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Hamilton Standard — United Aircraft Corporation

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FINAL REPORT

HYDROGEN DEPOLARIZED CELL PAIR DEFINITION FOR SPACE STATION APPLICATION

PREPARED UNDER CONTRACT NAS 9-12920

by

HAMILTON STANDARD
DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

by

CORNELIUS R. RUSSELL

MARCH 1973

ABSTRACT

HYDROGEN DEPOLARIZED CELL PAIR DEFINITION

FOR

SPACE STATION APPLICATION

CONTRACT NAS 9-12920

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This report pertains to evaluation testing of the cell pair design concept for hydrogen depolarized cells. The cell pair concept evolved from a design study which established this concept to be potentially the lightest, simplest, and lowest penalty hydrogen depolarized unit design for Space Station Prototype application.

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FOREWORD

This report was prepared by the Hamilton Standard (HS) Division of the United Aircraft Corporation for the National Aeronautics and Space Administration's Johnson Space Center, in accordance with contract NAS 9-12920. The report documents the work accomplished in performing task 3.2.9 of the statement of work, "HDC Cell Pair Definition for Space Station Application", during the period from 22 June through 1 December 1972.

Hamilton Standard personnel directly responsible for the conduct of this program were Mr. F. H. Greenwood, Program Manager; Mr. C. R. Russell, Engineering Project Manager; Mr. K. Barth, Space Systems Department Engineering Manager; Mr. J. C. Huddleston; Dr. J. R. Aylward and Mr. J. Bertrand. The assistance and guidance of Mr. A. F. Behrend, NASA Technical Monitor; Mr. R. J. Gillen, overall Program Supervisor; and Mr. W. Sanderson, technical consultant (Boeing Company), all of the NASA/Johnson Space Center, are appreciated.

Other Hamilton Standard personnel contributing actively to the program were Mr. H. Brose, Engineering Manager - SSP Program; Mr. J. Lovell, Chief, Advanced Engineering, Space Systems Department; and Mr. F. Sribnik, analyst.

Appreciation is expressed to all participants for their dedication and effort on conducting this test program. Acknowledgement is specifically given to Mr. J. Bertrand who was the principal test engineer, did most of the data plotting in this report, and also prepared and coordinated the test data which was microfilmed; to Mr. F. Sribnik, who designed the H543 computer program, and to Dr. J. R. Aylward for his assistance in editing the Gas Analysis section contained in the Discussion of this report.

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ABBREVIATIONS & SYMBOLS

ABBREVIATIONS & SYMBOLS

ASF/asf	amperes/square foot
cc	cubic centimeter
cfm	cubic feet per minute
CO_2	carbon dioxide
CO_3^{-2}	carbonate ion
Cs_2CO_3	cesium carbonate
dc	direct current
DP	dew point
E	cell voltage (IR free)
°F	degrees Fahrenheit
Ft.	foot
H_2	hydrogen
HDC	hydrogen depolarize carbon dioxide concentrator
Hg	mercury
hr.	hour
HSG	housing
H_2O	water
I	current
i	current density
in.	inches
IR	resistance drop
kg	kilogram
lb.	pound
mg	milligram
min.	minute
mm	millimeter
mv	millivolt
N/A	not applicable
Nom	nominal
O_2	oxygen

ABBREVIATIONS & SYMBOLS (Concluded)

P	pressure
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
psid	pounds per square inch differential
PH_2O	partial pressure of water vapor
PH_2	partial pressure of hydrogen
P&WA	Pratt & Whitney Aircraft, Division of United Aircraft Corporation
Q	Flow rate of gas
R.H.	relative humidity
SSP	Space Station Prototype
scc	standard cubic centimeter
sec.	second
SCFM	standard cubic feet per minute
SO_2	sulfur dioxide
SWEF	South Windsor Engineering Facility, Division of United Aircraft Corporation
T	absolute temperature
ΔT	temperature, differential (T_{DB}-T_{DP})
T_{in}	inlet temperature
TBD	to be determined
UAC	United Aircraft Corporation
VDC	volts, direct current
wt.	weight
wt-%	weight percent
μ	micron
%	percent
$\approx$	approximately equals
=	equals
<	much less than
η	efficiency

DEFINITIONS

DEFINITIONS

Cell	Electrochemical cell consisting of an anode screen, matrix with electrolyte, and cathode screen.
Cell Pair	Two cell packages with back to back hydrogen electrodes which share a common hydrogen chamber, housing and reservoir assemblies.
Dry Out	The condition of the cell, when the volume of the electrolyte is insufficient to completely fill the matrix due to loss of water.
Drive Cathode	Forcing cathode to certain potential with respect to some reference electrode.
Drive Anode	Same as above but with relationship to anode.
Efficiency	(Current efficiency) taken as moles of CO_2 transferred per mole of hydrogen oxidized at anode. Moles of hydrogen oxidized as directly related to the cell current.
Flooding	The condition of the cell when the electrolyte has absorbed an amount of water which results in an electrolyte volume exceeding the capacity of the cell matrix and electrodes.
H_2 Crossover	Occurs at dry out of the matrix and allows hydrogen and oxygen to pass through the matrix.
Normalize	As used in this report, normalizing refers to standardizing cell performance by adjusting to a specific current density and carbon dioxide concentration.
Purge, N_2	The flow of nitrogen gas through the cell anode passageways.
Purge, Heat	Refers to the technique of interrupting air flow through the cells resulting in an increasing electrolyte/cell temperature. Done to investigate possible long-term improvement in all performance.

DEFINITIONS (Concluded)

Reservoir	A porous material which absorbs the excess electrolyte during cell flooding and returns it to the matrix during drying conditions.
Steady State Operation	The operating condition when the cell voltage and current do not change significantly with time.

SUMMARY

This report pertains to evaluation testing of the cell pair design concept for hydrogen depolarized cells. As a result of the review of the Hamilton Standard designed Electrochemical CO_2 Collection Subsystem for the Space Station Prototype during the Approval Design Review Meeting in May 1972, the NASA directed that additional Hydrogen Depolarized Cell (HDC) performance demonstration was required prior to proceeding with subsystem fabrication for SSP. The areas of additional testing required were subsequently defined in joint NASA JSC and HS meetings in June 1972 which culminated in the issuance of a test plan and program schedule.

The test plan defined four tests and associated analyses and miscellaneous tasks. The objectives of the analytical and miscellaneous tasks in support of the test program were:

- Performance instrumentation error analysis for determining cell inlet CO_2 pressure, the flow rate of the H_2 + CO_2 cell effluent, CO_2 concentration within the cell effluent, and the cell CO_2 collection (transfer) rate.
- Normalize the 226-day test of Hamilton Standard Cell Pair S/N 010 to show CO_2 removal performance versus time.
- Define the cell purge technique (if any) to be employed during tests 1-4.
- Develop a computer mathematical model to determine the number of cell pairs required to satisfy the SSP requirements, based upon the CO_2 removal performance achieved in this test program.
- Modify the Hamilton Standard Electrochemical test facilities to -
  - enable running tests 1-4 under a constant (but adjustable) current density, and
  - minimize the leakage rate between the test chambers (containing the cells being tested) and laboratory room air.

The objectives of the test program were:

- Establish the adequacy of certain cell pair housings and "sputtered" electrodes.

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- Evaluate the effects of varying matrix compression over a range conducive with cell assembly tolerances and matrix void volume variations.

- Determine the desirability for including Tissuquartz in the proposed SSP reservoir cell configuration to enable the cell to withstand a significant step change in inlet air temperature.

- Establish a map of cell performance at varying current density, inlet air temperature, inlet dew point, and carbon dioxide concentrations and evaluate the change in this performance versus cell operating time.

  Note: Owing to the duration of the tests conducted under this program being extended from 2 to 7 months, a more simplified cell performance "map" consisting of cell voltage and current efficiency plotted as a function of time, was substituted.

Conclusions reached as a result of the analytical and miscellaneous tasks associated with this reported effort are:

- The RSS Measurement error for determining CO_2 transfer rate was ± 3.95% on the reported tests.

- Normalization of the seven month cell S/N 010 data revealed that CO_2 removal performance remained constant throughout the test except for a step decrease midway through the test following a facility fan failure which resulted in cell pair dryout.

- A procedure for purging the cell with nitrogen once each day was developed and employed on each of the four tests of this reported effort. The purge, discontinued after three months of test 4, was found not to improve CO_2 transfer efficiency. Elsewhere this report discusses whether periodic purging actually might have contributed to the higher than expected voltage decrease of the cells.

- A computer program was developed and used for determining the number of cell pairs required to satisfy SSP requirements based upon actual cell performance achieved. It was established that 33 cell pairs would satisfy the SSP application.

- Modifications were made to the facility to enable constant current testing at selected current densities. Owing to mechanical limitations it was, however, found impractical to reduce test chamber to laboratory room air leakage rates. It was not positively established whether the relatively high concentration of sulpher dioxide (20 PPM) which the test cells were consequently exposed to, contributed to the voltage degradation.

Conclusions reached from tests 1-4 are:

- Both the annealed and non-annealed housings were found acceptable.
- Although not positively demonstrated as superior, NASA and HS agreed that the electroplated electrodes would be used in all tests.
- Based on short term testing, in which matrix compression was varied over a range above and below the 0.024 inch nominal, cell voltage and CO_2 removal efficiency were found independent of matrix thickness within the range tested.
- It was positively established that Tissuquartz assembled in strips within the matrix resulted in the reservoir cell being able to withstand a ± 4°F air inlet step change...this configuration was subsequently employed.
- A map of CO_2 removal efficiency for different operating conditions was established over an extended test period. The originally planned test duration of six to eight weeks was extended. After five months of continuous testing, no permanent decrease in cell current efficiency (performance) occurred. Cell voltage decreased with time over five months, but remained sufficiently high to accommodate the necessary CO_2 transfer rate for the SSP application.

RESERVOIR CELL PAIR IN TEST FIXTURE MOUNTED

SS10112-4

CELL PAIR WITH RESERVOIR
(NOTE: MODEL PHOTOGRAPHED HAS PLEXIGLAS RESERVOIR. TITANIUM RESERVOIR EMPLOYED IN TEST PROGRAM)

SS10110-4

DISASSEMBLED CELL PAIR SHOWING LOCATION OF ELECTRODES AND MATRIX

SS10062-8

INTRODUCTION

In support of the NASA "Advanced Integrated Life Support System" (AILSS) study during 1968-1969, Hamilton Standard considered the merits of the Hydrogen Depolarized Cell (HDC) technique for CO_2 removal and collection. The trade-off studies showed the potential and advantages of the HDC compared to other more developed approaches. As a consequence of the potential offered, some HDC development and testing was done at Windsor Locks in parallel with the Molecular Sieve CO_2 subsystem then planned for SSP. It was recognized that advantages of weight, volume, and power inherent with the HDC CO_2 collection approach represented significant improvements over a Molecular Sieve subsystem if HDC development could be accelerated within the schedule and funding restraints of the SSP program.

Hamilton Standard initiated tests of HDC cells in early 1970 upon SSP funding; and by mid-1970 completed, designed and fabricated an all-metal HDC cell pair, having a one square foot electrode area, and designed to accommodate maintenance of low cabin CO_2 partial pressures. Although the SSP required maintenance of CO_2 partial pressures of three millimeters (mm Hg) in the cabin atmosphere, it was anticipated that the cell should be sufficiently flexible to accommodate normal earth standard atmosphere concentration of CO_2 (0.23 mm Hg) if that requirement should ever be imposed on the SSP. The "cell pair" design concept (as opposed to a cell "stack") was believed to be a desirable and necessary feature of the design to facilitate the intent of SSP "maintainability" considerations. The large size (one square foot electrode area per cell pair) was selected to reduce cell weight by reducing the percentage of wasteful peripheral material. A concept of nonmetallic "matrix-spacers" and electrode mounting recesses was chosen to accommodate optimization of the cell through investigations of matrix thickness and electrode thickness, by permitting variation of these components during cell assembly. Significantly, the cell pair configuration with physical separation of cells within the subsystem, allows a multiple cell subsystem to be evaluated by tests on a single cell pair (ref. page 33).

Following the successful verification testing of the one square foot "SSP" cell pairs in 1970 and 1971, program objectives required that emphasis be placed upon subsystem design optimization rather than cell optimization. Further HDC cell optimization was pursued under a separate (NASA/JSC) CR&D program (NAS 9-11830) oriented toward the development of an integrated water vapor electrolysis (WVE) and HDC unit for advanced spacecraft application. It was projected by Hamilton Standard that 24 cell pairs with the existing non-optimized performance would satisfactorily handle the six man SSP CO_2 removal requirement. Space for additional cells was initially planned to accommodate "cyclic" operation. The number of cell pairs was revised by Hamilton Standard from 24 to 27 following additional experience gained during the test of cell pair S/N 010 under the SSP program.

In mid-1972 as a result of the review of the HDC cell test data presented at the SSP Approval Design Review meeting, the NASA directed that further demonstration of repeatable performance was required prior to initiation of subsystem fabrication for SSP and that this activity be conducted under the technology effort of contract NAS 9-12920. A contract modification was issued by the NASA to implement this work.

The areas of the technology effort were defined specifically in a meeting during June 1972. These areas included:

- Identification of the hardware to be committed to testing and fabrication controls on the test hardware.
- Definition of the Design Support Test Plan, required measurements, measurement techniques and controlled testing conditions.
- Definition of the success criteria for the test program and acceptance test criteria for production cells.

As is shown in this report, the CO_2 removal performance of two reservoir test cells built and evaluated under the "special HDC test program" was satisfactory (65-75% efficiency) after five months of operation over a wide variety of conditions, with sufficient voltage (power) to allow creditable prediction of six to twelve month life, against an SSP requirement of a six month life.(1)

This technical report documents both the NASA funded special HDC test program as well as the continuation of the test on the two "SSP configuration" cells as conducted under United Aircraft funding to positively demonstrate the six month life capability.

(1) Since initial preparation of this report testing has been extended to seven months.

CONCLUSIONS

This technical report presents the results of a test program planned to determine and to evaluate the performance of the Hamilton Standard designed Hydrogen Depolarized Electrochemical Cell.

Supported by the documentation contained within this report and its Appendices, it is concluded that 33-36 Hamilton Standard designed cell pairs of the stated reservoir configuration would satisfactorily and reliably maintain the six-man SSP cabin(s) CO_2 partial pressure at or below 3 mm Hg for a time period exceeding six months, when the subsystem is operated at a hydrogen "back-pressure" of 5 psig. This number does represent an increase over the 27 cell pairs earlier believed to represent the required number for the 6-man SSP mission.

It is specifically concluded from an examination of data contained in this report that:

- No reversible loss in CO_2 removal efficiency has occurred after five months of continuous testing (seven months at present date).
- Temporary reductions in CO_2 transfer rate (efficiency) at a given operating current density did occur and are probably related to perturbations caused by variation of "input conditions" to the test cells being evaluated.
- Cell power (voltage) degradation did occur. The degradation rate did decrease with time. The time-voltage characteristics are such that a six-month cell life is assured for the stated number of cells.
- For 36 cell pairs the nominal current density required is 14.5 amps per square foot (asf). Although it is possible to decrease the number of cell pairs below 33-36, the endurance test did show that if fewer cells were used requiring operating at higher current density, a cell life problem would exist, whereas for the stated number of cell pairs it is Hamilton Standard's belief that cell life adequacy has been demonstrated.
- A considerable design margin exists between the 36 cell pair configurations and the 58 cell pairs which actually could be accommodated by the SSP HDC system.
- Cell voltage can be permitted to drop to 20 mv for 36 cell pairs, 24 mv for 33 cell pairs.
- Nitrogen purging of cells should be discontinued until further effort demonstrates that such purging does not detrimentally affect the long-term cell voltage (power) performance.

RECOMMENDATIONS

- Investigations should be undertaken to identify the causes and remedy the voltage degradation rates experienced by the Hamilton Standard hydrogen depolarized cells. In addition to the SSP imposed six to eighteen month life other reasons for endeavoring to reduce the decay rate are:

  1. Higher cell voltages will be necessary if the number of cells is to be reduced following CO_2 efficiency improvements.

  2. The criticality of minimizing external electrical resistance would be reduced, enabling the use of smaller wiring sizes, simpler wiring, reduced concern of terminal corrosion should it occur, and enabling the use of a smaller, more economical current adjustment device.

  3. Higher cell voltages are desirable because they enable operation at higher current density (assuming H_2O and O_2 generation consumption rates are acceptable), consequently providing an additional margin in cell life.

- Investigation should be made at further improving CO_2 removal efficiencies. Although the 65-75% efficiency as achieved throughout most of this test at 13-14 asf, was acceptable it would be desirable to achieve this same efficiency level at 20 asf in order to reduce the number of cells for a system.

- Periodic N_2 purging of the cells should be suspended until long-term effects on voltage decay are determined because the usefulness of nitrogen purging has been shown to benefit short term cell voltage only, whereas its long term effect upon cell voltage is unknown.

DISCUSSION

As described in the summary, work done in this program consisted of both analysis and testing.

The analysis, and other incidental and miscellaneous tasks, are described first. In general, these tasks were accomplished during the period June 20, 1972 to July 15, 1972. It should be emphasized that although the analyses were at all times regarded as important to the program, they were not emphasized to the same extent as the test program itself, which, as of December 1972 had been underway for six months.

ANALYTICAL PROGRAM

Several analytical and miscellaneous tasks were requested by the NASA and were performed at the beginning of this test program.

Measurement Error Analysis (Hamilton Standard Test Facility)

Appendix A of this report documents the root-sum-square (RSS) analysis which was performed to establish the accuracy of critical measurements and instrumentation from which cell performance was derived.

Four analyses were made:

1. Chamber CO_2 partial pressure (inlet CO_2 pressure to test cells);
2. Flow rate of H_2 + CO_2 from cell(s);
3. CO_2 concentration in cell H_2 + CO_2 effluent;
4. CO_2 transfer rate (a combination of 2. and 3. above).

From these analyses, it was concluded that the CO_2 transfer rate would be determined within ± 3.95% on an RSS (99%) basis. This overall CO_2 transfer measurement accuracy was acceptable to both the NASA and Hamilton Standard.

Normalization of S/N 010 Data

The NASA requested that as part of the subject program, the test data from cell S/N 010 be normalized for current and CO_2 inlet pressure to allow

evaluating cell performance versus time. Cell S/N 010 (a non-reservoir cell pair) had been run essentially continuously for a period of seven months in the Hamilton Standard test facility prior to the start of the reported effort and was of interest owing not only to the duration of the test but further because of the large amounts of data that had been accumulated.

Figure 1, shows the "normalized" performance of cell pair S/N 010 plotted as a function of test time. It appears that CO_2 removal performance remained nearly constant until day 111 when a facility fan failure, which occurred in the evening and was undetected for more than twelve hours, caused the unit to dry out. After rewetting, the indicated performance dropped and remained at a constant level for the remainder of the test (day 226).

In order to normalize the data two steps were required. First, the relationship between current (I), CO_2 partial pressure (P_{CO_2}) and cell current efficiency (η) determined from parametric testing, was used to calculate the factor, given by the relationship $\eta = K \sqrt{P_{CO_2}/I}$. Secondly, LIRA calibrations were applied to data prior to the calibration point where the data appeared inconsistent.

Notes which apply to figure 1 are given below:

(A) Facility fan failure caused cell dry out and H_2 crossover. Cell pair was shutdown and rewetted by resetting proper conditions.

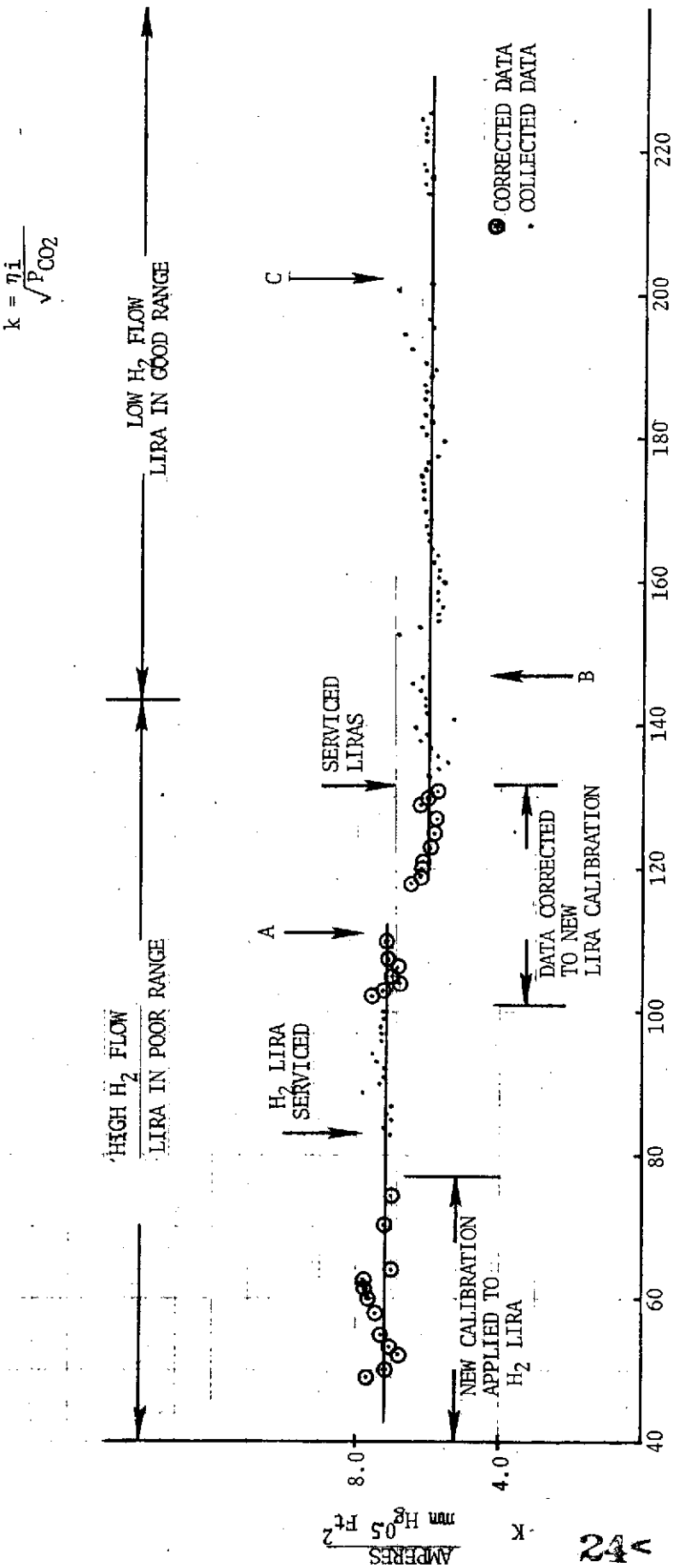
(B) Cell pair dried out due to chamber temperature going outside limits.

(C) Cell pair installed in series with another cell pair (cell Y).

Definitization and Background of Cell "Purge"

During mid 1972, Hamilton Standard observed that an improvement in cell power (voltage) resulted following a brief N_2 or air purge of the hydrogen passageway of a cell-pair. It was thought that the most likely cause for the cell voltage improvement when so purged probably related to the oxidization of certain contaminants on the anode. Although this reason was the most obvious; it was recognized that additional investigation was required to define the mechanism causing the improvement.

Although no extended duration testing was available to fully evaluate the impact on long term operation, a basis did exist for predicting that a long term cell voltage benefit might result from a periodic (once daily) short duration N_2 purge of the cell H_2 passageway. No reason was seen for damage or other adverse effects to the cell pair by such purges. Tests were made of two minute, five minute and eight hour purge durations, and it was determined that



NORMALIZED CELL PAIR S/N 010 DATA

FIGURE 1

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the five minute purge appeared most favorable (little or no further improvement was observed with purge durations exceeding five minutes and the two minute purge was shown to be less effective). A system impact evaluation[1] was made, and it was mutually agreed with the NASA that tests 1 - 4 of the Special HDC Test program would be started imposing a daily five minute N_2 purge each twenty-four hours. The NASA-Hamilton Standard agreed-on plan enabled decreasing purge frequency if warranted by test results.

It was recognized that other, perhaps more favorable, techniques existed for minimizing cell voltage degradation. Hamilton Standard proposed such an investigation to the NASA in June 1972, to permit positive results of this investigation to be implemented into the subsequent Special HDC Test program. The NASA, however, was unable to fund this investigation.

Later a short "purge" evaluation investigation was conducted under Hamilton Standard's IR&D program in September 1972, employing cell pair S/N 017. The results of this investigation are separately shown on pages 72 thru 78 of this report.

Cell Performance Mathematical Model

A computer program was developed for NASA by Hamilton Standard for use in interpreting cell performance established in this test program. The program shows the SSP cabin CO_2 pressure as a function of mission time for a wide variety of assumed conditions for different cell performances. Appendix B describes this program and gives sample computer forecasts for both the cell pairs evaluated under this project and for cell pair S/N 010. The program was to be sufficiently flexible to accommodate Life Systems, Incorporated, hydrogen depolarized cell performance, to allow forecast of cell numbers required, and to show instantaneous and cumulative consumption, removal, and generation rates of O_2, CO_2, and H_2O.

