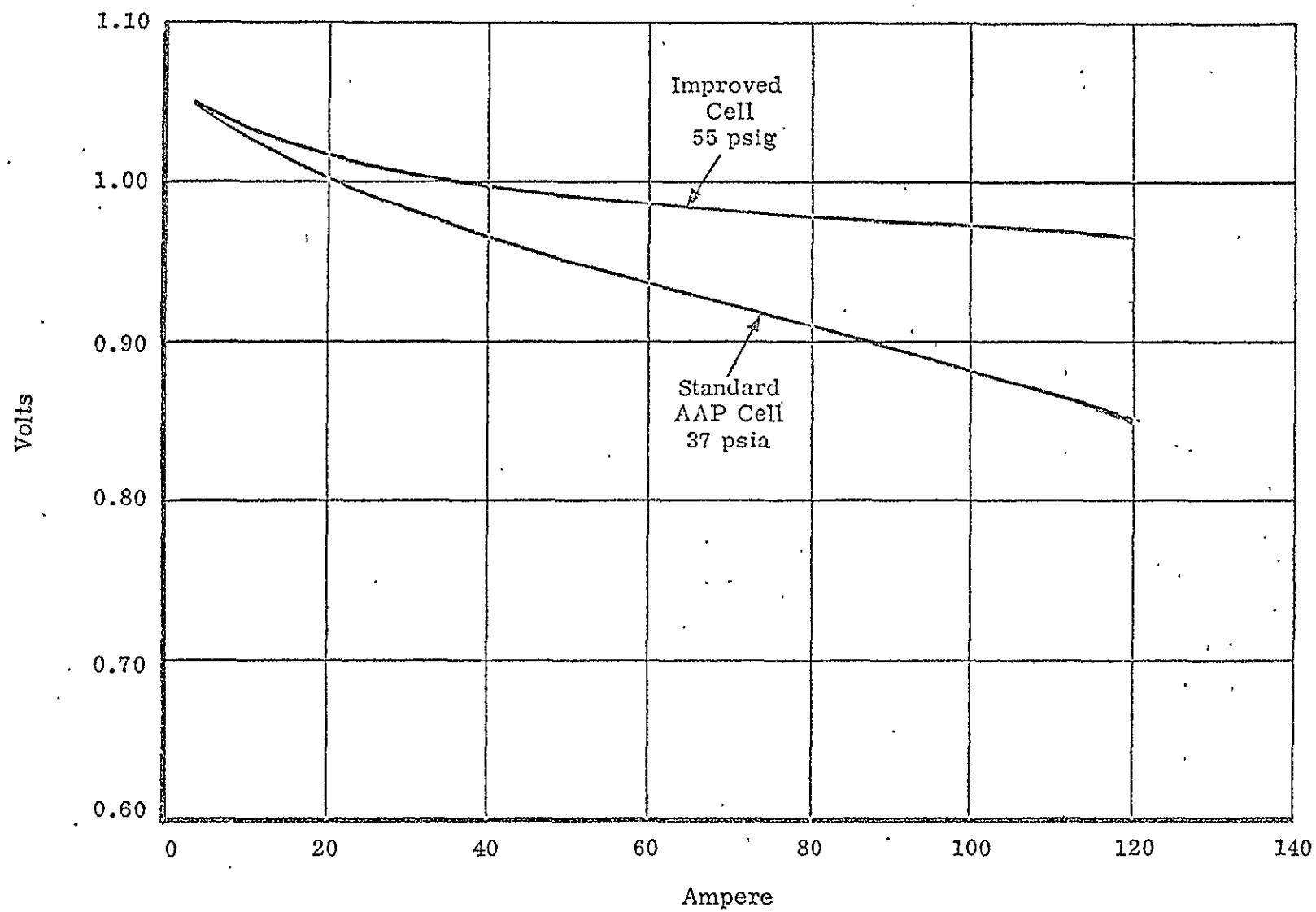


Figure 3.2-6. Effects of Matrix Improvements and Reactant Pressure on Cell Performance

o Reactant Prehumidification

Concentration gradients are induced laterally in the cell electrolyte matrix by the inflow of dry reactants. The resulting electrolyte maldistribution is a contributor toward long-term degradation. Examination of dismantled long-life cells indicates potential gas flow restriction due to inlet area drying. The importance of this parameter to cell life has been further demonstrated by obtaining a 25% improvement in 2000-hour performance when dual inlet feeds were employed in a 200 W, 28 V stack. Life and power density improvement is achievable through reduction of cell concentration gradients by means of prehumidification of the reactants. Two techniques should be evaluated for accomplishing this: gas recirculation by means of jet pumping (discussed more fully under Reactant Management) and use of a humidifier integral with the stack at the reactant inlet.

o Proportional Moisture Removal Valve (PMRV)

"On-off" type moisture removal valves, as used on the AAP and MOL fuel cells, contribute to concentration gradient formation and KOH loss due to high water vapor removal rates during the open portion of the valve cycle. The 2 kW NASA-AAP technology has demonstrated degradation levels of less than 20 $\mu\text{V}/\text{h}$ using cyclic moisture removal for 2500 hours life.

Proportional MRV's have been used successfully on another program for several years, and larger PMRV's have been development tested for the High Performance Fuel Cell. Operation of both 2 kW and 200 W, 28 Vdc full stacks with proportional moisture removal has demonstrated a degradation level of 10 to 15 $\mu\text{V}/\text{cell hour}$ for 1200 to 2000 hours.

o Variable Reactant Pressure

The improvement in electrochemical efficiency due to increased reactant pressures can be exploited to achieve higher power densities and reduce degradation.

A system designed for inherent voltage regulation can achieve long life within voltage limits by varying (increasing) reactant pressure over its operating life; a voltage-regulated approach can employ a continuous high reactant pressure over its lifetime to achieve the same effect.

The effects of various reactant pressures have been evaluated by A-C under the MSFC Reliability Assessment program, and are a function of load and accumulated life. Performance characteristics of present hardware over the 20 to 60 psia range should be verified in development testing.

• Stack Electrolyte Replenishment

One of the causes of performance degradation in alkaline fuel cells is depletion of the electrolyte by the following mechanisms:

- Chemical reaction with active impurities in the reactant gases
- Chemical reaction with asbestos constituents
- Carryover of minute quantities of electrolyte with product water

Performance recovery has been demonstrated on stacks by flushing and refilling with fresh electrolyte. This technique should be evaluated as a preventive maintenance action in advanced system applications.

• High Power Density

Increased cell operating power density offers obvious improvements in the system power-to-weight ratio. Fuel cells have demonstrated life capability in excess of 1000 hours at 200 ASF average at the stack level, and stable operation in the 300 to 800 ASF range for periods of one hour. Under this contract a small stack was operated at 400 ASF for more than 150 hours with little, if any, degradation. Operation at higher ASF levels should be conducted to obtain more design information.