As may be observed by study of Appendix B, it was concluded that 33 - 36 Hamilton Standard cell pairs would accommodate the necessary CO_2 removal rate, and still provide adequate margin in O_2 consumption, and H_2O generation rates.

Modifications of Hamilton Standard Test Facility

Hamilton Standard was requested to make modifications to the test facility in preparation for the reported program. The electrical circuitry was to be modified to permit constant current cell tests and the individual test chambers were to be further sealed to minimize leakage from the laboratory air.

[1] "Purge Definization Including SSP Impact Study", 5 July 1972, ECS-2128-L-002.

Modifications of the facilities were made to enable constant current cell operation. To reduce costs, a manual control device was incorporated, adjudged as satisfactory since all parametric tests in which accurate current adjustment was required were manned twenty-four hours a days.

An unsuccessful attempt was made to remedy the leakage rate of air from the laboratory to the test chambers. The test chambers had been constructed in such a manner, that the leakage could not be practically remedied. The agreed on test schedule and cost considerations did not permit a major rework of the facility. It was mutually agreed with the NASA, that tests would proceed without compliance with this request.

TESTS 1 - 3

Tests 1 through 3 were performed to provide assurance that the cells to be evaluated in test 4 -- the major portion of this program -- were configured to provide the best possible performance and highest probability of success. Appendix C "Test Plan" provides details of the test plan outlining the background and objective of each of the four tests. The tests are described in the text in the chronological order in which they were conducted.[1] In this way, the rationale associated with the test program as it progressed, is thought to be more meaningful.

Throughout this report, reference is made to the reservoir and non-reservoir cells or cell pairs. It should be noted that with minor differences the reservoir and non-reservoir cells are basically similar, employing the same cell pair housing designs. The reservoir cell, built and evaluated under the preceding NASA funded CR&D contract NAS 9-11830, contains a wick-fed enclosure attached to the cell in which wicking material is contained to provide an electrolyte accumulator to accommodate electrolyte transfer to and from the cell should cell electrolyte conditions change during operation. If for example, the water vapor pressure in the cell inlet air stream decreases, thereby tending to cause a reduced moisture of "wetness" of the electrolyte between the electrodes, electrolyte within the reservoir would "wick" into the cell acting to maintain the volume of electrolyte between electrodes to prevent cell "dry-out". If, in the other extreme, the water vapor pressure in the cell inlet air stream were to increase, the reservoir would act to absorb that additional volume of electrolyte developed between the electrodes to prevent "flooding". Although it is beyond the intent of this report to explain how the judicious selection of reservoir and cell matrix pair size

[1] Test number as employed in this report are different from the numbers assigned in the test plan, as follows:
Test 1 (reference test 3 in Test Plan, Appendix C).
Test 2 (reference test 1 in Test Plan, Appendix C).
Test 3 (reference test 2 in Test Plan, Appendix C).

enables such a two-way electrolyte "accumulator" flow capability reference is made to NASA - HS reports on preceding contracts.[1] They reported that water vapor electrolysis cells equipped with the electrolyte reservoir, were capable of tolerating 25 - 30°F variations in air inlet temperature, and still provide acceptable performance, whereas the non-reservoir cells, could not accommodate large changes in air temperature on humidity conditions. It was to provide this additional safety margin that the SSP was of the reservoir-type, in spite of the fact that the non-reservoir cells had sufficient tolerance to accommodate temperature changes which might arise aboard the SSP vehicle.

Figure 2 shows the schedule, the test cells and test chambers used and references figures within this report which show results of tests 1 - 4.

Test 1

Tests employing various matrix and reservoir materials and pore sizes had been investigated in previous NASA - HS work. It was generally found by these tests, that although the use of Tissuquartz[2] aided the wicking rate of electrolyte between the reservoir and cell (and vice versa), a compromise existed wherein the Tissuquartz would tend to "dry-out" faster than the small-pored asbestos under certain operating conditions, thereby causing a sharp increase in the internal resistance of the cells and a resulting decrease in cell power level. The tradeoff between a reservoir cell with and without Tissuquartz had been agreed upon as necessary by NASA and HS. Test 1 was subsequently conducted. Test 1 employed a non-Tissuquartz cell (cell pair S/N 011), exposed it to a step change in air inlet temperature of 4°F to determine if the non-Tissuquartz cell could adequately respond to the air inlet variation, and subsequently proceeded to repeat the same experiment with an otherwise identical cell containing Tissuquartz.

Table I describes the plan of test 1 and all configurations used.

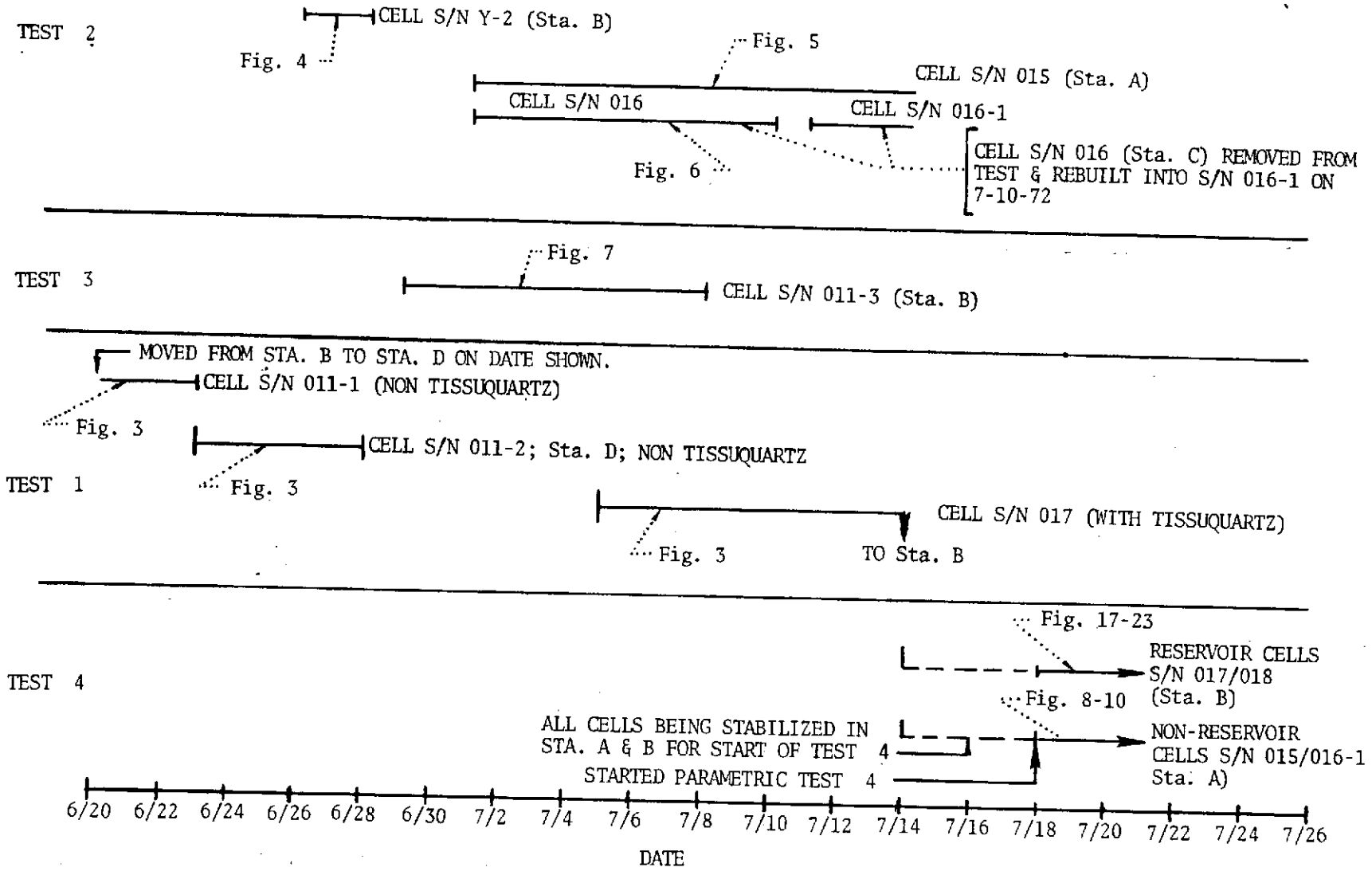
Figure 3 graphically shows the results of testing on cell pairs S/N 011-1 and S/N 011-2 (non-Tissuquartz cells) and on S/N 017 (Tissuquartz included in matrix).

---

[1] Huddleston, J.C.; and Aylward, J. R.: Feasibility Study of a Humidity Control and Oxygen Supply System Utilizing a Water Vapor Electrolysis Unit. NASA CR-115070, 1971.

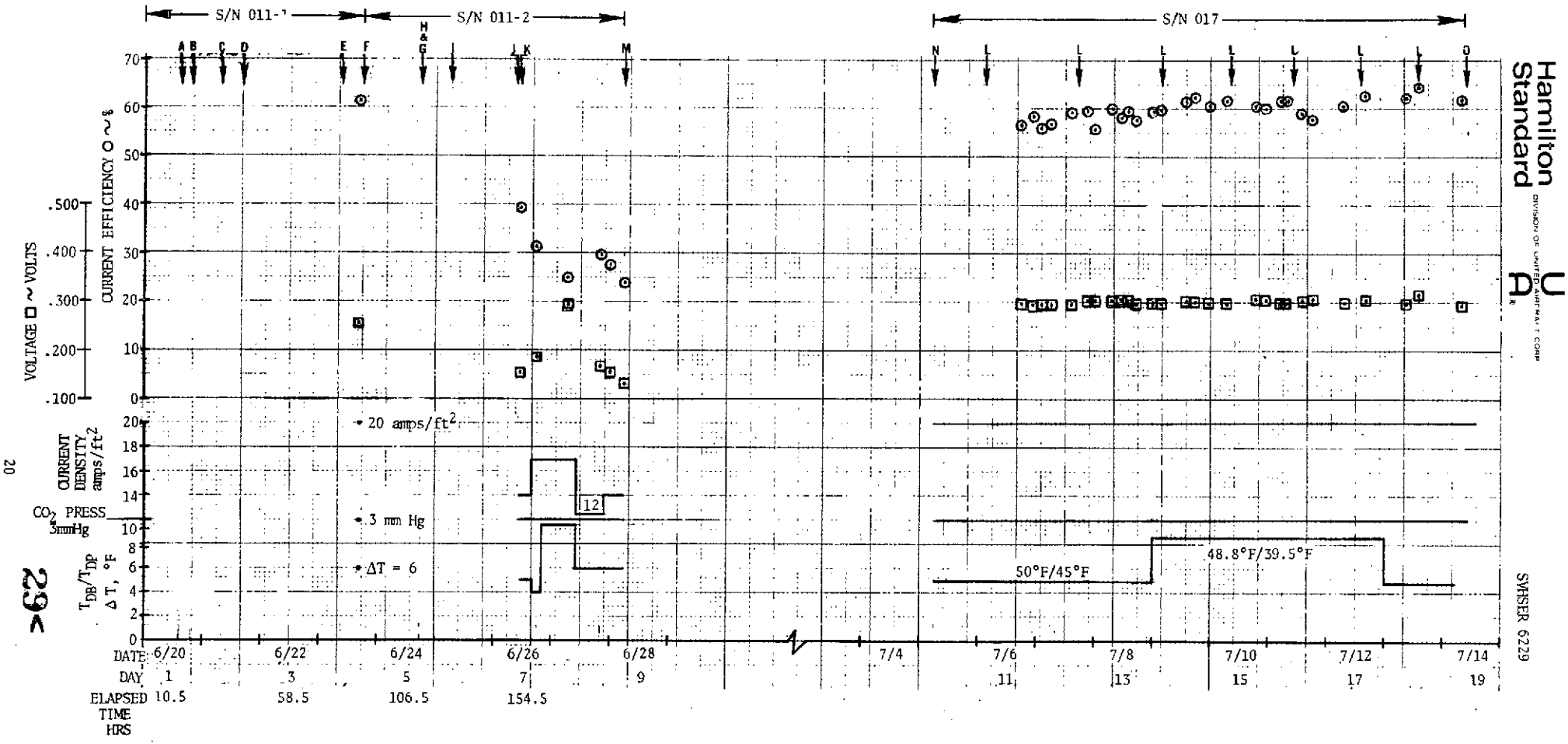
Huddleston, J. C.; and Aylward, J. R.: Development of an Integrated Water Vapor Electrolysis Oxygen Generator and Hydrogen Depolarized Carbon Dioxide Concentrator. NASA CR-115575, 1972.

[2] Tradename of Pallflex, Inc. for their quartz fiber fuel cell matrix material.



TEST DATES AND FACILITY LOCATIONS
TESTS 1 - 4

FIGURE 2



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A. Removed from Station B and started in Station D.
B. Automatic shutdown of H_2 sensor.
C. Restarted unit, reduced H_2 matrix pressure.
D. Shutdown 10 minutes N_2 purge open circuit overnight at 50° D.B., 40° D.P. - fan on.
E. Restarted unit.
F. Shutdown unit to rebuild.
G. Started rebuilt cell (S/N 011-2).
H. Noticed H_2 comb. gas level rising rapidly.
I. Cell open circuited, fan off.
J. Restarted cell.
K. Two N_2 purges - 5 minutes.
L. N_2 purge - 5 minutes.
M. Shutdown cell.
N. Started cell S/N 017.
O. Removed from Station D and placed in Station B with cell S/N 018.

TEST 1 RESULTS ON CELL PAIRS
S/N 011-1, S/N 011-2, AND S/N 017

FIGURE 3

Test Objective:	Determine if reservoir cell accommodates step ΔT change without use of Tissuquartz in matrix.
Cell Pair S/N: Hardware Configuration:	011-1 Platinum plated electrodes; annealed housings; reservoir (no Tissuquartz); 2 layers .023", 20 psid bubble-point asbestos; manual fill; 9-11 mg/cm^2 electrodes.
Cell Pair S/N: Hardware Configuration:	011-2 Sputtered electrodes; annealed housings; reservoir (no Tissuquartz); 3 layers 0.024, 40 psid SWEF asbestos; 65% Cs_2CO_3 electrolyte loading layers; manual fill; 14 mg/cm^2 electrodes.
Cell Pair S/N: Hardware Configuration:	017 Platinum plated electrodes; annealed housings; reservoir - with Tissuquartz strips; 3 layers 0.024", 40 psid SWEF asbestos; manual fill; 55% Cs_2CO_3 electrolyte; 9-11 mg/cm^2 electrodes.
Test Description:	Transfer cell S/N 011-1 to test station D; decrease ΔT by 4°F (step change); observe over 4-5 days for sign of matrix flooding; increase ΔT by 4°F (step change) and determine if dryout occurs.
Remarks:	Provides definition of reservoir cell configuration to be evaluated in Test 4.
Schedule:	See figure 3.

TABLE I

CELL CONFIGURATIONS FOR TEST 1

Following hydrogen cross-over in S/N 011-1 and S/N 011-2, it was decided with HS - NASA concurrence, to use Tissuquartz in the reservoir cell configuration for SSP and cell pair S/N 017 was subsequently built and evaluated for sensitivity to a ± 4°F delta temperature change. As indicated by figure 3, the Tissuquartz configuration responded successfully to this step input. Subsequently, cell pair S/N 018 was built (identical to S/N 017) and after conditioning, cell pairs S/N 017 and S/N 018 were used in Test 4 as reservoir cells.

The configuration of the Tissuquartz cell used is shown in Appendix D.

Test 2

Test 2 had two objectives. The first was to establish the adequacy of five cell housings which had been fully annealed to remedy deformation during machining.

Prior to annealing, the vendor had inadvertantly failed to clean the housings of machine"cutting" oil causing a surface oxide discoloration which, it was believed, might increase cell internal resistance. The original three cell housings purchased had not been subjected to the annealing process and as such, although not as flat as the annealed cells, had no suspicious surface oxidization and were regarded as acceptable cells. Prior to test 2 of this program, it had not been determined whether the five annealed housings were representative of good housings or whether performance of tests using them would be compromised.

The second objective was to establish the adequacy of sputtered electrodes. In an attempt to reduce the cost of cell pair deliverable hardware, several sets of electrodes had been procured having the platinum coating sputtered onto the base tantalum, instead of being electrolytically deposited. Insufficient experience had been derived to establish the acceptability of the sputtered configuration. A cost savings of $5,000 to $6,000 justified the alternate coating if it was satisfactory.

Table II describes the plan of test 2 and the cell configurations used.

Figure 4 shows the unsuccessful attempts to achieve acceptable performance on cell pair S/N Y-2 which employed sputtered electrodes and a heavier catalyst loading.[1] Based on the poor performance of cell pair S/N Y-2 together with cell pair S/N 011-2, which also employed sputtered electrodes, HS and NASA agreed that subsequent cells should be built using electroplated electrodes and that the standard 9-11 mg/cm^2 catalyst loading should be employed.

Figures 5 and 6 (cell pairs S/N 015, S/N 016, and S/N 016-1) show the result of tests following fabrication of cells employing electroplated electrodes and the standard 9-11 mg/cm^2 catalyst loading.

The acceptable performance realized on cell pairs S/N 015, S/N 016 and S/N 016-1 further showed that no significant difference resulted from the use of annealed versus non-annealed housings.

Cell pair S/N 016 (see figure 6) experienced a hydrogen cross-over problem following the installation of a charcoal particulate filter in the air stream inlet on July 6, 1972. The cross-over was subsequently attributed to absorbtion of moisture in the inlet air stream to the cell, resulting in a depression of the inlet dew point and a consequently high dry bulb/dew point temperature differential in the order of 14-15°F. The charcoal filter had been inserted in the test chamber of the cell inlet in an attempt to prevent deleterious effects due to leakage into the test chamber of contaminants contained in the laboratory air.

[1] 14 mg/cm^2 instead of 11 mg/cm^2 was employed with the objective of improving performance.

Test Objective:	1. Establish adequacy of annealed housings. 2. Establish adequacy of sputtered electrodes.
Cell Pair S/N: Hardware Configuration:	Y-2 Sputtered electrodes; clean housings; non-reservoir; SWEF asbestos; 3 layers 0.20"; 65% Cs_2CO_3 loading; manual fill; condition 49°DB/45°DP; 9-11 mg/cm^2 electrodes.
Cell Pair S/N: Hardware Configuration:	016 & 016-1 Sputtered electrodes; annealed housings; non-reservoir; SWEF asbestos; 3 layers 0.020"; 65% Cs_2CO_3 loading; manual fill; conditioned 49°DB/45°DP; 9-11 mg/cm^2 electrodes.
Cell Pair S/N: Hardware Configuration:	015 Platinum plated electrodes; non-annealed (clean) housings; non-reservoir cell; 3 layers 0.020" SWEF asbestos; 65% Cs_2CO_3 manual fill; conditioned 49°-45°F; 9-11 mg/cm^2 electrodes.
Test Duration:	7 - 9 Day Test 1st Day - Run in cell pairs. Install each cell pair separately in chamber "A" and "B" respectively; purge 5 minutes at end of 24 hours operation with N_2; data logger set at 15 minute read-out; chamber conditions as shown in figures 4 & 6. 2nd-end 7th day - Purge every 24 hours for 5 minutes; same as above.
Remarks:	Case 1 - If all cells meet success criteria annealed housings are okay for use in test program and sputtered electrodes are acceptable and will be used subsequently. Case 2 - Cell S/N 016 or S/N 016-1 fails...don't use annealed housings. Case 3 - Cells S/N Y-2 or S/N 016 (or S/N 016-1) fail.. don't use sputtered electrodes. If performance of all cells similar, annealed housings okay to use.

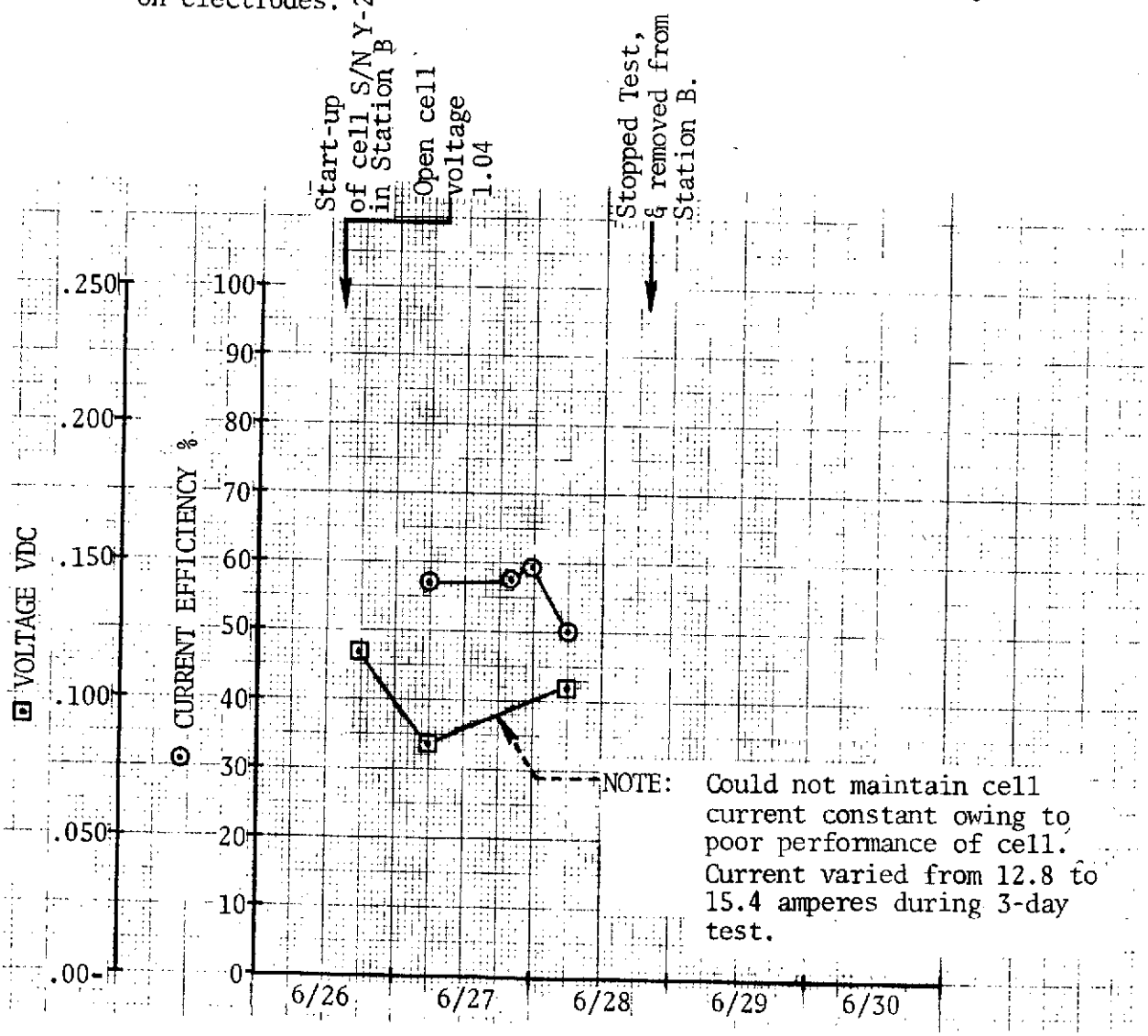
TABLE II

CELL CONFIGURATIONS FOR TEST 2

Cell pair S/N 016 was rewetted successfully and the hydrogen cross-over was stopped. To eliminate the risk of having a non-representative cell in the parametric/endurance test program, cell pair S/N 016-1 was assembled for use in test 4.

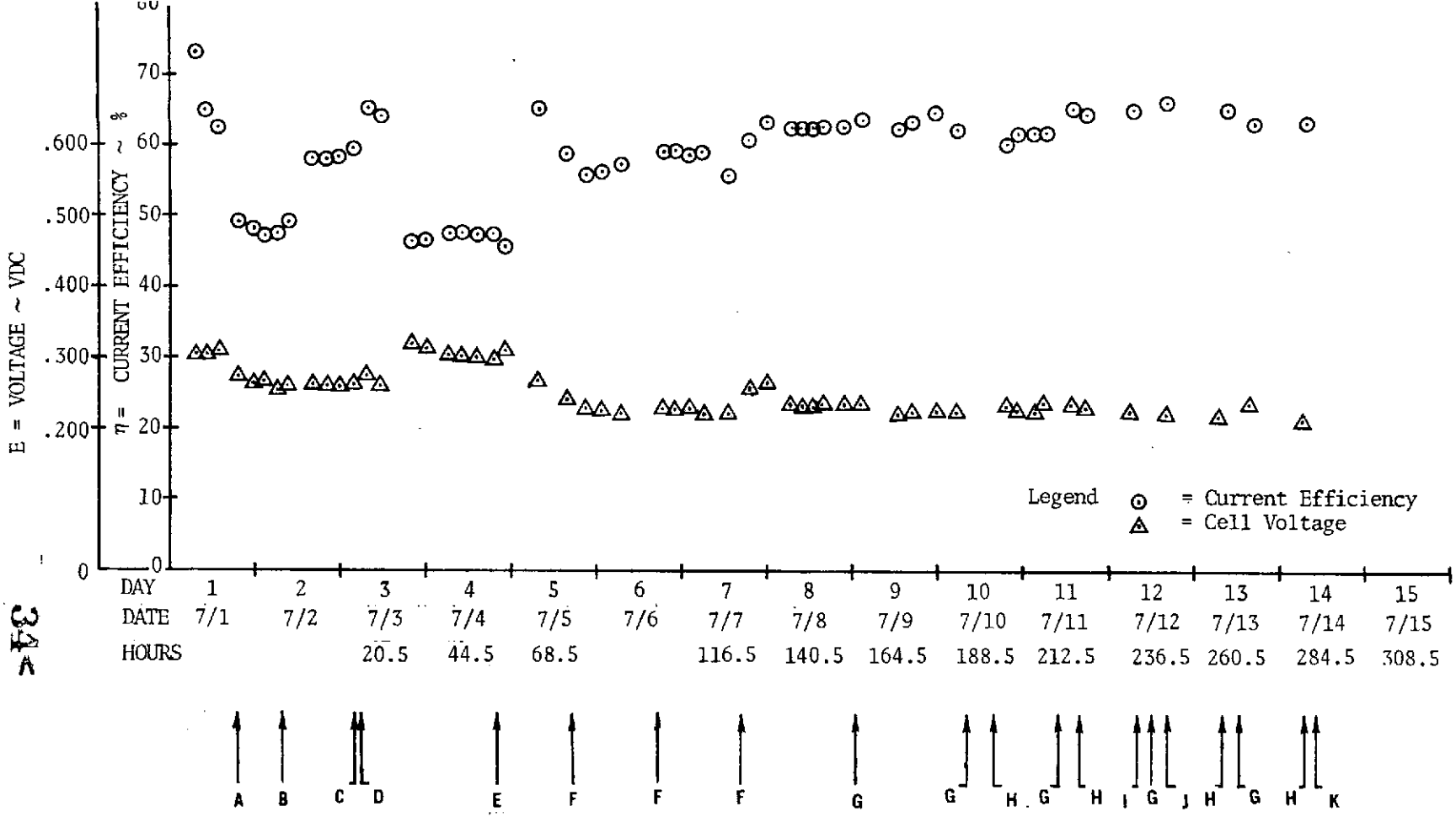
Appendix D defines the detailed design configuration of all the test cell pairs.

- Assembled June 26, 1972
- Installed Station B
- Results of Test
  - Efficiency 55% (& decreasing)
  - Voltage/Power Poor
    .119 - 0.086 volts
    1.5 watts
- Conclusions (June 28-30)
  Poor performance
  Poor voltage/power
- Recommendations
  Based upon poor results of this test of S/N Y-2 together with cell S/N 011-2, HS recommended & NASA concurred to use electroplated electrodes from June 30, 1972 forward, and to discontinue use of heavier (14 mg/cm^2) catalyst loading on electrodes.



TEST 2 (S/N Y-2)

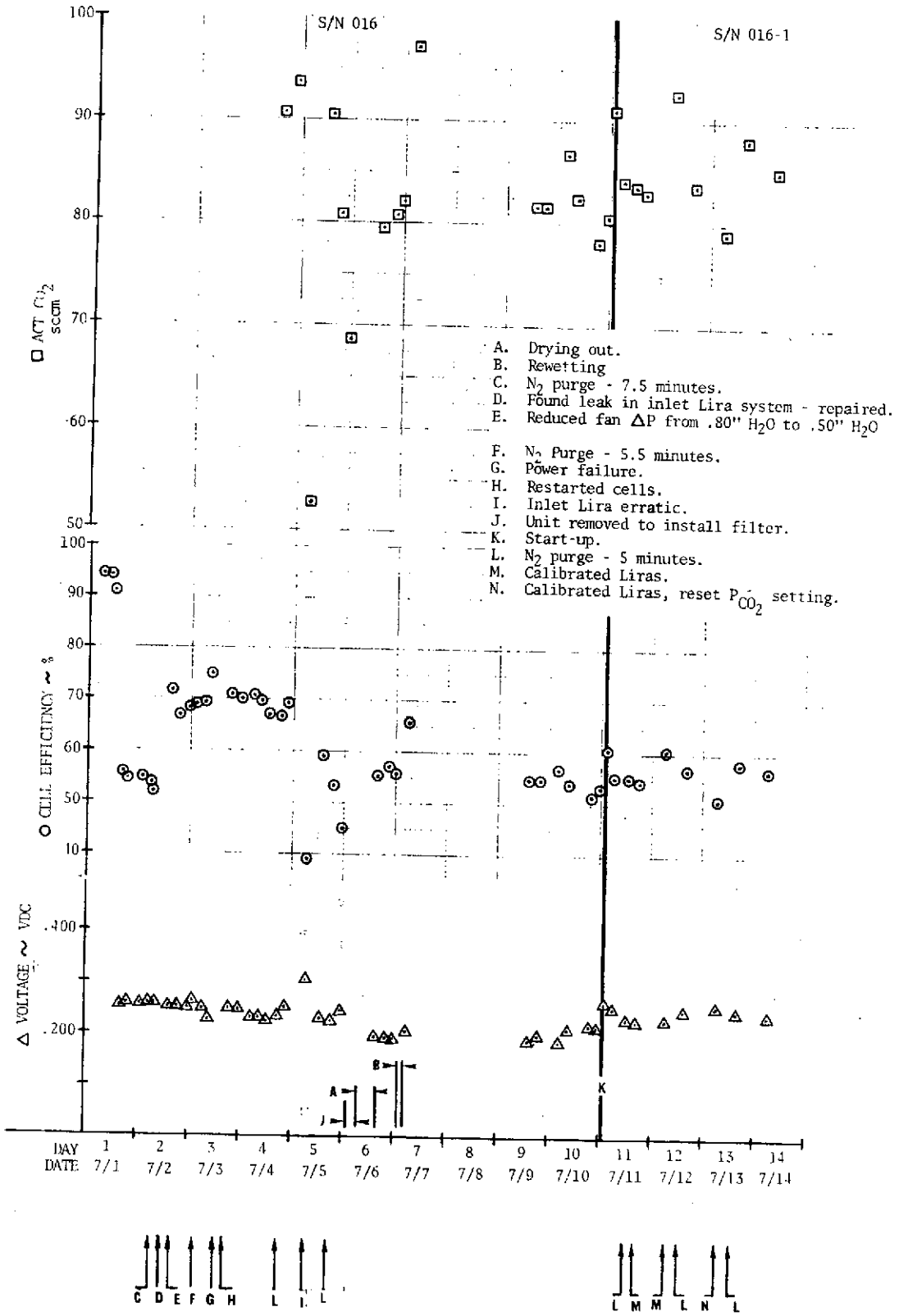
FIGURE 4 33<



A. Check Lira calibration.
B. N_2 purge - 7.5 minutes.
C. Reduce spacer thickness to yield matrix thickness of 0.0235".
D. N_2 purge - 5.5 minutes.
E. N_2 purge - 7 minutes - check Lira calibration.
F. N_2 purge - 5 minutes - check Lira calibration
G. N_2 purge - 5 minutes.
H. Check Lira calibration.
I. Lira cal. could not set cal. pressure.
J. Changed Lira (1% CO_2) sampling pump.
K. Started 2 cell operation S/N 015 & S/N 016.

TEST 2 (S/N 015)

FIGURE 5



TEST #2 (S/N 016/016-1)

FIGURE 6

35<

Test 3

Test 3 was performed to verify that small variations in matrix compression from the 0.024 inch thick nominal would not significantly affect cell performance. It was known that minor variations in both distance and matrix density in the electrode gap could occur between production cell lots. A test was designed in which the thickness of the spaces employed around the periphery of the cell, which establishes electrode separation distance, would be decreased every several days and the effects upon cell operation noted. If only minor performance variations resulted, the test would demonstrate the relative insensitivity of matrix compression over the range evaluated.

Table III describes the plan of test 3 and cell configurations used.

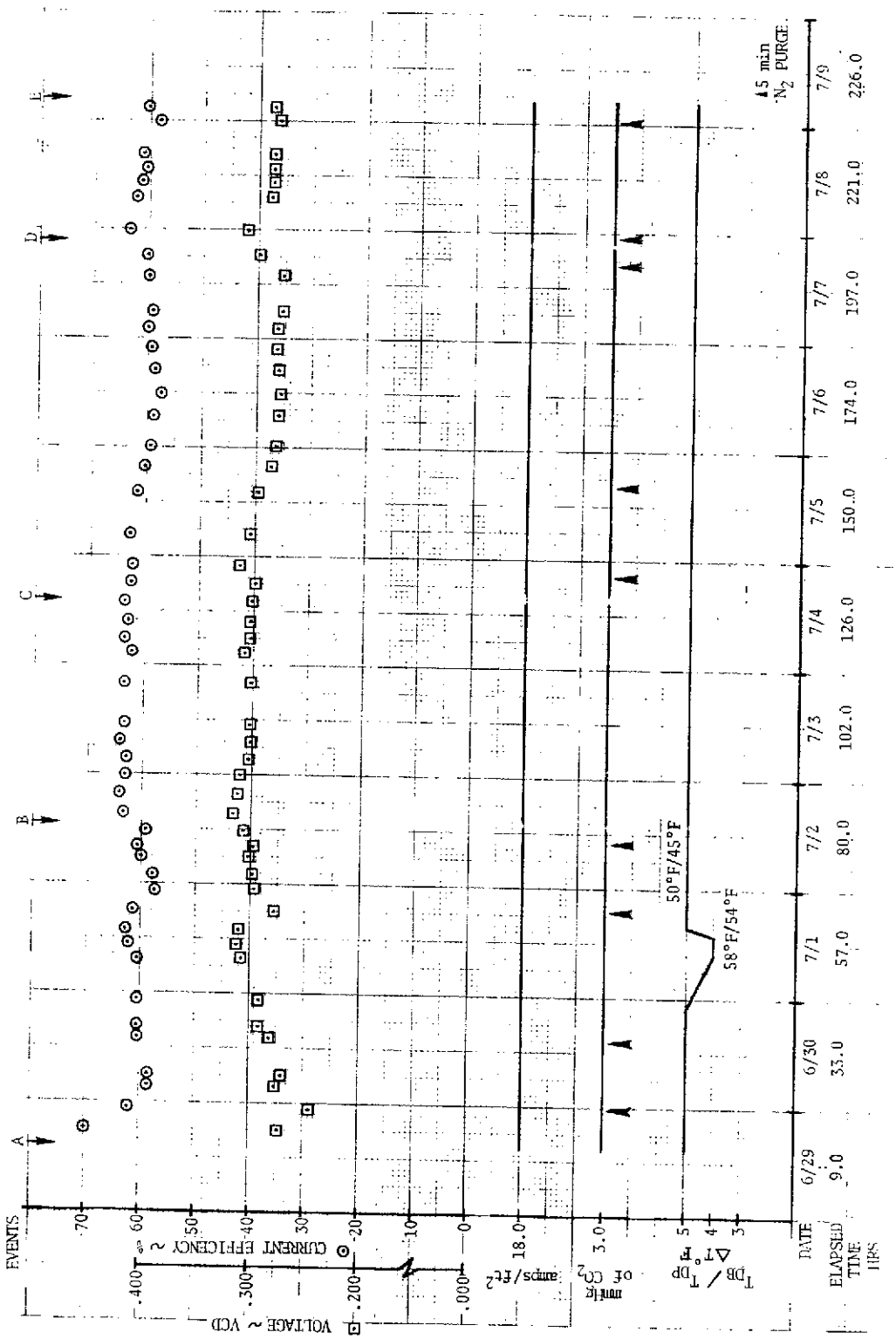
Test Objective:	Verify adequacy of matrix compression range.
Cell Pair S/N:	011-3
Hardware Configuration:	Electroplated electrodes; Pratt & Whitney Aircraft asbestos, 3 layers 0.020; 65% Cs_2CO_3 loading; manual fill; condition 45/49° DP/DB respectively; 9-11 mg/cm^2 electrodes. 0.030"/ 0.025"/ .0225" spacers in tests 3A, 3B, and 3C respectively.
Test Duration:	9 day test.
Test Description:	Figure 7 shows that cell pair 011-3 was assembled and tested for three days with 0.030" spacers, next tested with 0.025" spacers for five days, and finally tested for two days with 0.0225" spacers.

TABLE III

CELL CONFIGURATIONS FOR TEST 3

Figure 7 shows that cell performance is essentially independant of matrix thickness over the range of 0.030" to 0.022"[1]. Since the matrix thickness of cells can be accurately controlled ($\pm \sim 0.002$")[1], this test eliminates "risk" associated with small variations in matrix thickness, which could arise during assembly operations, from the 0.024" nominal design thickness.

[1] Matrix thickness as defined by the thickness at the perimeter of the cell near the spacers. As discussed elsewhere in this report, matrix thickness increases in the center of the cell owing to housing deflection.



A. Installed in Station B with .030" spacer. Start-up at 1500 hours.
B. Shutdown; replace spacer with .025". Start-up at 1350 hours.
C. Rig shutdown due to plant power failure. Start-up at 1645 hours.
D. Shutdown; replaced spacer with .0225". Start-up 2249 hours.
E. Shutdown; removed from Station B.

TEST 3 PERFORMANCE CELL S/N 011-3

FIGURE 7

Test 4

In accordance with the test plan, test 4 consisted of parametric and extended duration tests of two non-reservoir and two reservoir cell pairs. Although the reservoir configuration had been preselected for the SSP application, NASA and HS had agreed that this program should subject both configurations to evaluation, to provide a side-by-side comparison. As is discussed on page 17 of this report, the two configurations are nearly identical employing the same housings and electrodes. The major difference was in the attachment of a small electrolyte accumulator to the housings in the reservoir configuration. Other less major differences existed between the two, such as the inclusion of Tissuquartz strips in the reservoir cell matrix, and a different cell spacer thickness (0.030" versus 0.024") in the reservoir cells, to accommodate the addition of the Tissuquartz.

The test plan contained in Appendix C shows that the cell pairs were to be subjected to two parametric tests: the first to be done early in test 4, and the second to be done at the conclusion of this program after a four to five week endurance test. By comparing the cell pair performances of the two parametric tests, any degradation of the cell pair with time was to be noted and a "projected" performance after six months established. The six month performance projections were to be used to determine the number of cell pairs required to satisfy the SSP CO_2 collection requirement.

Test 4 was extended past the originally scheduled completion data (August 31, 1972), first by the NASA until September 22, 1972, and subsequently by Hamilton Standard funding. As of the end of January 1973, cell pairs S/N 017 and S/N 018 had been under continuous operation since the 5th and 10th of July 1972, respectively, for six and one-half months, demonstrating the six month SSP life requirement.

The remaining portions of this report relate to test 4, in which the conduct of the test, data gathering and evaluation of data are grouped into the following subsections: test of non-reservoir cell pairs; test of reservoir cell pairs; evaluation of CO_2 removal efficiency and the number of cell pairs required for SSP; nitrogen purging evaluation; degradation of cell voltage (power); gas analyses; and finally an outline of Hamilton Standard sponsored IR&D activities associated with this program. The IR&D activity, although not exclusively relating to test 4, is of interest since a major portion of the investigation was done upon two of the test 4 cell pairs (S/N 016-1 and S/N 017).

Test of Non-Reservoir Cell Pairs S/N 015 and S/N 016-1

General.- Figures 8 through 10 plot current efficiency and voltage for non-reservoir cell pairs S/N 015 and S/N 016-1 versus time from the start of testing through September 7, 1972. Cell pairs S/N 015 and S/N 016-1 had been assembled and subjected to test on July 1, 1972 and July 11, 1972, respectively. Parametric testing was initiated on July 18, 1972 with the two cell pairs mounted within the same test chamber in electrical series, parallel air flow, and in hydrogen-series flow. Hydrogen supplied from the test facility flowed through cell pair S/N 015 first, and then through S/N 016-1. 38<

A. Efficiencies approximately 10% low due to instrumentation error. (Please see page 54 for details).
B. Voltage reading low by .012 mv - see note above.
C. Lira cal.
D. N_2 purge - 5 minutes.
E. P_{CO_2} to 1.5 mm Hg
F. P_{CO_2} to 2.0 mm Hg
G. P_{CO_2} to 2.5 mm Hg
H. P_{CO_2} to 3.0 mm Hg
I. Shutdown units, removed cell S/N 015, restarted S/N 016 at 2030, 51/45°F, 24 asf, 3.0 mm Hg-CO_2
J. Temp. change to 47/41°F
K. Temp. change to 55/49°F

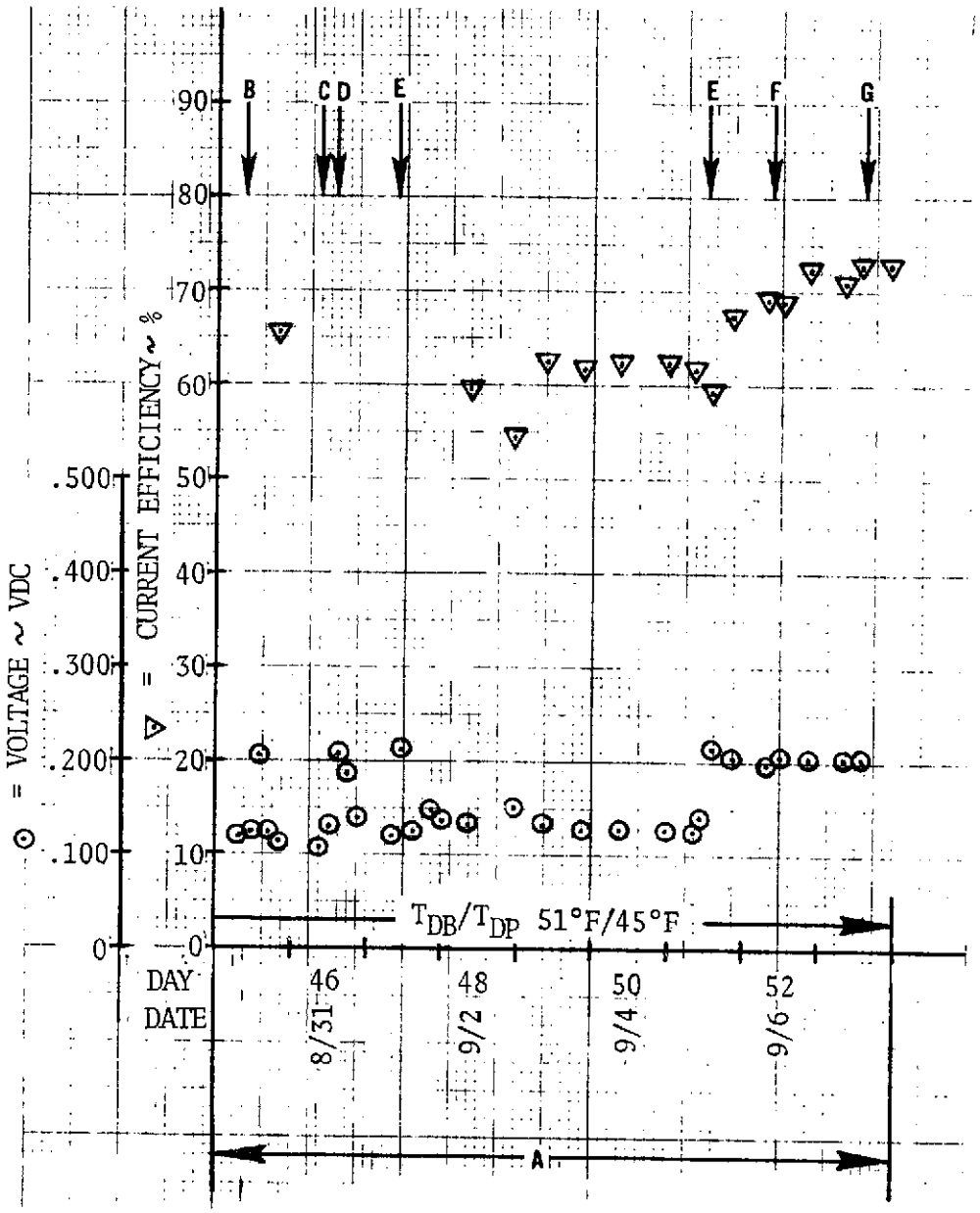
TEST 4 PERFORMANCE RESULTS THROUGH JULY 25, 1972 (NON-RESERVOIR CELLS. S/N 015 & S/N 016-1)

FIGURE 8

A. Efficiencies approx. 1.0% low due to current monitor instrumentation - see note on figure 8.
B. Voltage reading low by .012 mv - see note on figure 8.
C. Lira calibration & N_2 purge (5 min.) each morning between 9:00 to 10:00.
D. Cell open-circuited for 1/2 hour.

STATION A-CELL PAIR S/N 016-1 ENDURANCE TEST
(Condition P_{CO_2} = 2.5 mm Hg; asf = 18)

FIGURE 9



A. Lira cal. and N_2 purge (5 min.) each morning between 9:00 and 10:00.
B. Cell open circuited for 5 min.
C. Cell powered for 10 min.
D. Drive cathode - 10 min.; Drive anode - 10 min.; Open circuit N_2; Open circuit H_2.
E. Heat purge 60 min.
F. N_2 purge 21 min, cleaned cell anode and cathode connections; sprayed with battery terminal protector.
G. Removed cell from Station A.

STATION A - CELL PAIR S/N 016-1 ENDURANCE TEST
(Condition P_{CO_2} = 2.5 mm Hg; asf = 18)

FIGURE 10

As with all cell pair tests in this and other Hamilton Standard HDC tests, the cell pairs were contained in a plastic test fixture equipped with a variable speed fan at the outlet-end, which enabled presetting air flow through each cell pair. The test fixture was clamped to the cell pair in such a manner as to give assurance that air flow measured represented actual air passage through and not around the cell pair. The fixture, by nature of being clamped to the cell pair, caused a "quiet" zone surrounding the cell faces. This simulates the actual multi-cell installation wherein a teflon baffle located between cell pairs acts to prevent air flow. An analysis made showed that the difference between cell housing temperatures for the actual SSP multi-cell installation and individual cell pairs tested within the clamp-on plastic test fixture is of the order of 0.5°F, and as such is insignificant.

Appendix D defines the configurations for cell pairs S/N 015 & S/N 016-1. Reference is made to the section of the report discussing the reservoir cell pair performance which cites a voltage/current measurement error which occurred during the period July 25, 1972 to August 2, 1972. Figures 8 and 9 have been corrected as a result of this error.

H_2 Cross-Over Cell Pair S/N 015 - One of the two non-reservoir cell pairs (S/N 015) was removed from test on July 21, 1972 following a hydrogen cross-over problem. The H_2 cross-over occurred one hour after the imposition of a 24 amp/ft^2 current density condition. Cell pair S/N 016-1 together with cell pairs S/N 017 and S/N 018 were continued under test and successfully withstood the remainder of the test program.

A failure investigation of cell pair S/N 015 was made and is discussed below.

Background of Failure: At 2300 hours on July 20, 1972, the current density of all cell pairs was increased from 12 asf to 24 asf. At approximately 0100 on July 21, 1972, two hours after the current increase, the combustible gas monitor in Station A showed that one or both of the non-reservoir cell pairs were leaking hydrogen. Station A was shutdown automatically, cell pairs S/N 015 and S/N 016-1 open-circuited, and hydrogen back pressure reduced to ambient.

Failure Investigation: The combustible gas detector probe was employed with the cells still in place to locate the general location of the leak. It was determined that only cell pair S/N 015 leaked and that the leakage path was across the matrix (no "seal" leakage noted) in the vicinity of the #1 air channel. (Air channel #1 is nearest the electrical tabs adjacent to the seal area.)

Cell pair S/N 015 was removed from Test Station A and was protectively enclosed in polyethylene until July 31, 1972 when a check was made to establish the magnitude of the leak. At that time is was determined that the hydrogen leakage rate was 300 SCCM when a 5 psi pressure differential was imposed across the matrix.

42<

Cell S/N 015 was disassembled using a procedure which provided for examination of each component in place before removing from the assembly, and separately encasing each component in polyethylene to allow for subsequent detailed examination.

The hydrogen leakage path was clearly evident as a result of the visual examination. The leakage was found to be in and adjacent to the perimeter seal area of the cell at the #1 air channel. Photographs were taken of the subject area and show damaged asbestos matrix in this area. The damaged matrix allowed hydrogen to escape from the hydrogen passageway to the air-side of the cell through the damaged asbestos after passing through both anode and cathode electrodes. Figures 11 through 13 document the leakage area.

Discussion: The following explanations were considered as possible causes of the damaged asbestos:

1) imperfection in the asbestos material itself;

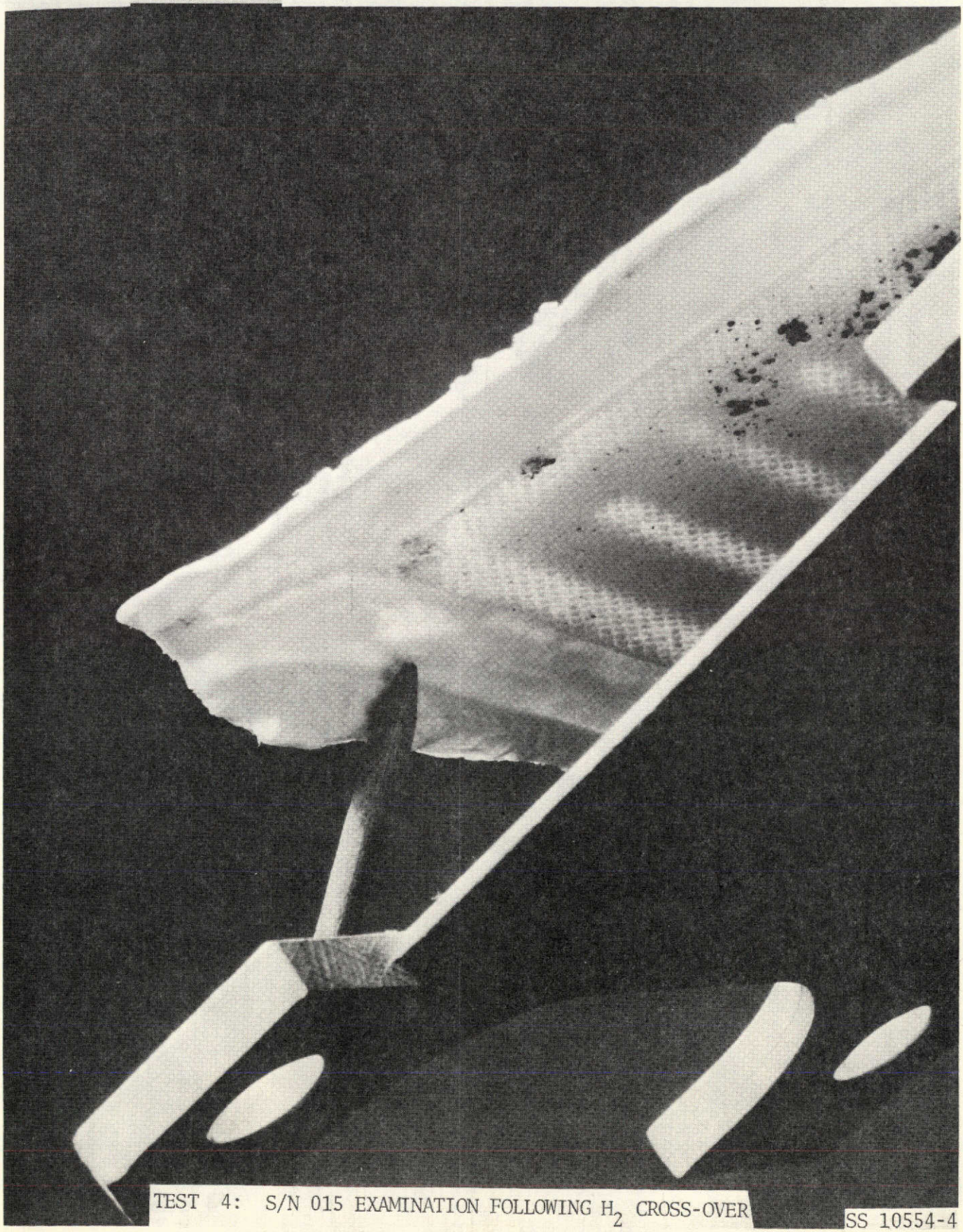
2) damage to the matrix during cell assembly; and

3) damage to the matrix on July 3, 1972 when 0.027" spacers were replaced with 0.0235" spacers.

The first and second explanations above are believed unlikely due to the fact that the imperfection as documented by the photographs would have been obvious prior and during assembly. The third explanation is most probable. In the process of reinstalling the thinner spacer, the cell pair housing bolts had to be loosened to allow the removal of the 0.027" spacer. During the loosening process, it is probable that a small and irregular shaped piece of asbestos in and around the seal area pulled away from the main asbestos. Since the housing bolts were not removed but only loosened in this process, the damage would not have been detected. It is likely that the relatively high compression in the seal area would have provided an effective hydrogen seal under nominal cell operating conditions (no leakage noted when cell operation was resumed) but that under the 24 asf operation conditions (with consequent higher cell operating temperatures and, therefore, dryer matrix configurations), the subject defective area would allow hydrogen leakage.

Assuming the validity of the foregoing explanation, it is concluded that the H_2 cross-over failure of cell pair S/N 015 was a mechanical failure of the matrix most probably resulting from changing spacers on a cell pair previously assembled in the CR&D test program. As such, the failure would not have occurred in a subsystem deliverable cell pair.

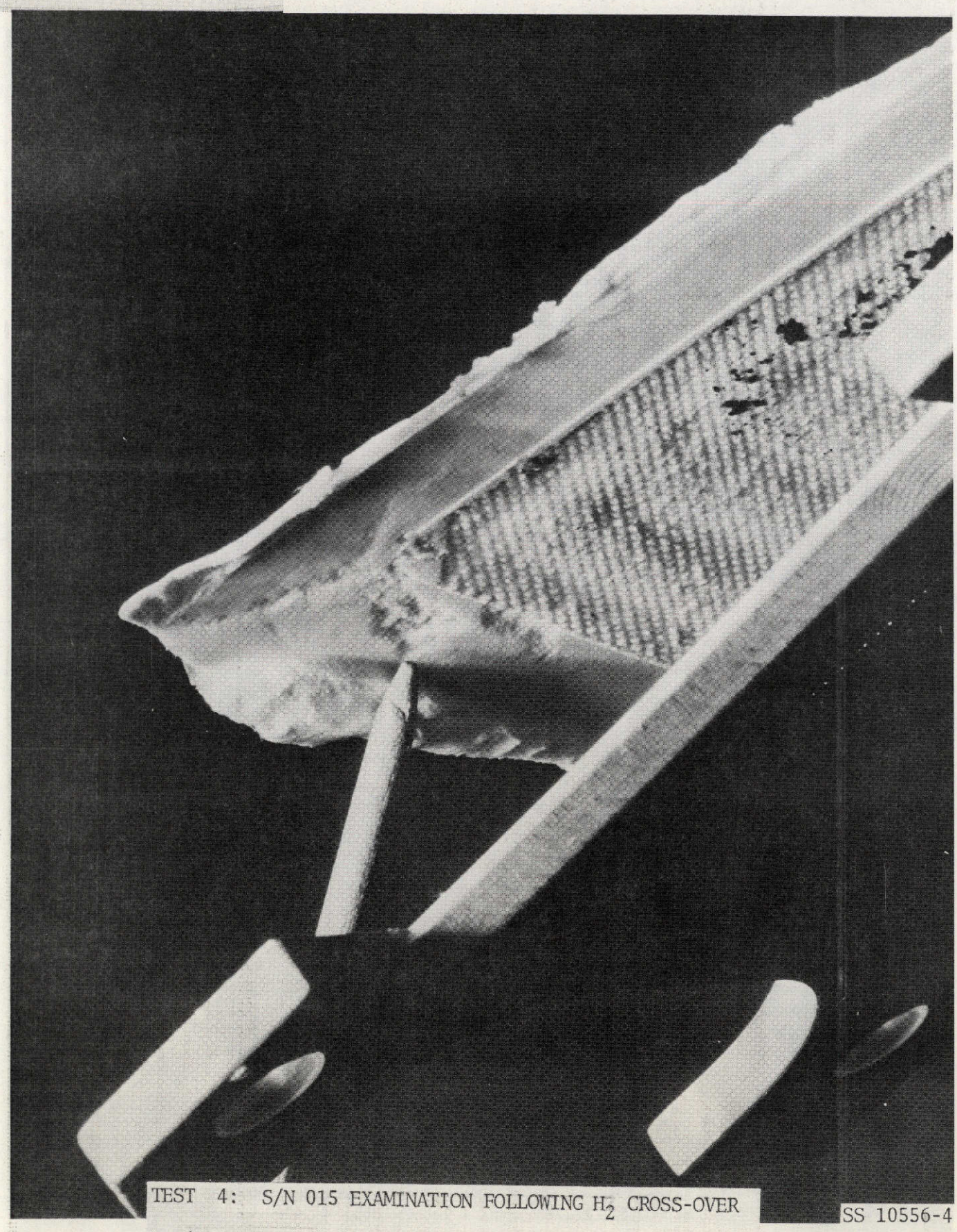
Performance Results.- From the start of testing it was apparent that the non-reservoir cell pairs were operating at approximately the same efficiency levels but at a slightly lower power (voltage) than the reservoir cells.



TEST 4: S/N 015 EXAMINATION FOLLOWING H_2 CROSS-OVER SS 10554-4

(ILLUMINATED BEHIND DAMAGED MATRIX AREA)

FIGURE 11 44<

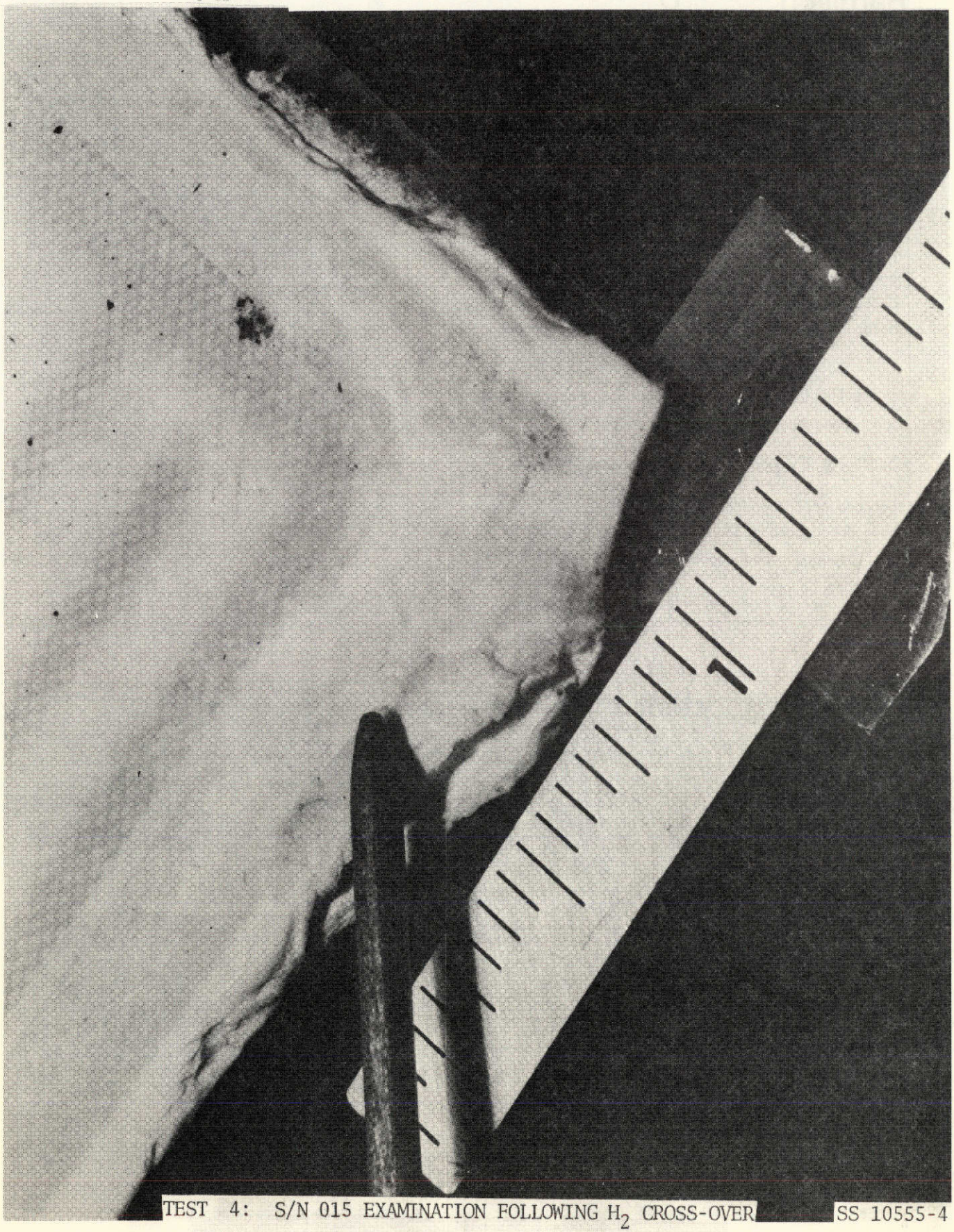


TEST 4: S/N 015 EXAMINATION FOLLOWING H_2 CROSS-OVER

SS 10556-4

(ILLUMINATED IN FRONT OF DAMAGED MATRIX AREA)

FIGURE 12



TEST 4: S/N 015 EXAMINATION FOLLOWING H_2 CROSS-OVER SS 10555-4

(PHOTOGRAPHIC ENLARGEMENT OF DAMAGED MATRIX AREA)

FIGURE 13

Typical values are given in Table IV. It will be observed that the reservoir cells. with their inherent ability to maintain the matrix in a 'wet' condition, have a superiority of 50-100 mv.

CONDITION	DATE	PERFORMANCE	
		NON-RESERVOIR CELL PAIRS S/N 015/016-1	RESERVOIR CELL PAIRS S/N 017/018
3 mm Hg CO_2/20 asf	7/18/72	E = 225 mv η = 62-1/2%	E = 300 mv η = 63%
3 mm Hg CO_2/12 asf	7/19/72	E = 330 mv η = 85%	E = 385 mv η = 81-1/2%
3 mm Hg CO_2/24 asf	7/22/72	E = 160 mv η = 51%	E = 260 mv η = 53-1/2%
2.5 mm Hg CO_2/18 asf	8/18/72* *Approx. 6 weeks after start of testing	E = 120 mv η = 60%	E = 200 mv η = 57%

TABLE IV

TEST 4 - RESERVOIR VERSUS NON-RESERVOIR PERFORMANCE COMPARISON

Because of the H_2 cross-over problem described in the preceding paragraph, which resulted in the removal of cell pair S/N 015 from test on July 21, 1972, it was decided by the NASA to "turn-over" cell pair S/N 016-1 to Hamilton Standard for "purging" and other studies on the Hamilton Standard IR&D program.[1] Such studies employing cell pair S/N 016-1 and starting on August 29, 1972 are described below.

IR&D Activities - Cell S/N 016-1: During the period of August 29, 1972 through September 7, 1972, cell pair S/N 016-1 was subjected to certain investigations and events described in Table V.

Figure 14 shows the variation in cell voltage preceding and following both the 30 minute and the five minute open-circuiting of cell pair S/N 016-1. As noted, although the 30 minute open-circuit condition caused an improved cell voltage for a few hours, no residual benefit resulted.

[1] Less interest existed in the non-reservoir cell from the onset of testing because the Hamilton Standard HDC Subsystem design employed the reservoir cell.

DATE	DESCRIPTION OF INVESTIGATION	REFERENCE
8/29/72	30 minute open-circuit operation	Data Logger microfilm 1400-1430 hours
8/30/72	5 minute open-circuit operation	Data Logger microfilm 1339 hours
8/31/72	Drive cathode 10 minutes Drive anode 10 minutes Open circuit N_2 purge Open circuit N_2 purge	N/A
9/01/72	Heat purge (continue cell operation except shutoff air flow through cell for 60 minutes.)[1]	S/N 016-1 data sheet. Data Logger 0905 hours.
9/05/72	Repeat heat purge above.	S/N 016-1 data sheet. Data Logger 1012 hours.
9/06/72	Cleaned terminals on 016-1. Twenty-one minute N_2 purge during operation.	Data Logger microfilm 1040 hours.
9/07/72	Removed 016 from test.	Data Logger microfilm 1315 hours.

TABLE V

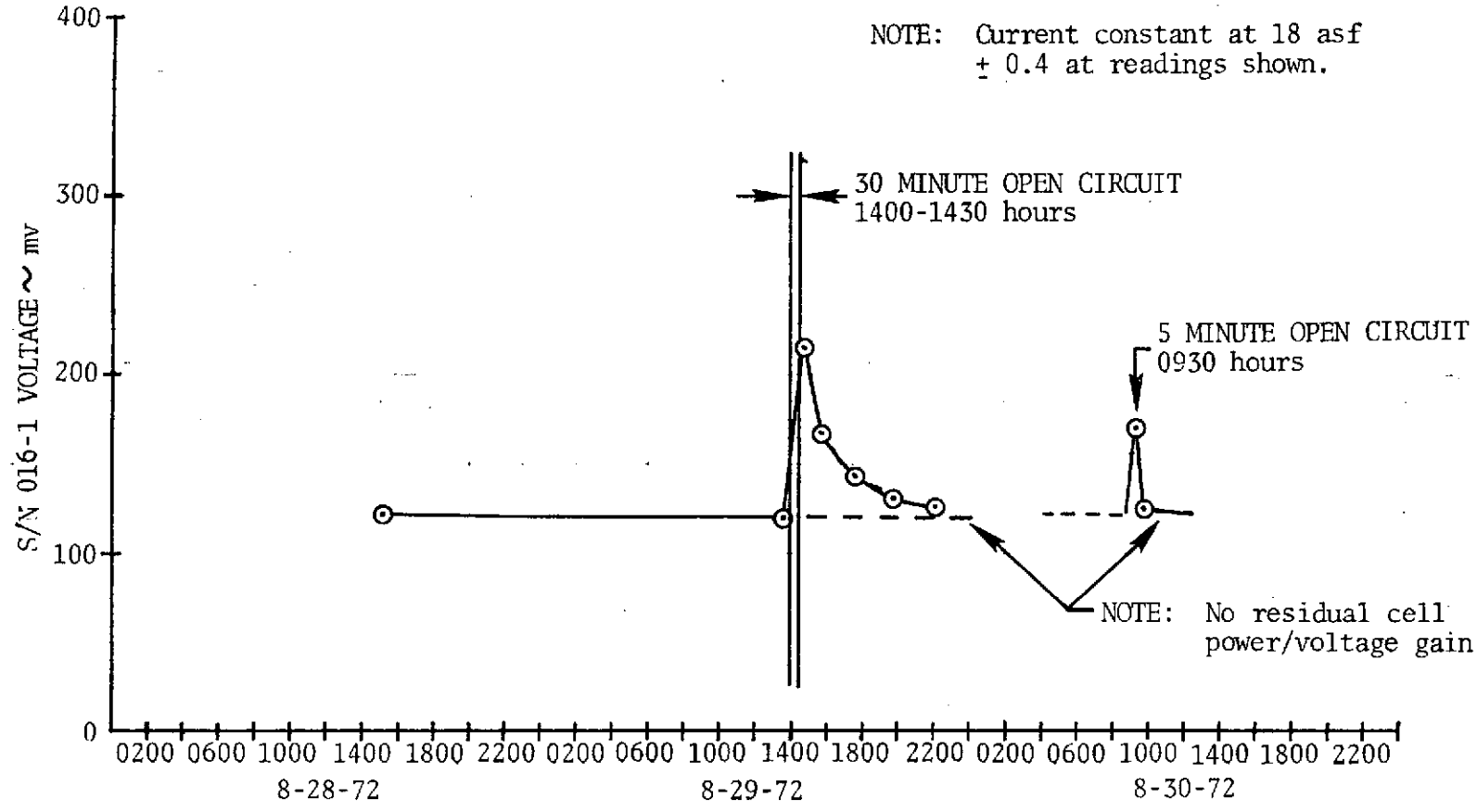
HAMILTON STANDARD IR&D TEST ACTIVITIES ON CELL S/N 016-1

Figure 15 shows the evaluation made to determine effects of "driving" both electrodes. As noted, no benefit to cell power resulted sixteen hours later. A temporary decrease in current efficiency is associated with electrode driving.

Figure 15 also shows the results of stopping air flow, for a one hour period, with continued operation of the cell.[2] A cell voltage benefit

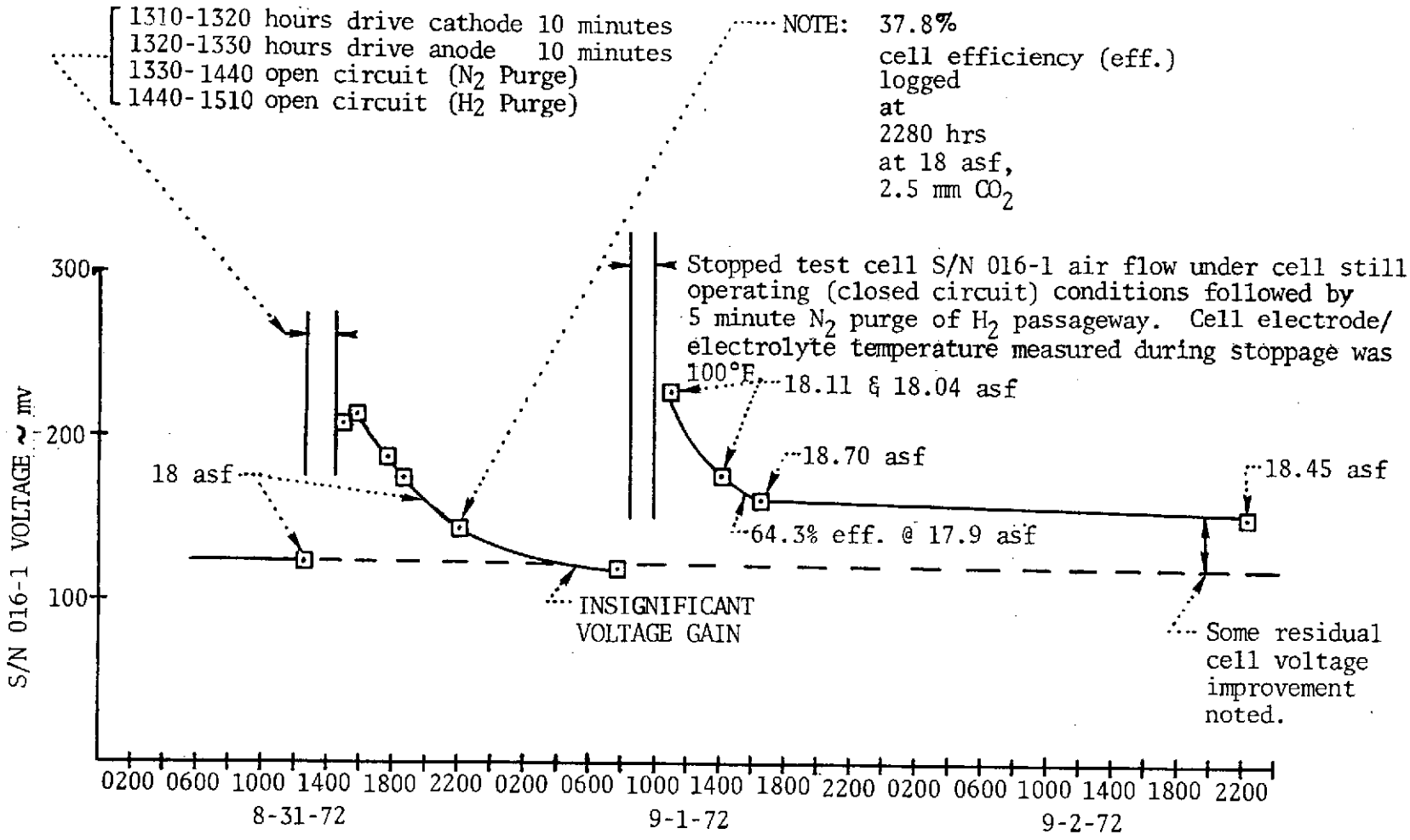
1 Purges, to be consistent with terminology used in telecons with the NASA, refer to various thermal, electrode "driving" and open-circuiting measures evaluated as to their effect upon restoring cell power.

2 The one hour cessation of air flow was selected in order to increase the electrode electrolyte temperature to 100°F. Calibrated thermocouples were used during the air stoppage to measure the cathode and air passage surface temperatures.



OPEN CIRCUIT OPERATIONS ON CELL PAIR S/N 016-1
30 MINUTE AND 5 MINUTE

FIGURE 14



RESULTS OF ELECTROCHEMICAL "DRIVING"
AND TEMPERATURE "PURGES" OF CELL S/N 016-1

FIGURE 15

(~50 mv improvement @ 18 asf) was achieved 36 hours later. It is noted that current efficiencies were not penalized by this activity.

Figure 16 shows the results of the second air stoppage "temperature purge" of cell pair S/N 016-1 on September 5, 1972. The test was performed in a similar manner to the test of September 1, 1972. Figure 16 has been adjusted to 18 asf current conditions to permit a direct comparison of results with the September 1, 1972 test. It was noted that no residual improvement in cell voltage was achieved 24 hours after test.

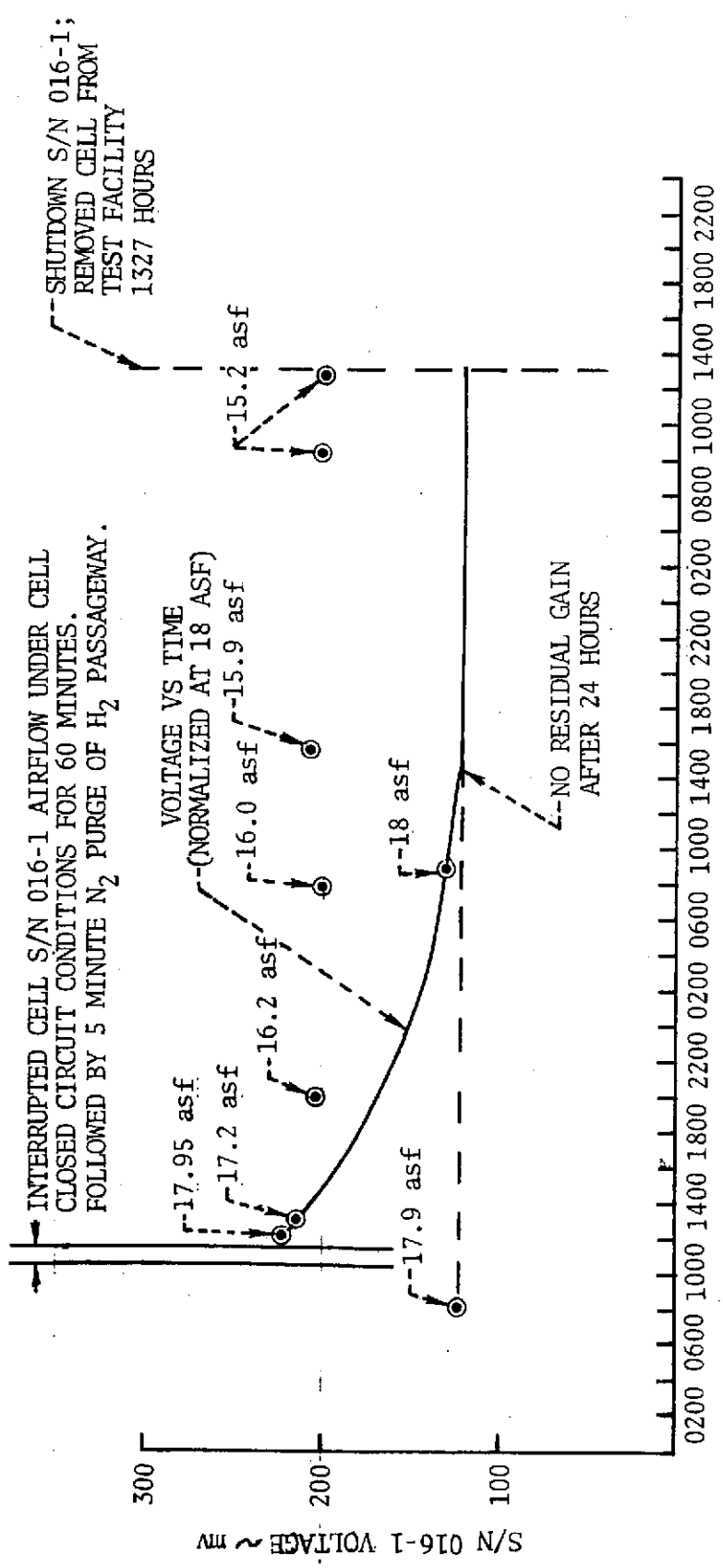
Cell pair S/N 016-1 was removed from test on September 7, 1972 to permit continuation of the IR&D effort on another cell.

Test of Reservoir Cell Pairs S/N 017 and S/N 018

General.- Figures 17 to 23 plot voltage and CO_2 removal efficiency (current efficiency) for reservoir cell pairs S/N 017 and S/N 018 from the start of the parametric and extended duration test on July 18, 1972. Cell pairs S/N 017 and S/N 018 had been assembled and subjected to test on July 5 and July 10, 1972, respectively. The configurations of cell pairs 017 and 018 were identical and are defined in Appendix D. Appendix C gives details pertaining to the objectives of the testing of these cell pairs and the test plan to be followed.

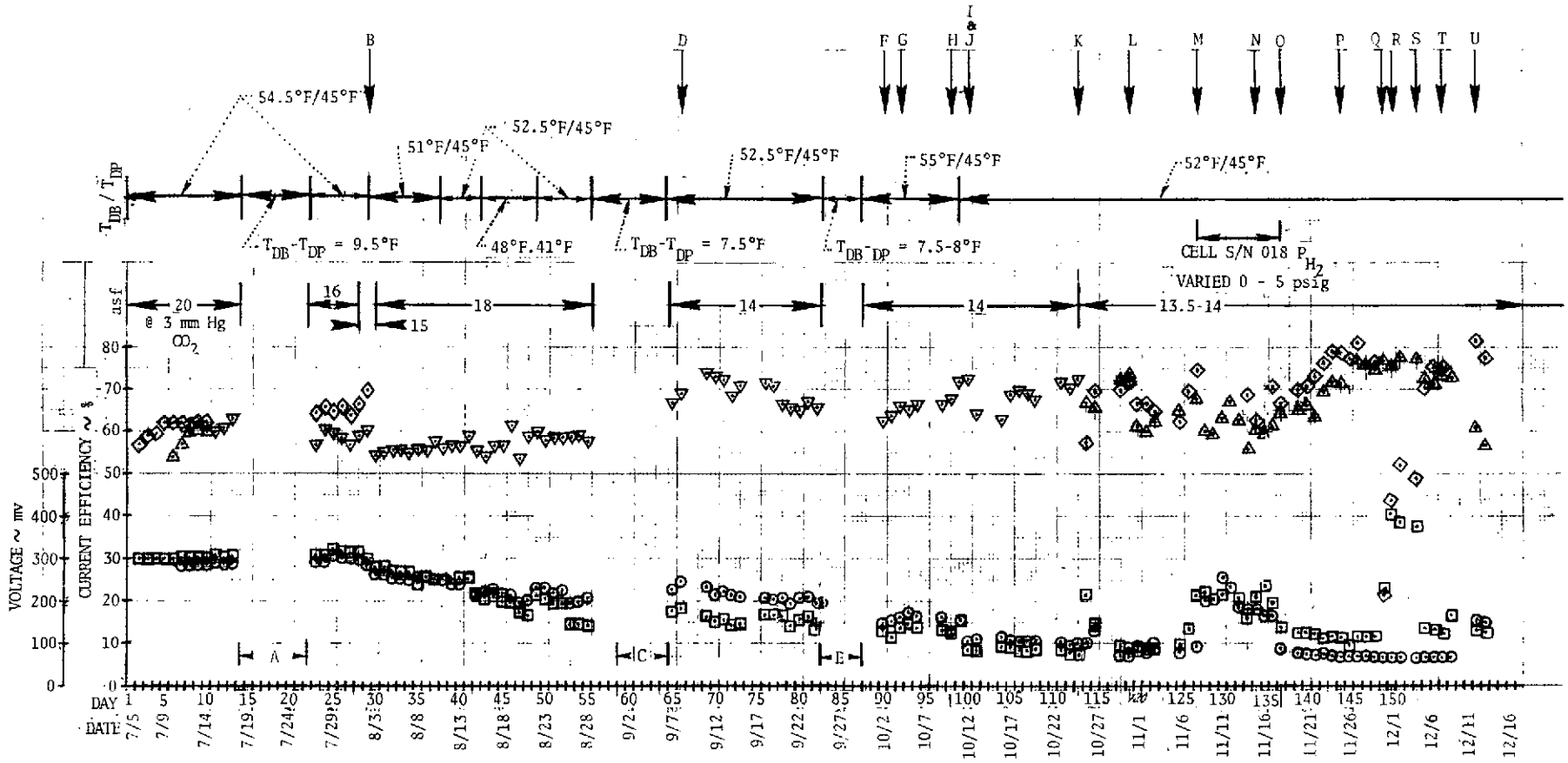
Page 66 discusses the cell voltage degradation rate and attempts to show that the voltage degradation, observed in figures 17 to 23, is not important as such, but only has significance if within the required life of the cell it decreases to the point where insufficient current is available to provide the necessary CO_2 removal rate. For the proposed Hamilton Standard 33-36 cell pair subsystem (nominally, 14-15 asf operation), this minimum voltage is 20 mv. After five months of operation, cell pairs S/N 017 & S/N 018 had 128 mv (at 13.6 asf) and 70 mv (at 13.3 asf), respectively. Figure 24 plots voltage degradation rate versus time during three months of operation, and shows that the degradation rate is decreasing with time. It is projected that both cell pairs have sufficient power (voltage) to operate satisfactorily for at least another several months.

As will be noted from figure 17, the NASA funded portion of this test program extended through September 21, 1972. In order to demonstrate that the cells did possess adequate (6 months) life, Hamilton Standard continued the test of cell pairs S/N 017 and S/N 018. It was agreed with the NASA that this continuation was meaningful. As discussed with the NASA, it would be the intent of the company sponsored IR&D program and using cell pairs S/N 017, S/N 018 and S/N 016-1 to conduct investigations directed at identifying the cause of and attempting to reduce cell voltage degradation rates. A secondardy objective was to evaluate specific electrode structure variations which



RESULTS OF SECOND TEMPERATURE PURGE OF CELL S/N 016-1

FIGURE 16



A. Parametric Test No. 1
B. Reversed unit fans to correct high ΔT, resulting from improper air airflow direction.
C. Parametric Test No. 2.
D. N_2 purge 21 min., cleaned corros. off anode and cathode, sprayed with battery terminal protector
E. Parametric Test No. 3.
F. Reduced temp. from 56.5°F/49°F to 52.5°F/45°F.
G. Raised dry bulb from 52.5°F to 54.5°F.
H. 11:30 shut off fans; 12:35 restarted fans.
I. Set asf at 14.6 for asf decay test; reduced dry bulb to 52°F.
J. Stopped N_2 purge 09:50 - 10/10.
K. Discontinued cell series operation. Transferred cell S/N 017 to Sta. A; continued cell S/N 018 in Sta. B.
L. Reduced cell outlet pressure from 5 psig to 0.7 psig in Cell S/N 017
M. Reduced cell outlet pressure from 5 psig to near ambient.
N. Inserted ref. electrode in reservoir of S/N 017. 10 min. N_2 purge.
O. Raised P_{H_2} to 5 psig.
P. Set asf to 13.8.
Q. Cell S/N 017 P_{CO_2} = 3 mm Hg, airflow 135.5 scfm, asf 10.
R. Reduced asf from 10 to 5.
S. Cell S/N 017 changed P_{CO_2} to 2.5 mm Hg, current to 13.7 amperes. Airflow reduced from ~13 to ~ 6.4 CFM, and H_2 flow increased from ~400 to 750 CCC.
T. N_2 purge cell S/N 017 - 7 min.
U. Cell S/N 018 Sta. A, cir. fan shut off during weekend due to powerstat short. ΔT (DB-DP) exceeded 10°F.

▽ CURRENT EFFICIENCY (S/N 017 & 018)
△ CURRENT EFFICIENCY (S/N 018)
◇ CURRENT EFFICIENCY (S/N 017)
□ VOLTAGE (S/N 017)
○ VOLTAGE (S/N 018)
◇ CORRECTED EFFICIENCY FOR INSTRUMENTATION ERROR (Ref. pp 54)

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TEST #4 (S/N 017/018)
JULY 5, 1972 THROUGH DECEMBER 12, 1972

FIGURE 17

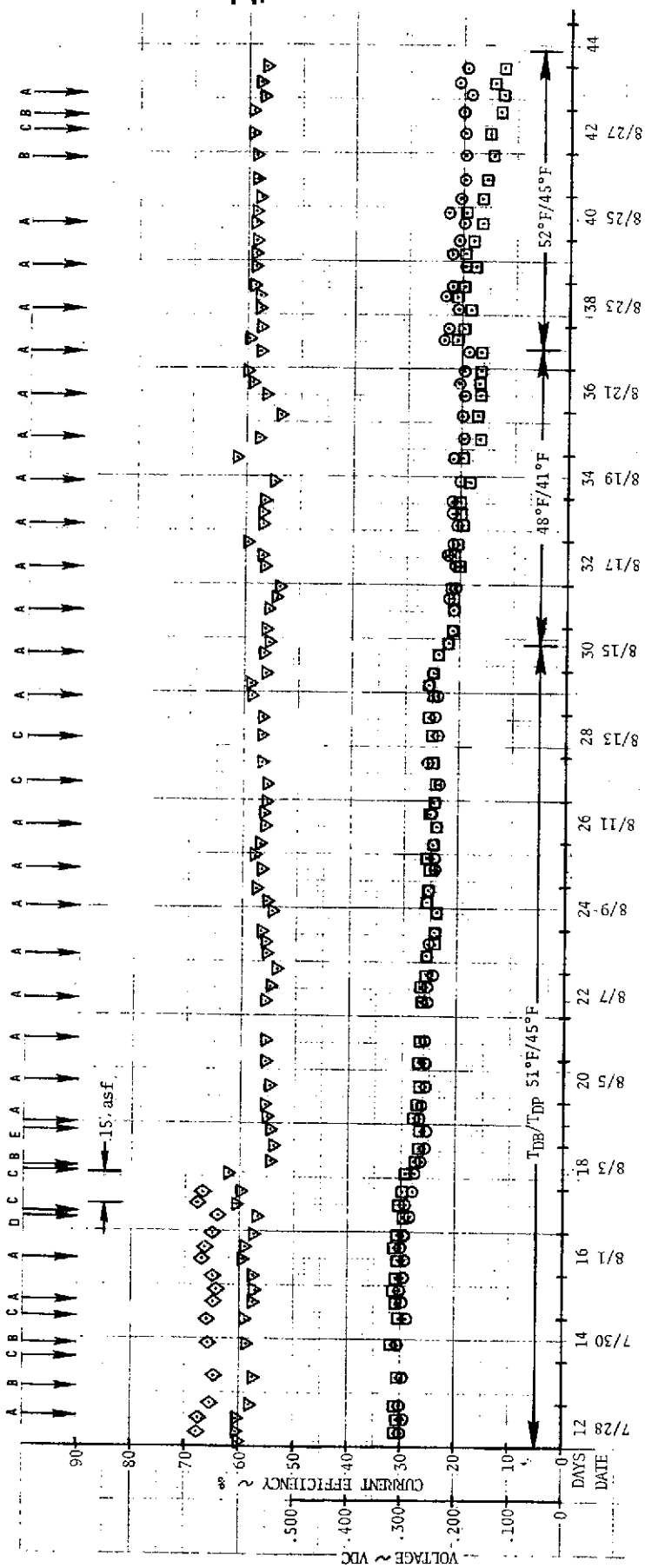
▽ Current efficiency
◇ Corrected current eff. for asf instrumentation error (ref. pg. 54)
□ Voltage Cell S/N 017
○ Voltage Cell S/N 018

A. Lira cal.
B. N_2 purge - 5 min.
C. P_{CO_2} to 1.5 mm Hg
D. P_{CO_2} to 2.0 mm Hg
E. P_{CO_2} to 2.5 mm Hg
F. P_{CO_2} to 3.0 mm Hg
G. Temp. changed to 47/41°F.
H. Temp. changed to 55/49°F.
I. Voltage reading high by .020 to .030 mv
J. Voltage reading low by .020 mv
K. End of parametric testing.
L. Changed to 18 asf P_{CO_2} = 2.5 mm Hg, 45°F D.P./51°F D.B.

TEST 4 (S/N 017/018), 1st PARAMETRIC TEST
JULY 7, THROUGH JULY 27, 1972

FIGURE 18

(1) Planned temperatures of 51°F-45°F; 47°-41°F; and 55°-49°F (Dry Bulb/Dew Point respectively) were through error not subjected on cells. Problem discussed on pg. 52. Temperature ranges given above represent temperatures actually imposed.



◇ Corrected current eff. for asf instrumentation error (ref. pg. 54)
▽ □ Efficiency
□ Voltage Cell S/N 017
○ Voltage Cell S/N 018

A. N_2 purge - 5 min., and Lira cal.
B. Lira cal.
C. N_2 purge.
D. Reversed unit fan for correct flow direction.
E. Evid. of some flooding on cell pair S/N 017.

TEST 4 (S/N 017/018), EXTENDED DURATION TEST
JULY 28, THROUGH AUGUST 28, 1972

FIGURE 19

A. N_2 purge - 5 min., and Lira cal.
B. N_2 purge - 5 min.
C. P_{CO_2} to 2 mm Hg
D. P_{CO_2} to 3 mm Hg
E. Lira cal.
F. N_2 purge - 5 min., P_{CO_2} to 2 mm Hg for holiday weekend.
G. Labor Day holiday weekend.
H. End of parametric testing - set new conditions - asf = 14, P_{CO_2} = 2.5 mm Hg, and temp. = 52.5°F/45°F.
I. Post Lira cal.

▽ Efficiency
□ Voltage Cell S/N 017
○ Voltage Cell S/N 018

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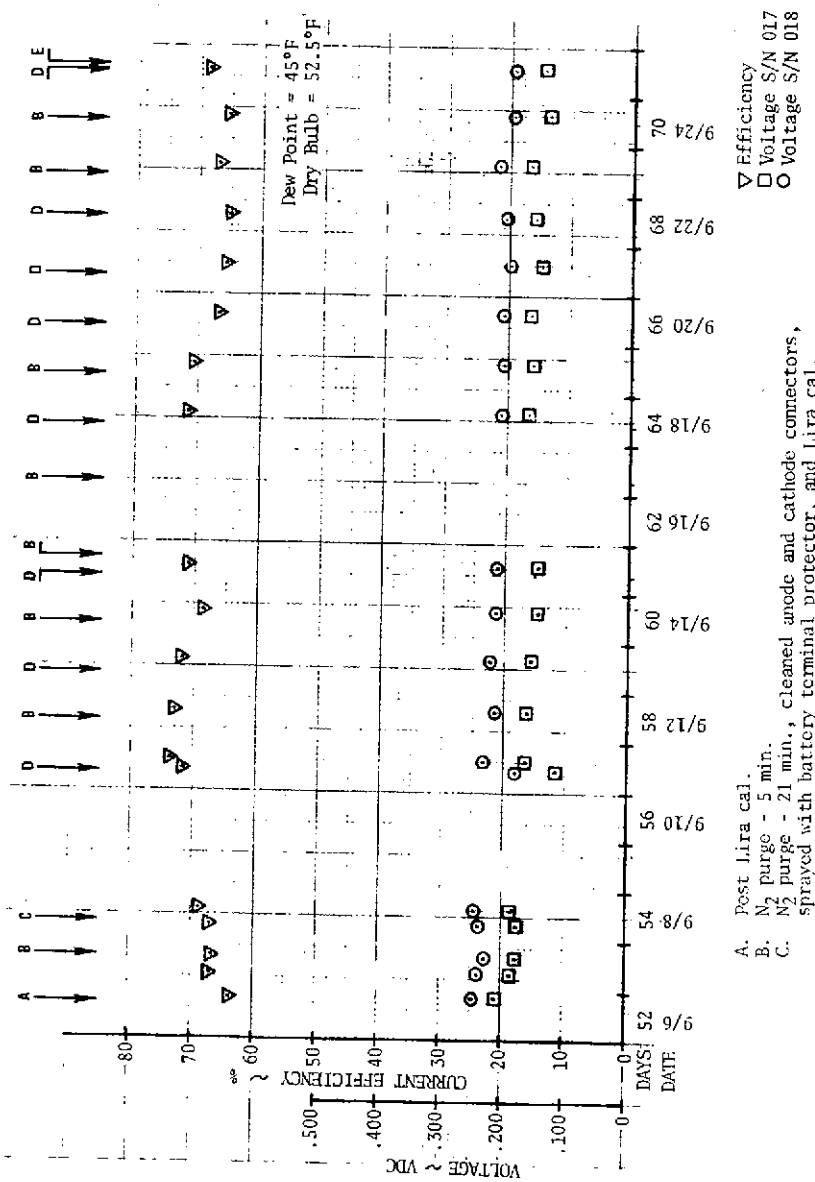
TEST 4 (S/N 017/018), 2nd PARAMETRIC TEST
AUGUST 29, THROUGH SEPTEMBER 6, 1972

FIGURE 20

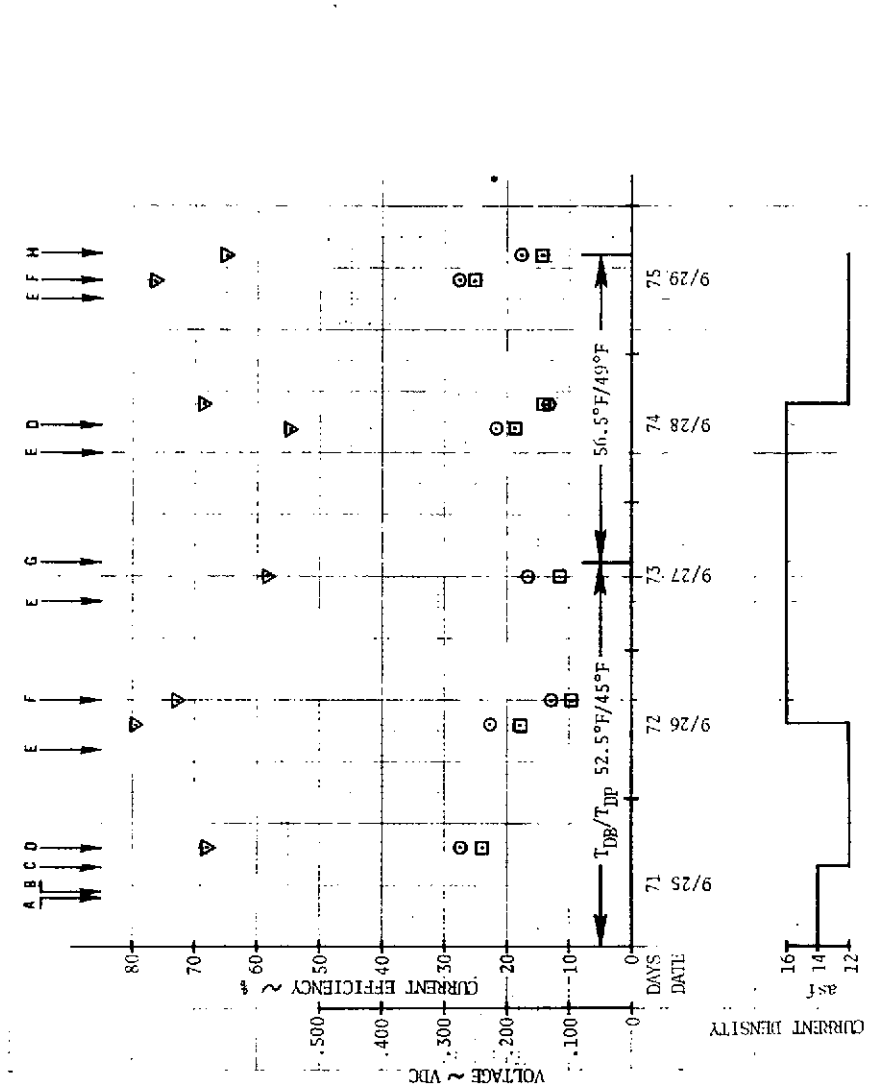


A. Post Lira cal.
B. N_2 purge - 5 min.
C. N_2 purge - 21 min., cleaned anode and cathode connectors, sprayed with battery terminal protector, and Lira cal.
D. Lira cal. and N_2 purge - 5 min.
E. Started 3rd parametric test.

TEST 4 (S/N 017/018), EXTENDED DURATION TEST
SEPTEMBER 6, THROUGH SEPTEMBER 25, 1972

FIGURE 21

57<



TEST 4 (S/N 017/018), 3rd PARAMETRIC TEST
SEPTEMBER 25, THROUGH SEPTEMBER 29, 1972

FIGURE 22

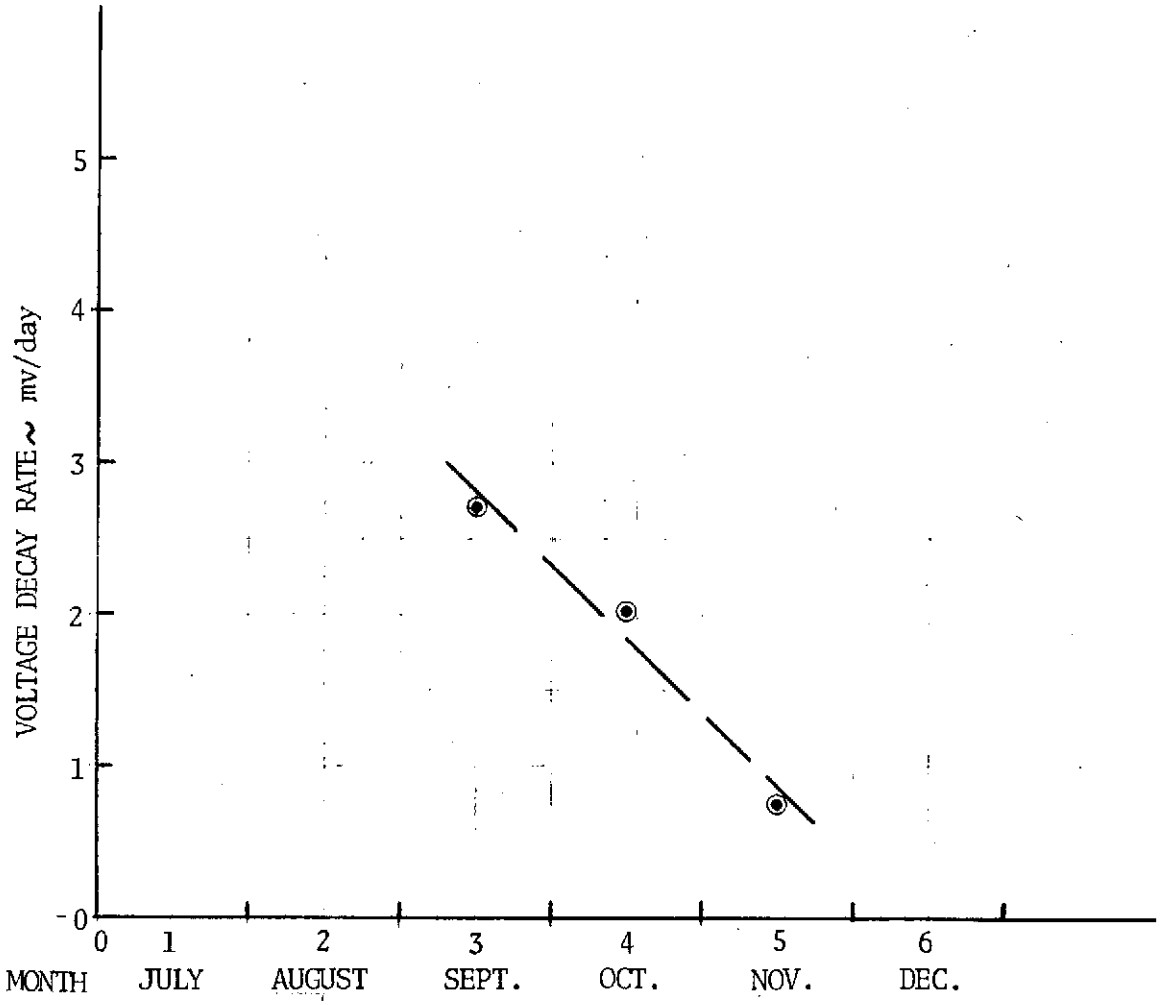
A. Started endurance test - asf = 14, P_{CO_2} = 2.5 mm Hg N_2 purge - 5 min.
B. N_2 purge - 5 min.
C. Lira cal. and N_2 purge - 5 min.
D. Reduced temp from 56.5°F/49°F to 52.5°F/45°F.
E. Raised dry bulb to 54.5°F.
F. 11:30 shut off fans, 12:35 restarted unit fans.
G. Set asf at 14.6 for asf decay test, lowered dry bulb to 52°F.
H. Lira cal.
I. Dew point controller inoperative, operating conditions off.
J. Found dew point controller inoperative - fixed.

▽ Efficiency
□ Voltage S/N 017
○ Voltage S/N 018

TEST 4 (S/N 017/018), EXTENDED DURATION TEST
SEPTEMBER 29, THROUGH OCTOBER 25, 1972

FIGURE 23

SWHSER 6229



TEST 4 (S/N 017/018), VOLTAGE DECAY RATE WITH TIME

FIGURE 24

offer potential for cell current efficiency improvement and ultimate optimization. It should be noted that improvement in these areas, although unnecessary to satisfy SSP requirements, were nonetheless desirable.

Initial High Differential Temperature Operating Conditions Imposed on Cell Pairs S/N 017 & 018 - The Hamilton Standard HDC CO_2 collection subsystem was designed to allow the electrolyte accumulator (reservoir) to be located either upstream or downstream of the cell pairs. It was planned to operate with the reservoir upstream during all tests in the subject special test program.

Direct current (DC) fans were employed in Hamilton Standard cell tests to permit evaluating individual cell pair performances at flows outside nominal design conditions. The plan for the parametric extended duration test called for air inlet conditions programmed over three conditions as follows: 49°F/55°F, 45°F/51°F, and 41°F/47°F dew point/dry bulb temperatures, respectively. At all three conditions, the dry bulb/dew point temperature differential was, therefore, to be maintained at 6°F.

During the installation of the cell pairs into test facility station B (S/N 018 on July 10, 1972; S/N 017 on July 14, 1972), the DC fans were inadvertently reversed, thereby causing:

1. Air flow through the cells to be in the opposite direction to that intended. (Resulting in electrolyte reservoir being downstream.)

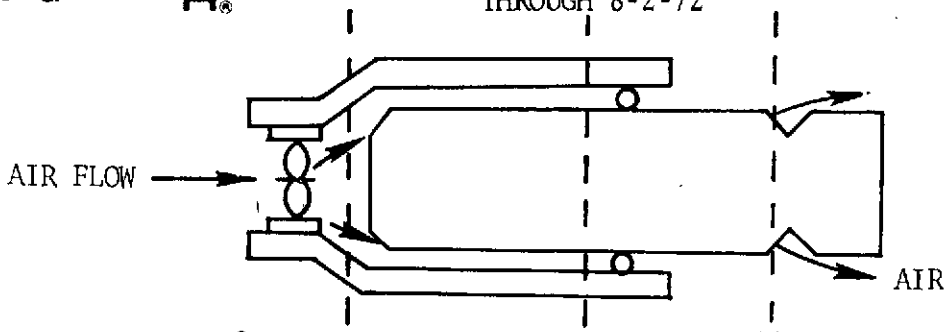
2. The fan air temperature rise (approximately 3-4°F) to be additive to the 6°F dry bulb/dew point differential programmed temperature of the cell inlet.

On August 1, 1972, the improper air flow direction was noted. After discussion with the NASA JSC, it was decided to reverse the fan motors on August 2, 1972 to eliminate the unrealistically high inlet temperature.

Figure 25 attached shows a profile of estimated temperatures and electrolyte concentrations existing at various positions in the cell and reservoir.

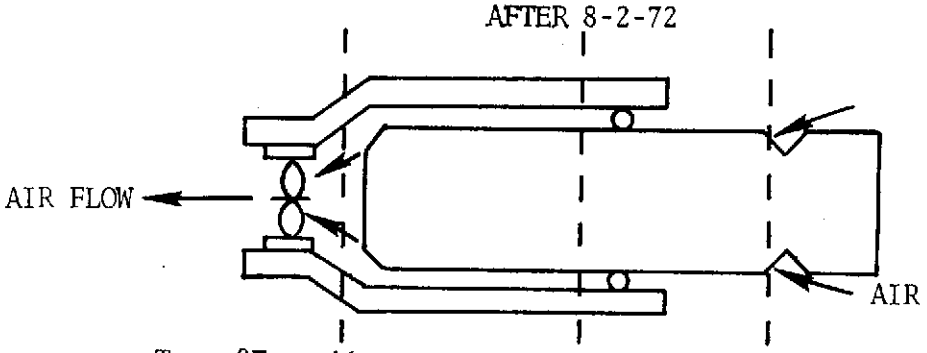
Since cell pair S/N 017 was started in station B on July 5, 1972 under the proper air flow direction, its installation into station B on July 14, 1972 would have resulted in "dryer" operation from that date until August 2, 1972. Following the air reversal on August 2, 1972, no flooding of electrolyte from #017 would have been anticipated since the cell pair had initially been run under the later conditions. Some flooding at the outlet of the cell was observed on August 4, 1972, in contradiction of the above discussion.

THROUGH 8-2-72



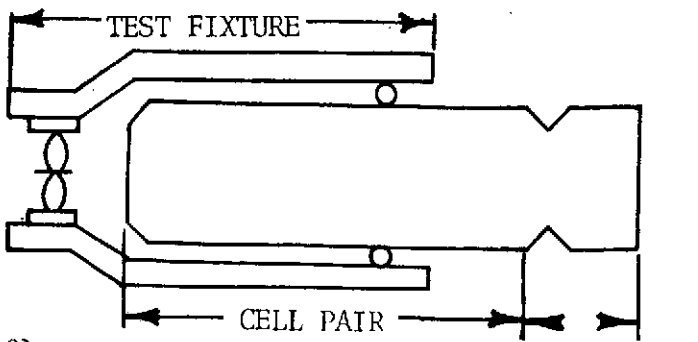
AIR	T_{DP}, °F	45		46
	T_{DB}, °F	55		61
ELECTROLYTE	T_{DP}, °F		46.5	45
	T_{DB}, °F		65	53
	Conc. %		71	58
	RH, %		50	74.1

AFTER 8-2-72



AIR	T_{DP}, °F	46		45
	T_{DB}, °F	57.5		52
ELECTROLYTE	T_{DP}, °F		46	45
	T_{DB}, °F		61	52
	Conc., %		67.5	55
	RH, %		57.8	76.9

LEGEND:



TEST 4 (S/N 017/018)
ESTIMATED ELECTROLYTE CONCENTRATIONS BEFORE AND AFTER AIR FLOW REVERSAL ON AUGUST 2, 1972

FIGURE 25 62<

Voltage/Current Instrumentation Error.- In the quick-look review of test data in early August, it was discovered that a disagreement between the two measurement techniques for determining cell voltage and current had existed beginning at approximately 1530 hours on July 25, 1972. The disagreement was discovered on August 2, 1972 and a complete calibration check made of both instrumentation techniques. It was determined that the automatic data recording system (Data Logger) was operating properly and that the error was in the Digitec current and voltage monitoring equipment. The Digitec monitoring equipment had been recently calibrated, was still within the calibration period, but was found to be "off-zero". It is suspected that the equipment zero adjustment had been inadvertently moved when calibration work was done on a nearby temperature recorder on July 25, 1972. In view of the fact that the Data Logger gave an accurate print-out of all voltages and currents every fifteen minutes since the start of test, an accurate history of cell power characteristics during this week-long period was available and employed to correct previously recorded data.

Figure 26 displays both the Digitec "recorded" data and the Data Logger "actual" currents and voltages for all cells tested. Cell performance curves figures 17 through 19, were adjusted in accordance with the errors shown on figure 26.

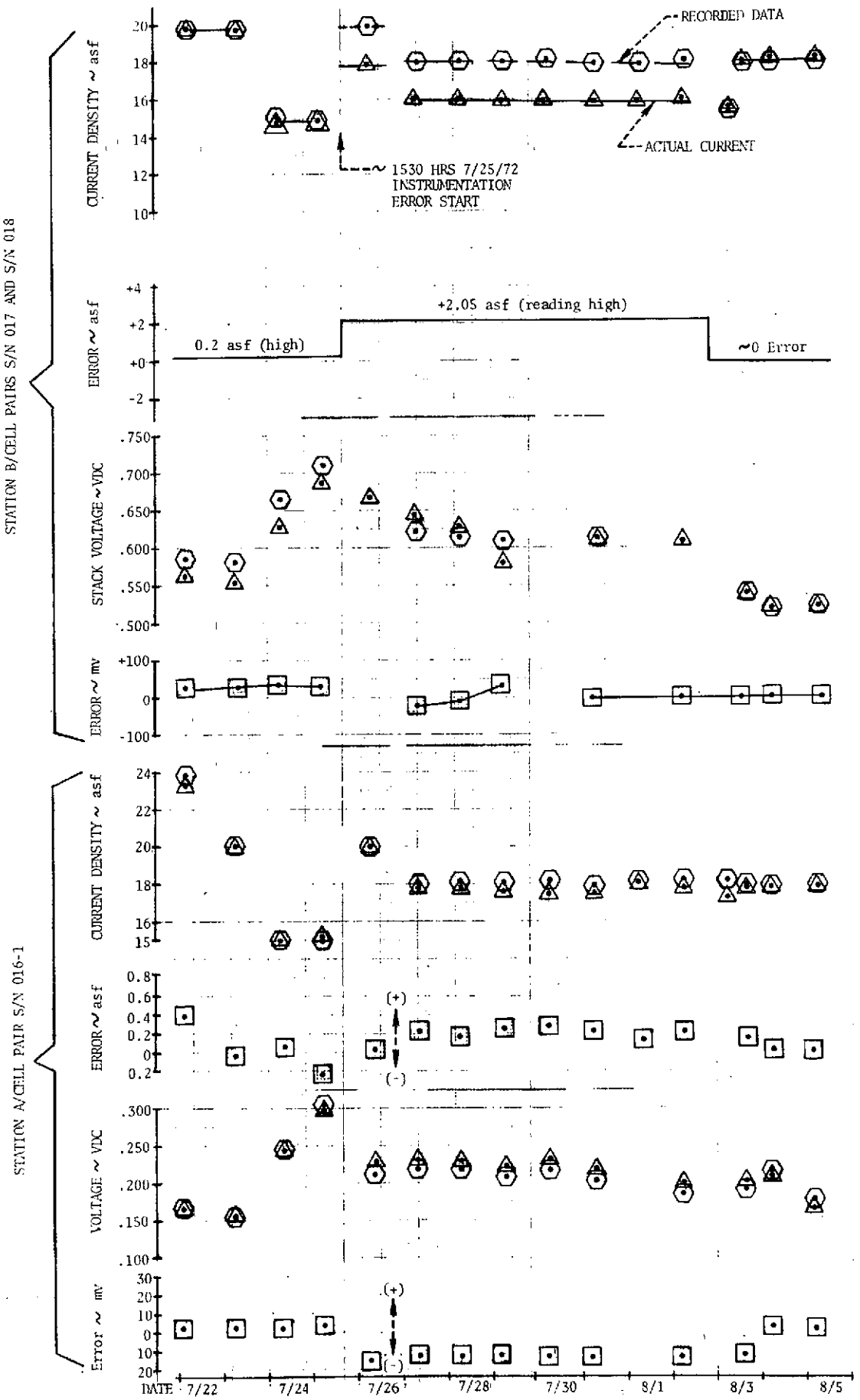
CO_2 REMOVAL EFFICIENCY AND NUMBER OF CELLS REQUIRED FOR THE SSP

Figure 17 plots current efficiency versus time for cell pairs 017 and 018. The cell pairs were located in series in Station B until October 25, 1972 after which date the cell pairs were separated and run individually in Station A and B, respectively. As will be noted from figure 17 one efficiency (representing the average for the two cell pairs is shown through October 25, 1972, while efficiency for each cell pair is shown after this date.

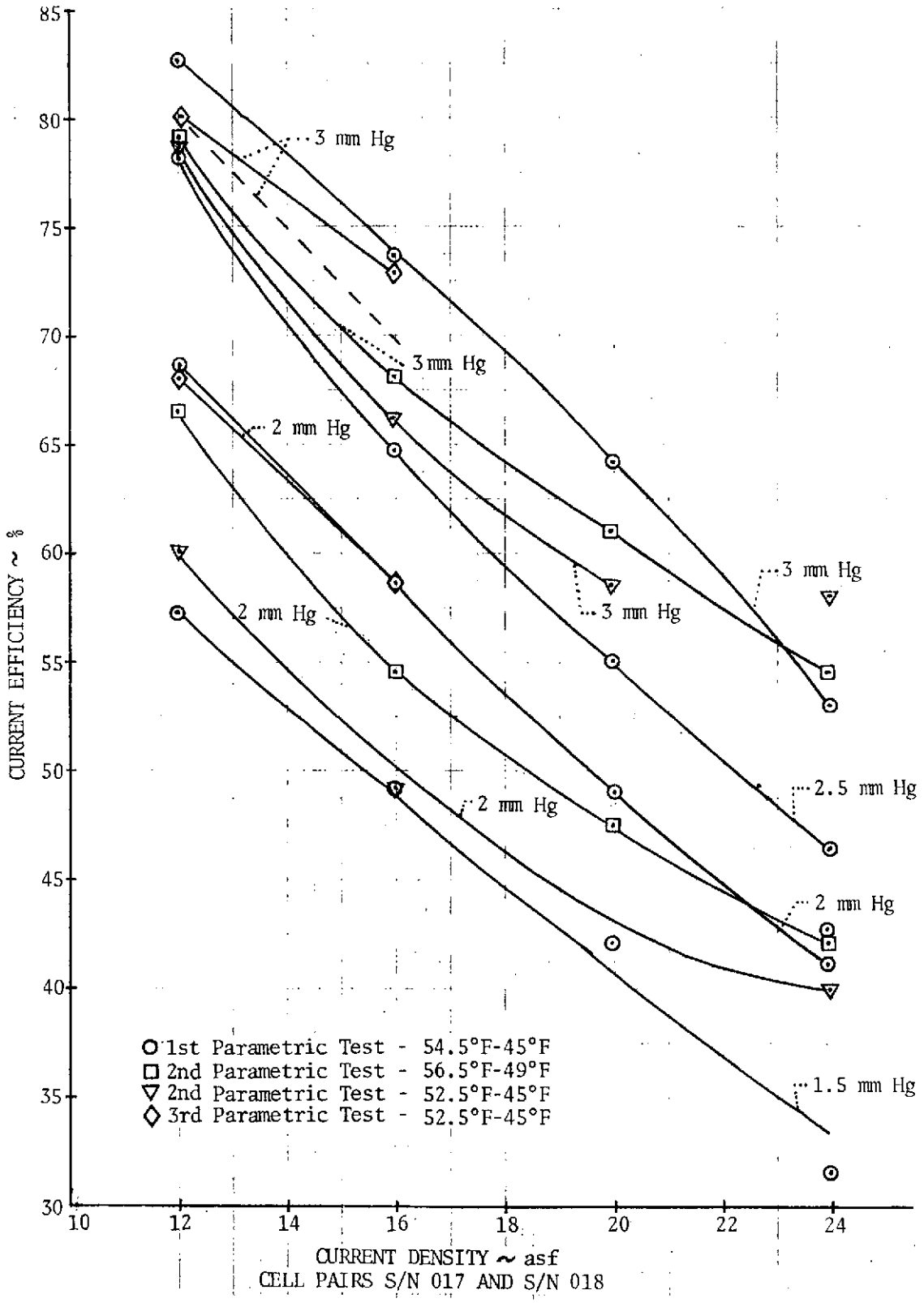
Figure 17 shows that three parametric tests were run during the first three months of operation as follows:

18 - 26 July	Parametric Test 1
1 - 6 September	Parametric Test 2
25 - 29 September	Parametric Test 3

During the parametric tests current density, CO_2 partial pressure and air temperature/dew point were varied to determine the effect upon CO_2 removal efficiency. Figures 27 and 28 show the results of the three tests. Also included in figure 27 is the variation of current efficiency versus current density for the 2.5 mm Hg CO_2 condition as determined from the first parametric test. The 2.5 mm Hg point is of particular interest due to the fact that most of the first five months test data on cell pairs 017 and 018 were run under 2.5 mm Hg CO_2 conditions, as shown in figure 17.



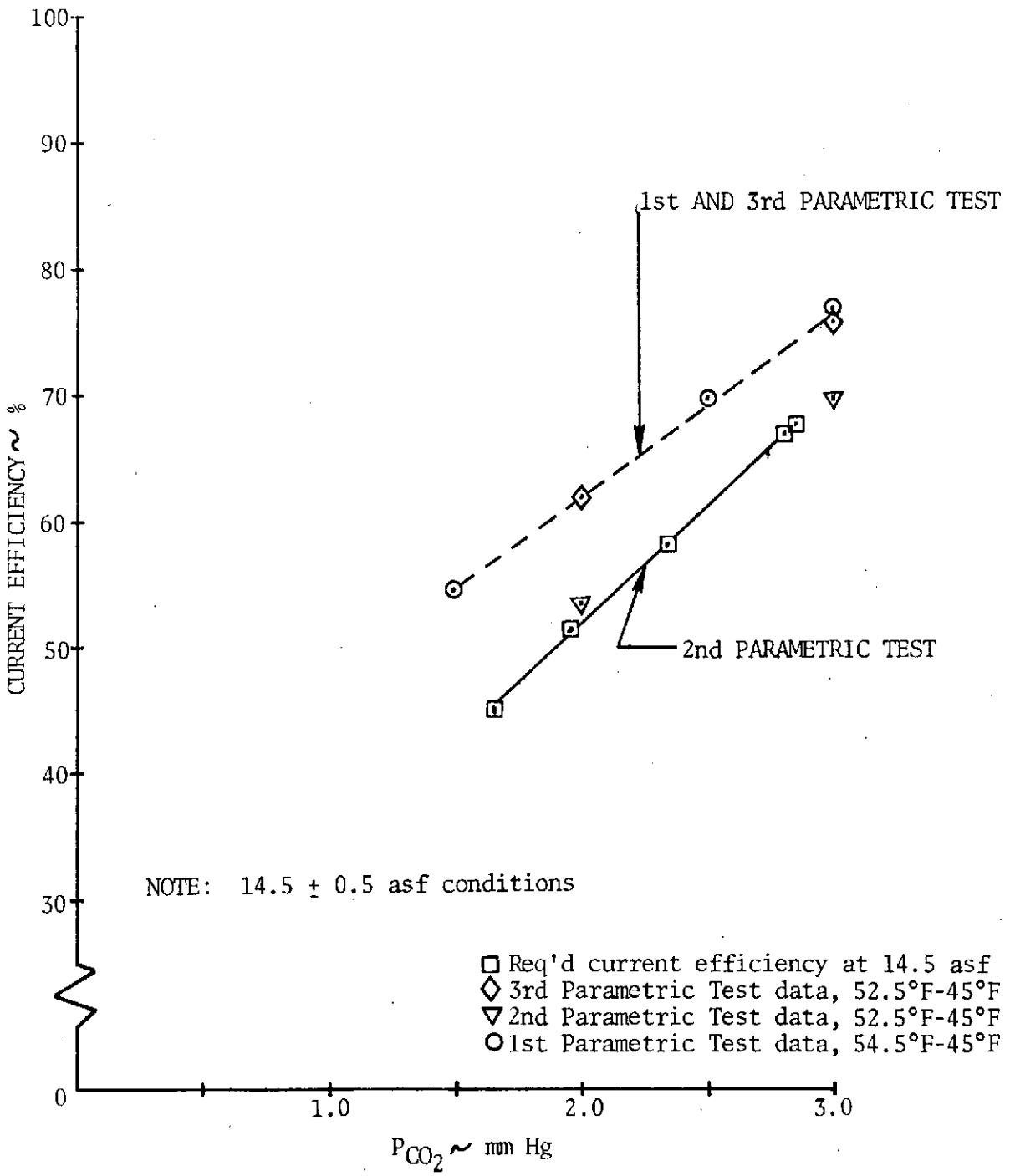
VOLTAGE/CURRENT INSTRUMENTATION ERROR JULY 25 TO AUGUST 2, 1972
FIGURE 26



TEST 4 CURRENT EFFICIENCY VS. CURRENT DENSITY, CELLS 017/018, 1st - 3rd PARAMETRIC TESTS

FIGURE 27

65<



TEST 4 CURRENT EFFICIENCY VERSUS CO_2 PARTIAL PRESSURE
CELLS S/N 017/018, 1st - 3rd PARAMETRIC TESTS

FIGURE 28

Figure 29 projects the results of the 2.5 mm Hg CO_2 condition throughout the five month test at intervals of two to three days taking into account actual test current density variations, so that test efficiencies can be directly compared with those efficiencies achieved in the first parametric test (hereafter referred to as projected efficiencies).

Figure 29 shows variations in daily HDC current efficiences compared with CO_2 removal efficiencies during the first parametric test series. Variations occur generally over the range of ±5% to -10%. Of 91 days plotted of the five month test period, 22 days have efficiencies higher than the first parametric test; 69 below.

It is noteworthy that in late November early December, the cell efficiency level was about 5% higher than during the first parametric test. Due to the frequency of instrumentation calibration during this period[1], the data is believed particularly creditable. It is concluded that no inherent decay or decrease in cell pair S/N 018 CO_2 removal efficiency had occurred after five months of operation.[2] It is also obvious that on a number of occasions efficiency was below that originally achieved and the determination of the numbers of cells and current density to satisfy the necessary CO_2 removal rate at all times throughout the test period would necessarily have to be accommodated.

No thorough explanation can be attributed to each variation of efficiency from day-to-day throughout the period shown. General observation can be made however:

1. The frequency (or infrequency) of LIRA calibrations, can not be attributed as a cause of the variations. With only a few exceptions data collected on days following a September - December daily calibration was consistent with preceding and subsequent data.

2. The variations cannot be explained on the basis of random measurement or reading errors. It is recognized that measurement and reading errors of about 4% exist and certainly contribute to the efficiency fluctuations, but study of figure 29 eliminates the likelihood that long-term, short-term, or random measurement errors are significant.

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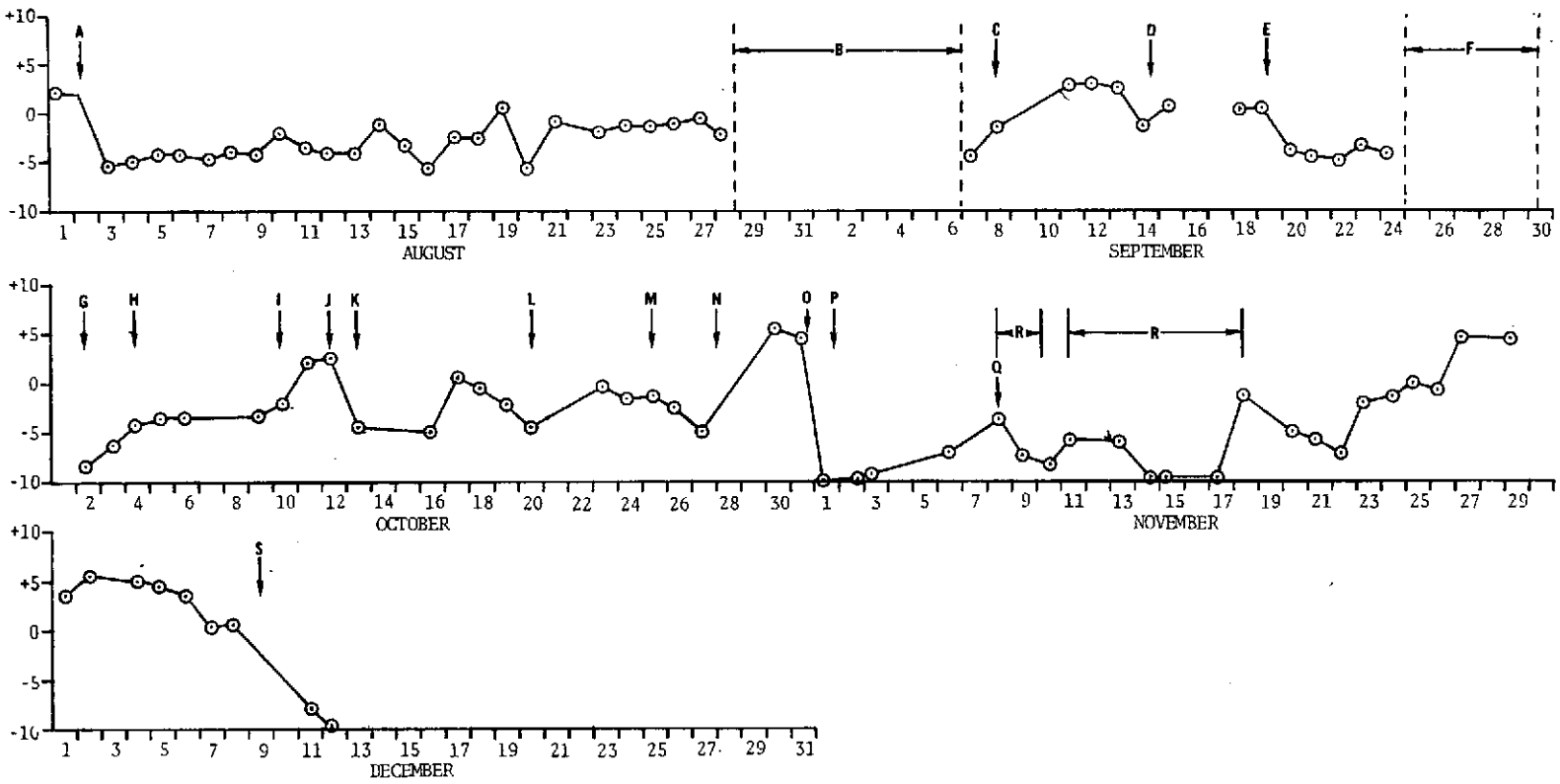
[1] LIRA CO_2 concentration measuring instruments were calibrated on days identified with " " on figure 29.

[2] The test of cell pair 018 was initiated on July 10, 1972.



A. Reversed air flow through cell pairs S/N 017 and S/N 018, air ΔT reduced from 55°F/45°F to 52°F/45°F (T_{DB}/T_{DP}).
B. Parametric test #2.
C. 21 min N_2 purge, cleaned corrosion off anode-cathode, connectors sprayed with protector.
D. ΔT incr. ~ 0.8°F.
E. ΔT incr. ~ 20.7°F.
F. Parametric test #3
G. Changed air conditions from 56.5°F/49°F to 52.2°F/45°F.
H. Incr. dry bulb from 52.5°F to 51.5°F.
I. Cell pair S/N 018 fan shut off 60 min.
J. Discontinued N_2 purges, lowered T_{DB} to 52°F from 54.5°F.
K. Facility DP controller failure, temp to 44°F/40°F.
L. ΔT incr. ~ 0.7°F.
M. Cell pair S/N 017 moved from Station A.
N. H_2 flow rate decr. between October 27 and 30.
O. Dew point temp. incr. from 44 to 48°F, ΔT reduced consequently from 7°F to 4°F.
P. Higher H_2 flow rate restored.
Q. Stopped H_2 flow - 5 min.
R. PH_2 reduced below 5 psig.
S. Facility heater failure detected.

TEST 4 (S/N 017/018), VARIATION IN CO_2 REMOVAL EFFICIENCIES FROM EFFICIENCY ACHIEVED DURING 1st PARAMETRIC TEST THROUGH DECEMBER 12, 1972

FIGURE 29

3. CO_2 removal performance depression following a perturbation to the cells, was temporary on all occasions. Over a period of 2 to 25 days, cell performance returned to the originally projected level.

4. No clear relationship between projected performance variation and current density, H_2 inflow rate, matrix pressure, and inlet air temperature was observed. Although exceptions can be found, a performance improvement usually followed an increase in ΔT (T_{DB}-T_{DP}), and similarly, performance degradation followed a ΔT decrease. As discussed above, the change was temporary, and in time efficiencies were restored to their former levels at the newer ΔT.

It is to be noted from figures 27 and 28 that over the range of 2.0 to 3.0 mm CO_2 the first and third parametric test gave approximately the same CO_2 removal efficiency at 14.5 ± 0.5 asf. The efficiency achieved during the second parametric test was, for reasons not understood, lower by 7 to 10%. Computer runs were made to determine the number of cell pairs needed to accommodate the SSP requirements based both upon the results of the first and third parametric test, and the second test.

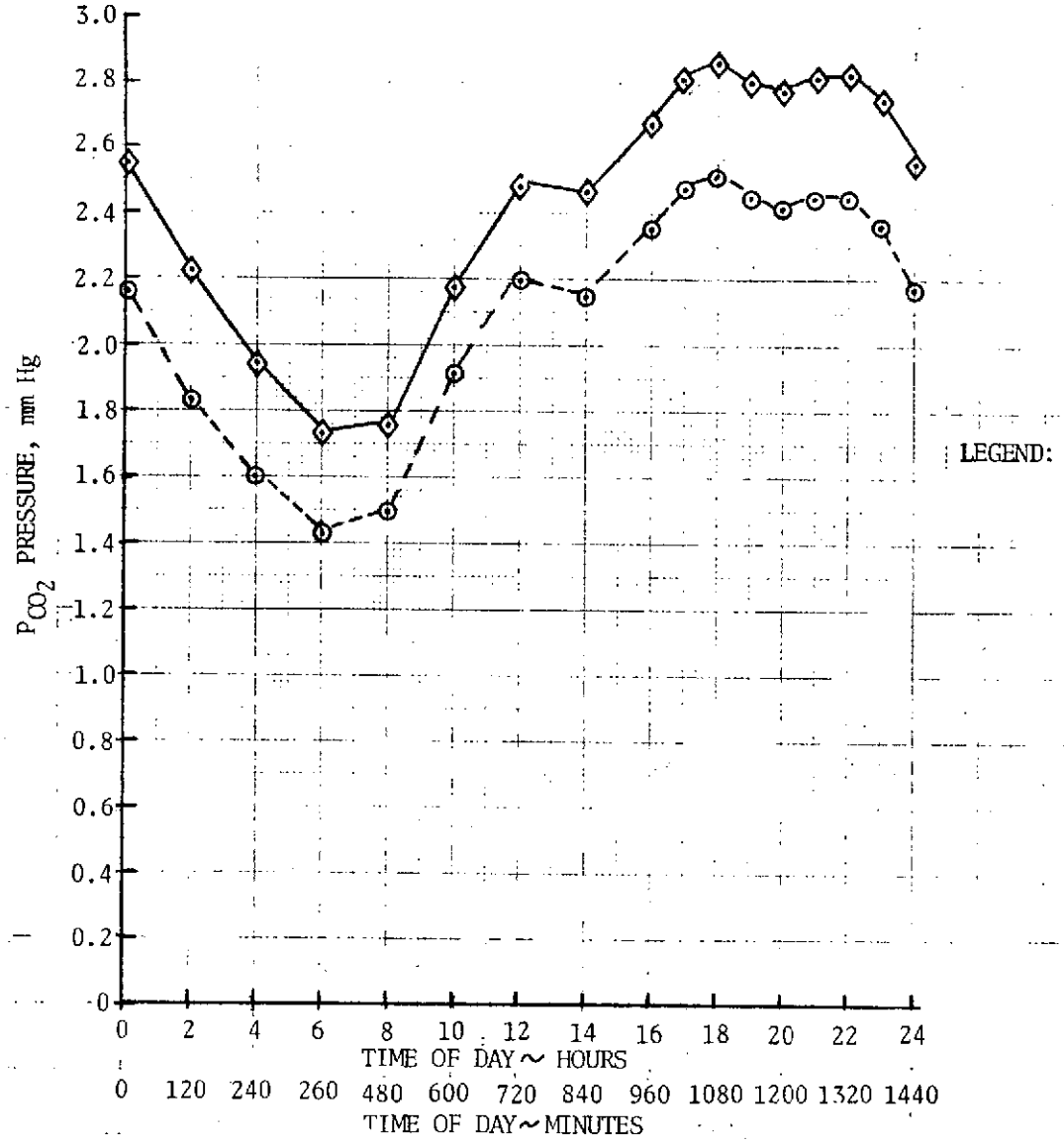
Appendix B gives the results of three of the many computer runs which were made to determine the number of cell pairs required. Figures B1-B3 attached to Appendix B extract information from test results and graphically display the findings.

Figure 30 shows CO_2 partial pressure ($^PCO_2$) at the HDC inlet versus time for 33 and 36 cell pairs operated at a nominal 14.0 asf current density using fixed external resistance, and based upon CO_2 removal efficiency at this current density equal to that achieved during the first and third parametric tests. As is observed from the figure for the case of 33 cell pairs a peak cabin pressure of 3.02 $^PCO_2$ mm Hg resulted. The figure obviously shows that an insignificant increase in current density above 14.0 asf, say 1405 asf, would adequately maintain the cabin below the 3 mm Hg CO_2 maximum. For 36 cell pairs, operating at this same efficiency at 14.0 asf, the figure clearly shows a satisfactory margin in cabin CO_2 partial pressure.

Figure 31 shows CO_2 removal efficiency plotted against CO_2 partial pressure for actual test data and also for computer program inputs. The following observations are made:

1. The computer input for the 14 asf fixed resistance case based upon the results of the first and third parametric tests, actually is conservative with respect to actual test results by a margin of 2-1/2 to 4%.[1]

[1] Since a 14 asf condition was not imposed during any of the three parametric tests, the 12 and 16 asf results were interpolated to obtain 14 asf "actuals". Figure 28 shows the linear variation of CO_2 removal efficiency as a function of CO_2 partial pressure over the range in question thereby satisfying this assumption.

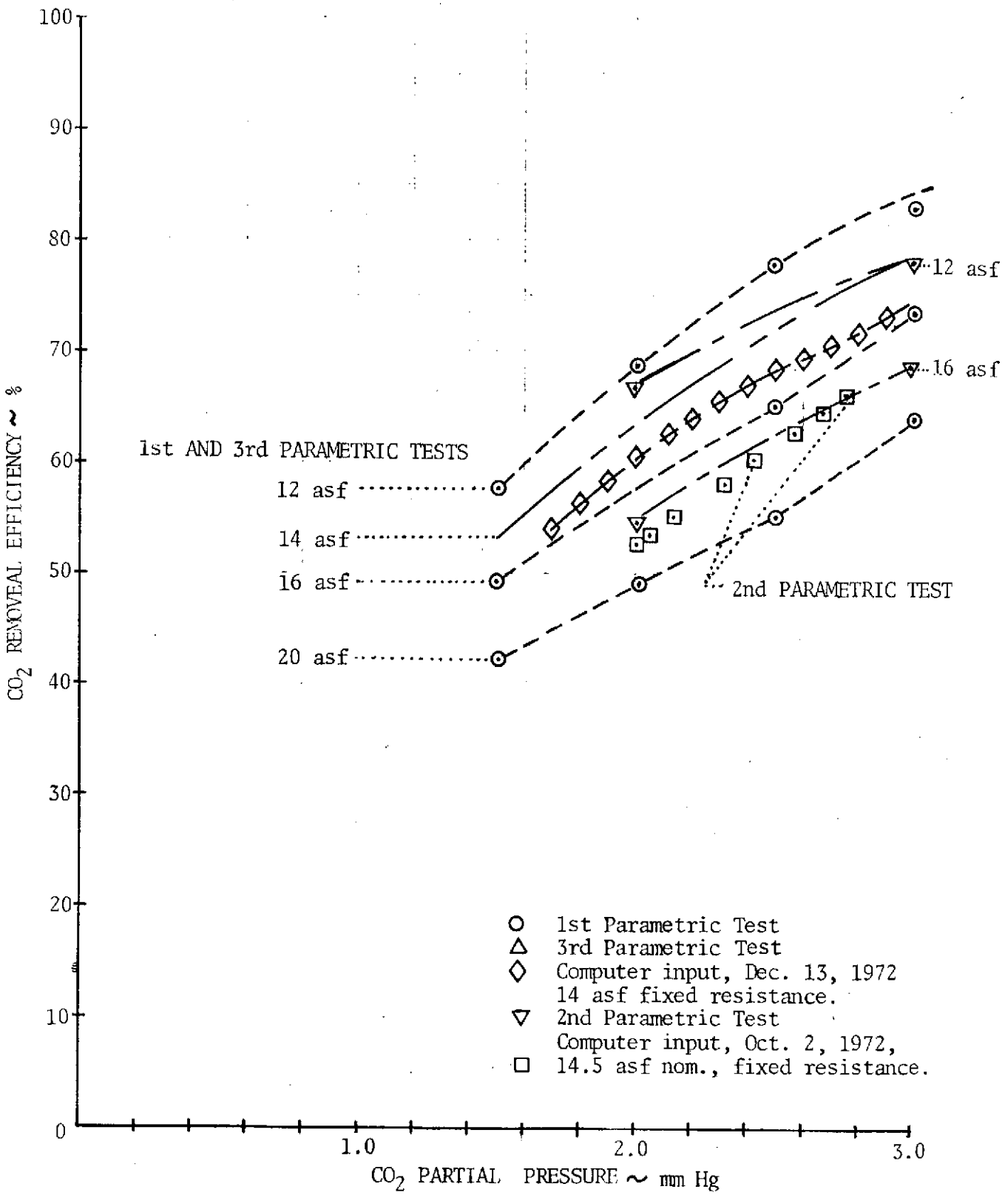


NOTE: [1] P_{CO_2} pressures shown are HDC inlet. Cabin pressure 0.15 mm Hg higher.

[2] Reference computer runs, Appendix B of this report.

TEST 4 (S/N 017/018), P_{CO_2} PRESSURE VERSUS TIME OF DAY VERSUS NUMBER OF CELL PAIRS - COMPUTER PROJECTIONS BASED UPON 1st AND 3rd PARAMETRIC TESTS

FIGURE 30



TEST 4 (S/N 017/018), PERFORMANCE FOR PARAMETRIC TESTS 1 - 3 AND EFFICIENCIES USED IN COMPUTER INPUT

FIGURE 31

2. In similar manner, the computer input used to project the number of cell pairs required based upon the results of the second parametric tests, is conservative compared with actual test results.

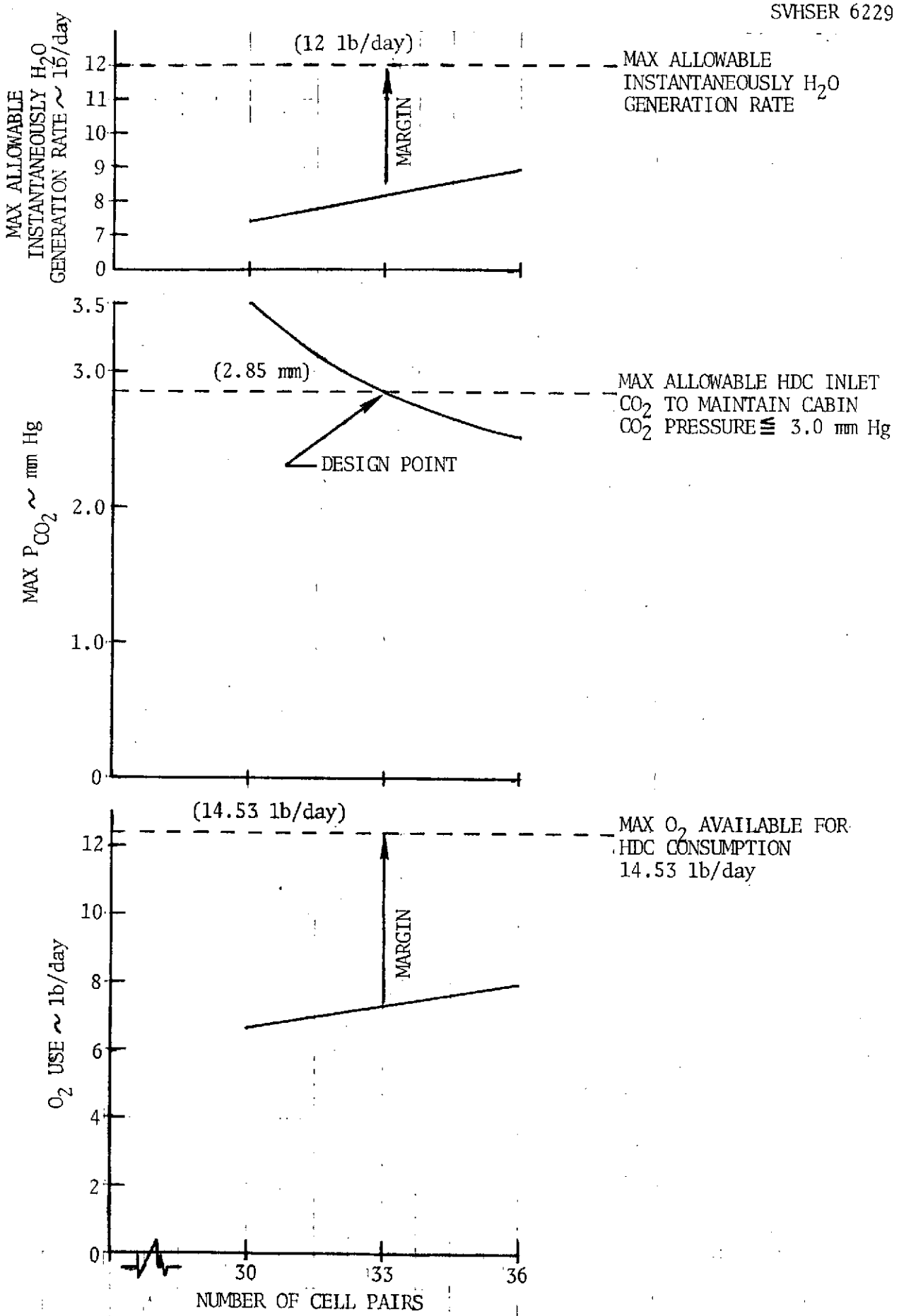
Figure 32 plots first and third parametric test computer results for 30, 33, and 36 cell pairs against O_2 usage, peak CO_2 pressure, and maximum instantaneous water generation rates. As cited in the discussion of figure 31, the computer predictions would have the previously referred to conservatism built-in. Figure 32 shows that margin which exists with respect to maximum allowable O_2 consumption and water generation rates.

Figure 33 shows the results of second parametric test-based computer runs, and defines O_2 usage and maximum P_{CO_2} densities. The figure reflects the lower CO_2 removal efficiencies obtained in the second parametric tests and shows that it would be necessary to increase current density from 14 to 16 asf if 33 cell pairs were employed. The 9 lb/day of O_2 consumption still provides adequate margin considering that about 14.5 lb/day can be accommodated. Although not shown, water generation would amount to 10.25 lb/day for 33 cell pairs operating at the 16 asf, leaving a margin of about 1.75 lb/day below the generation rate allocated to HDC for SSP.

It is concluded that 33 cell pairs would accommodate the necessary CO_2 transfer rate at all times for the six-man SSP, even if certain of the perturbations which caused temporary loss in performance during the first five months of this test program were to occur aboard the SSP vehicle. The likelihood of the latter occuring aboard the SSP vehicle is believed to be low. ΔT, for example, although varying throughout this test over the range of 4°F to 10°F because of test facility limitations, will inherently be controlled within ± 1°F aboard the SSP.[1] Further, the rates at which inlet variation to the cells could occur aboard the SSP are low due to system volume, whereas the small size of the test chambers, about 12 ft^3, permitted both rapid changes and wider excursions in inlet conditions to the cell pairs being evaluated. In a similar manner many of the other perturbations which arose would not have occurred aboard the SSP because of unvarying conditions and procedures, higher reliability of supporting subsystems and the automatic isolation (thereby protection) of the cells even if a significant perturbation were to occur.

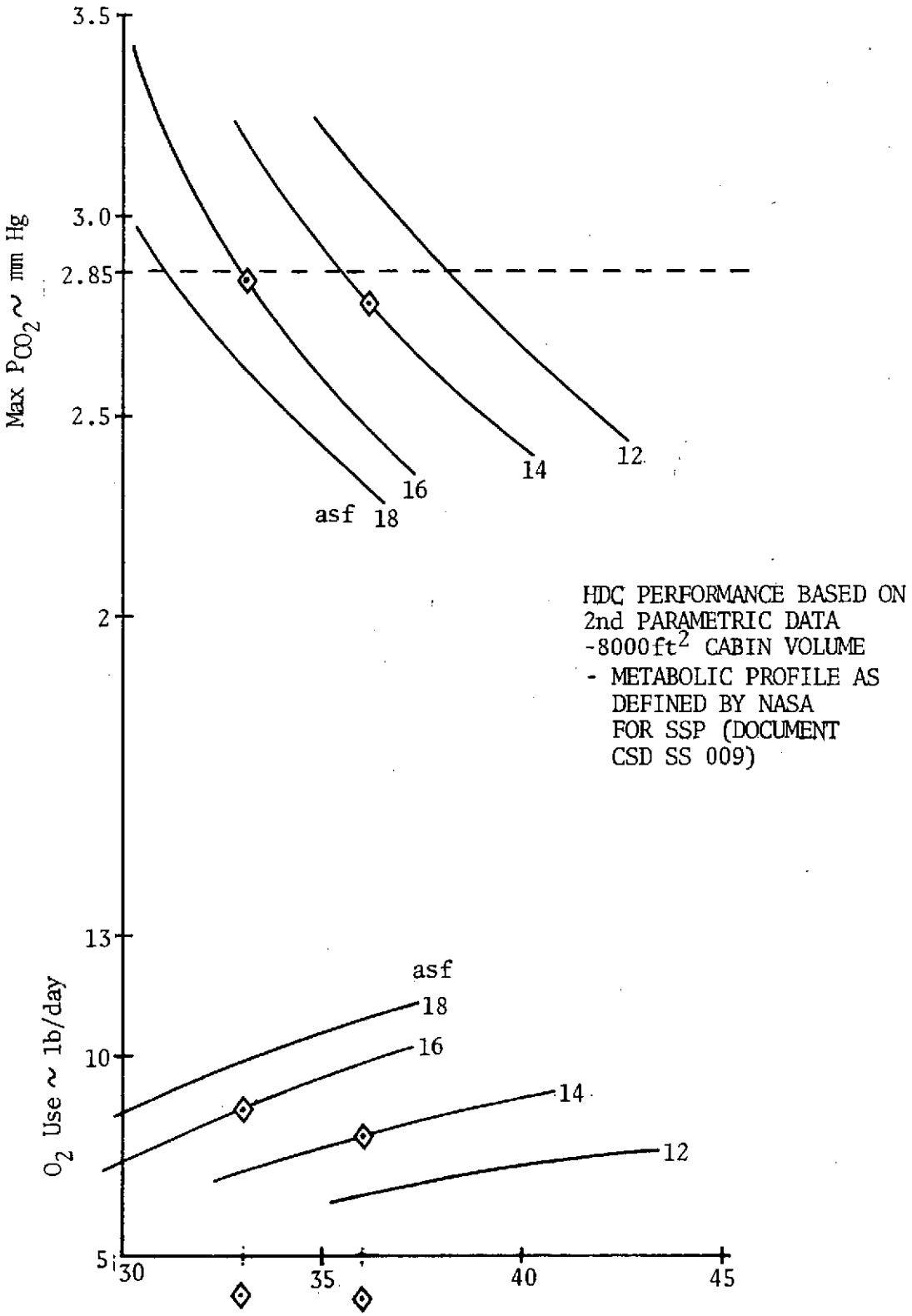
It is reemphasized that even if the perturbations discussed above were to exist, 33 cell pairs would be adequate to meet the SSP requirements.

[1] The "ΔT" aboard SSP is the result of temperature rise across cabin temperature control fans - and as such will be relatively constant.



TEST 4 (S/N 017/018), COMPUTER RESULTS FOR 1st AND 3rd PARAMETRIC TESTS, SHOWING MARGIN TO SSP ALLOWABLE

FIGURE 32 73<



TEST 4 (S/N 017/018), COMPUTER RESULTS FOR 2nd PARAMETRIC TEST, SHOWING MARGIN TO SSP ALLOWABLE

FIGURE 33 74<

CELL POWER (VOLTAGE) DEGRADATION

Assuming adequate cell "life", the only significant operating performance parameter for a hydrogen depolarized cell is current efficiency. Considerable attention during the reported test program was given to cell voltage (power) degradation, owing to cell "life" concerns of the NASA. A cell has useful life until its terminal voltage degrades to the point that minimum inherent external resistance in the subsystem circuitry causes cell current to fall below that level necessary to accommodate the required removal rate of CO_2.

For the Hamilton Standard SSP subsystem, 50 milli-ohms external circuit resistance was the minimum[1] design value with a 36 cell pair module.

At 15 amperes current, the minimum cell power required of 36 cells in electrical series would be

$$I^2R = (15)^2\ (.050) = 11.25 \text{ watts.}$$

The nominal electrical power (at 15 asf) required for each cell pair would be

$$\frac{11.25 \text{ watts}}{36 \text{ cell pairs}} = \frac{0.31 \text{ watts}}{\text{cell pair}}.$$

Again at 15 asf, minimum cell voltage required would be

$$E_{minimum} = 0.31 \text{ watts}/15 \text{ amperes} = 0.020 \text{ volts} = 20 \text{ mv.}$$

The 20 mv per cell pair voltage requirement thus derived represents a worst case average cell condition and includes some conservatism since the cell operating current efficiencies would increase with cell current density reductions below 15 asf[2] tending to partially offset further decrease in current.

Hamilton Standard's experience on cell pairs operating over an extended period was that the rate at which cell voltage or power degraded, decreased with time. On cell pair 010 the power decreased from the original 5 watts to 2.8-3.2 watts over the first three months and no further decrease with time was observed.

Although the rate of power degradation on cell pairs 017 and 018 was unexplainably greater than cell pair 010, it was the consistent belief of Hamilton Standard during this special test program and the continuation of these tests under IR&D funding, that the rate of degradation was decreasing with time, and had in fact reached such a low level of decay that six month life would be achieved on both cells (i.e. neither cell would have less than 20 mv at 14 asf) at the end of six months. After approximately five months of operation, cell pairs 017 and 018 had cell voltages of 69 mv and 110 mv, respectively.

---

1 Minimum circuit external resistance based upon #12 to #14 gauge interconnecting wiring and using achievable contact resistance values.

2 The Hamilton Standard cell pair uses a 1 ft^2 electrode, so that series current and current density are numerically equal.

Figure 34 shows a plot of cell voltages for cell pair 018 from the start of test in early July, 1972. An examination of figure 34 to establish decay rate versus time shows:

Month	Current	Voltage Decay Rate
1 (July 1972)	20 asf	-0-
2 (Aug. 1972)	18 asf	4 mv/day
3 (Sept. 1972)	14 asf	2.7 mv/day
4 (Oct. 1972)	14 asf	2.0 mv/day
5 (Nov. 1972)	14 asf	0.72 mv/day

It can be clearly seen (see figure 24) that the voltage degradation rate is decreasing with time, as appears characteristic of Hamilton Standard reservoir and non-reservoir cells, and it would be predicted that if the cell pairs continued under test for the next few months, the decay rate will be arrested in December or January and no further decay experienced.

Additional investigations into the cause of this degradation are being made and will be described in the final report of contract NAS 9-12920 However, it should be reemphasized that low cell voltage is only important if it decreases below the point where sufficient current is available to accommodate the required CO_2 removal rate.

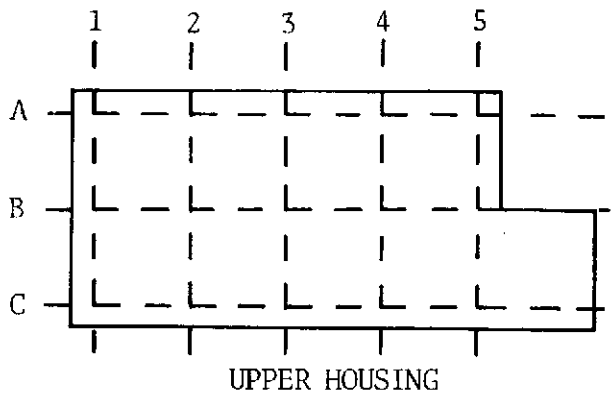
HOUSING DEFORMATION

It appears reasonable that optimum cell performance could only be achieved by having the proper matrix compression and electrode gap across the cell. Such uniformity cannot be achieved if the housings deflect significantly. An effort was initiated to determine the extent to which housings did deflect and to further investigate pre-bending of housings as a means of maintaining uniform matrix thickness.

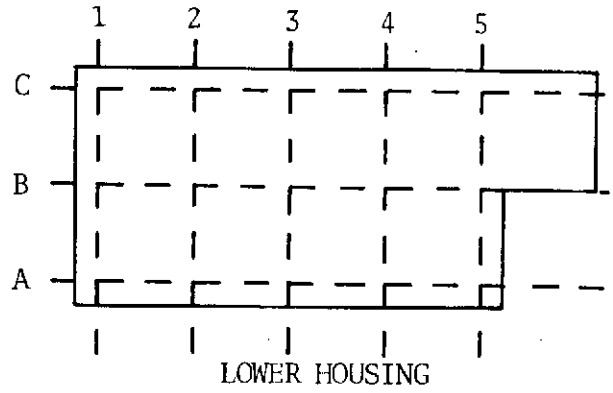
Tables VI and VII show the deflections of two different configurations of cell pair housings, as a function of internal hydrogen pressure. Table VI shows deflections versus internally applied pressure for non-pre-bent housings (such as those used in cells S/N 015, S/N 016-1, S/N 017 and S/N 018); Table VII , deflections for the pre-bent housings later used in the build-up of cell S/N 020 which, as of 30 December 1972, had not yet been subjected to operating tests. It is to be noted that the thickness of the cell pair S/N 020 housings did not change (or change noticeably) with increase in internal pressure,

TABLE VI

DEFLECTIONS OF NON-PRE-BENT UPPER & LOWER HOUSINGS
OF CELL PAIR S/N 011-3 AS A FUNCTION OF INTERNAL PRESSURE



UPPER HOUSING



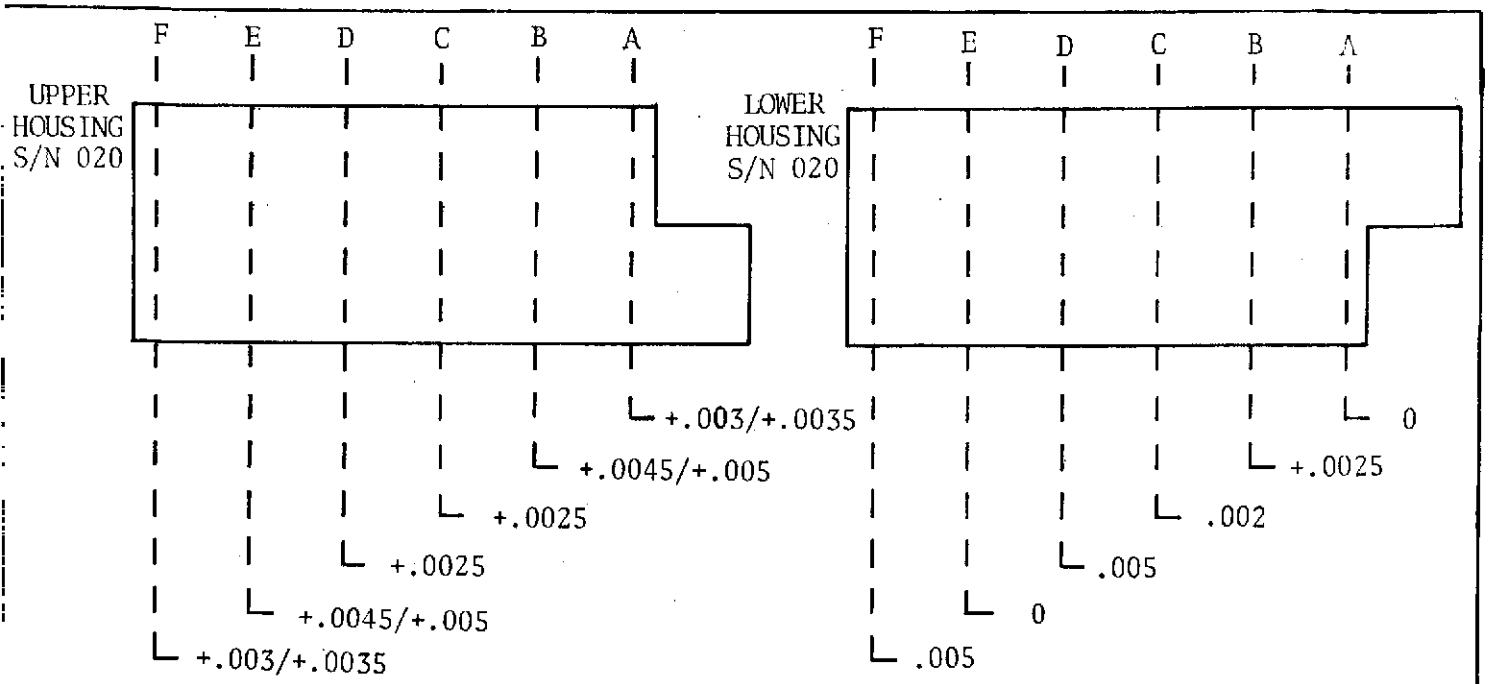
LOWER HOUSING

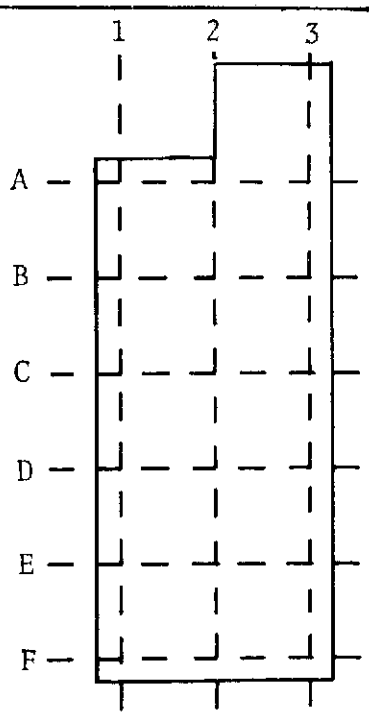
	UPPER HOUSING					LOWER HOUSING				
	Internal Pressure, psig					Internal Pressure, psig				
LOCATION	0	1	3	5	7	0	1	3	5	7
1A	+.0272	+.0273	+.0273	+.0276	+.0269	+.0042	+.0045	+.0047	+.0045	+.0047
1B	+.0239	+.0236	+.0237	+.0236	+.-237	+.0090	+.0094	+.0096	+.0098	+.0100
1C	+.0078	+.0079	+.0078	+.0075	+.0077	+.0025	+.0024	+.0038	+.0033	+.0030
2A	+.0254	-	-	+.0262	+.0264	+.0087	-	+.0098	+.0097	+.0105
2B	+.0273	-	-	+.0303	+.0331	+.0180	-	+.-195	+.0215	+.0240
2C	+.0071	-	-	+.0074	+.0080	+.0088	-	+.0095	+.0100	+.0102
3A	+.0153	+.0148	+.0151	+.0163	+.0169	+.0116	+.0119	+.0126	+.0131	+.0138
3B	+.0178	+.0178	+.0198	+.0217	+.0246	+.0172	+.0180	+.0193	+.0224	+.0242
3C	+.0010	+.0012	+.0012	+.0019	+.0036	+.0062	+.0063	+.0063	+.0075	+.0089
4A	+.0052	-	-	+.0081	+.0089	+.0186	-	+.0193	+.0195	+.0207
4B	+.0136	-	-	+.0172	+.0197	+.0206	-	+.0220	+.0237	+.0261
4C	0	-	-	+.0011	+.0025	+.0084	-	+.0087	+.0098	+.0107
5A	0	+.0008	+.0004	+.0008	+.0009	+.0185	+.0181	+.0182	+.0186	+.0188
5B	+.0055	+.0055	+.0051	+.0055	+.0059	+.0130	+.0128	+.0128	+.0132	+.0138
5C	0	-.0011	-.0015	-.0017	-.0011	0	+.0002	-.0002	+.0003	+.0005

NOTE: 1. Deflection shown in inches, using location 5C as zero reference.
2. Positive deflections shown indicate housing outward bowing.

TABLE VII

PRE-BENT CELL THICKNESS (S/N 020) AS A FUNCTION OF INTERNAL PRESSURE





NOTE: Measurements shown in inches.

LOCATION	Pressure 0 psig	5 psig
A1	0.718	0.717
A2	0.718	0.717
A3	0.712	0.712
B1	0.716	0.716
B2	0.719	0.719
B3	0.713	0.715
C1	0.707	0.707
C2	0.716	0.715
C3	0.705	0.705
D1	0.707	0.707
D2	0.715	0.714
D3	0.711	0.707
E1	0.713	0.715
E2	0.718	0.719
E3	0.716	0.715
F1	0.709	0.709
F2	0.711	0.711
F3	0.711	0.711

whereas the non-pre-bent housing did have an outward bow of as much as 0.050" (in terms of cell thickness) at it's center when pressurized to 5 psig internally. It is apparent that significant "bowing" or displacement of housings resulting from both matrix compression during assembly and internal H_2 pressure might seriously affect cell operation.

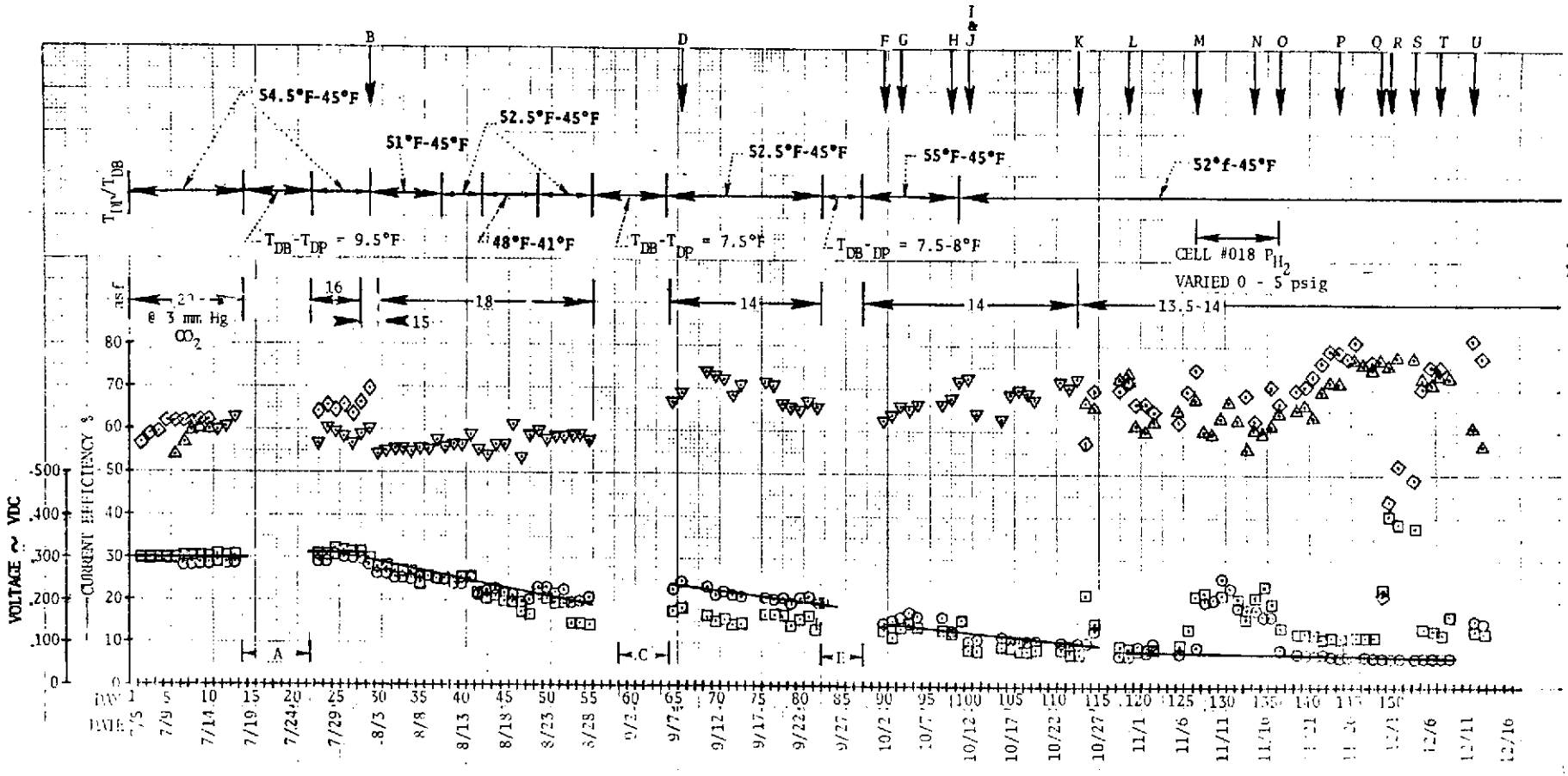
The cells used in extended duration test 4 of this program (cells S/N 015, S/N 016-1, S/N 017 and S/N 018) employed plastic shim stock as the spacer material used to control electrode gap (matrix thickness). During disassembly of cell pairs S/N 015 and S/N 016-1 it was noted that the torque of the cell pair perimeter bolts was significantly less than when the cell pairs were initially assembled. It was obvious that plastic deformation versus time had occurred. It has since been analytically confirmed that this cold-flow effect of the plastic spacers would have caused a gradual accentuated "bowing" of the housings to a level four times greater than would have occurred had there been no cold flow in the spacers. The cold flow time effect upon cell voltage might be significant and should be further investigated as a likely contributor to the voltage decay experienced.

In any event it is concluded that pre-bent housings employing a non-cold flow sensitive spacer material should be used to eliminate the obvious undesired non-uniformity in cell thickness. As may be observed from Table VII employing this proposed configuration would eliminate significant change in electrode gap over the face of the cell and for the entire H_2 pressure range of 0-5 psig.

NITROGEN PURGING

Background

During mid-1972, Hamilton Standard had observed that an improvement in cell power (voltage) resulted following a brief purge of the hydrogen passageway of a cell pair with nitrogen or air. It was thought that the most likely cause for the cell voltage improvement when so purged probably related to the oxidization of certain contaminants on the anode. Although this reason was the most obvious, it was recognized that additional investigation was required



A. Parametric Test No. 1
B. Reversed unit fans to correct high ΔT, resulting from improper air airflow direction.
C. Parametric Test No. 2.
D. N_2 purge 21 min., cleaned corros. off anode and cathode, sprayed with battery terminal protector
E. Parametric Test No. 3.
F. Reduced temp. from 49°F/56.5°F to 45°F/52.5°F.
G. Raised dry bulb from 52.5°F to 54.5°F.
H. 11:50 shut off fans; 12:35 restarted fans.
I. Set asf at 14.6 for asf decay test; reduced dry bulb to 52°F.
J. Stopped N_2 purge 09:50 - 10/10.
K. Discontinued cell series operation. Transferred cell #017 to Sta. A; continued cell #018 in Sta. B.
L. Reduced cell outlet pressure from 5 psig to 0.7 psig in cell 017.
M. Reduced cell outlet pressure from 5 psig to near ambient.
N. Cell 017 inserted ref. elect. in res. N_2 check 10 min. N_2 purge N_2 check.
O. Raised P_{H_2} to 5 psig.
P. Set asf to 13.8.
Q. Cell 017 P_{CO_2} = 3 mm Hg, airflow ~ 13.5 cfm, asf 10.
R. Reduced asf from 10 to 5.
S. Cell S/N 017 changed P_{CO_2} to 2.5 mm Hg, current to 13.7 amperes. Airflow reduced from ~13 to ~ 6.4 CFM, and H_2 flow increased from ~400 to 750 SCCM.
T. N_2 purge cell 017 - 7 min.
U. Cell 018 Sta. A cir. fan shut off during week due to powerstat short ΔT(DP-DP) exceeded 10

▽ CURRENT EFFICIENCY (017 & 018)
△ CURRENT EFFICIENCY (018)
◇ CURRENT EFFICIENCY (017)
□ VOLTAGE (017)
○ VOLTAGE (018)
◇ CORRECTED EFFICIENCY FOR asf INSTRUMENTATION ERROR (see para. 6.2 for discussion)

TEST 4 (S/N 017/018), VOLTAGE AND CURRENT EFFICIENCY VERSUS TIME - SHOWING VOLTAGE DECREASE RATES (JULY 5, 1972 THROUGH DECEMBER 12, 1972)

FIGURE 34

to define the mechanism causing the improvement.

Although no extended duration testing was available to fully evaluate the impact on long term testing, a basis did exist for predicting that a long term cell voltage benefit might result from a periodic (once daily) short duration nitrogen purge of the cell pair H_2 passageway. No reason was seen for damage or other adverse effects to the cell pair by such purges. Tests were made of two minute, five minute and eight hour purge duration. It was determined that the five minute purge appeared most favorable, since little or no further improvement was observed with purge durations exceeding five minutes, and the two minute purge was shown to be less effective. A system impact evaluation was made and as previously stated, it was mutually agreed with the NASA that tests #1 - #4 of the Special HDC Test program would be started imposing a daily five minute nitrogen purge, each 24 hours. The NASA - Hamilton Standard agreed on plan permitted decreasing purge frequency if warranted by test results.

It was recognized that other, perhaps more effective, techniques existed for minimizing cell voltage degradation. Hamilton Standard proposed such an investigation to the NASA in June 1972 in order that positive results of this investigation could be implemented into the Special HDC Test program. However, the NASA was unable to fund this investigation and suggested that at some future time the SSP program should sponsor it.

Discussion

Figure 35 shows the variation in series voltage and current for cell pairs 017 and 018 at various times of the day during the period September 7, 1972 through September 24, 1972. It will be observed that immediately following a five minute nitrogen purge, cell pair voltages typically increased 50 mv (one-half of the 100 mv shown since the cells were in series). Extremes in voltage rise existed over the range of 40 to 80 mv per cell pair. Accompanying the cell voltage increase, current flow is observed to increase 0.5 to 0.7 amperes following a purge.

Figure 35 also denotes those times when data was taken with respect to the time of day at which the purge was imposed. As shown, the purge was normally performed at 0800 to 0900 hours each day[1] and the data taken at 1500 to 1600 hours each afternoon, 6 to 8 hours after purging the cell pairs.

The erratic variation of current with time on any given day resulted from adjustments made in external resistance, typically done starting 1 to 2 hours before the afternoon data collection, to maintain the cell at 14 asf conditions as directed by the test plan.

[1] Except during the parametric tests, when purge times were selected to better accommodate data collection.

TEST 4 (S/N 017/018) CELL VOLTAGE AND CURRENT FLUCTUATIONS AS A RESULT OF DAILY PURGES (SEPTEMBER 7, TO SEPTEMBER 24, 1972)

(Temperature Variations Not Investigated or Corrected For)

FIGURE 35

In an overall view, figure 35 shows that:

- The immediate rise in cell voltage following nitrogen purges was rapidly dissipated (i.e., within 24 hours cell voltage decreased to its pre-purge value).

- Cell current typically increased 0.7 amperes following a purge but, as with voltage, rapidly degraded to the pre-purge current level unless maintained by external resistance change.

- Some residual gain in cell voltage may have resulted from the nitrogen purge. This is evidenced by the decay from 400 to 300 mv during the September 8 - September 11 period, during which no daily purges were made.[1]

Figure 36 shows data collected on cell pairs 017 and 018 for the 24 hour period following nitrogen purge and taken approximately one month apart. Variations in cell pair voltage (2 cell series), current density, CO_2 transfer rate, and current efficiency are shown as a function of time.

The following observations were made:

- Regarding current efficiency and CO_2 transfer rate seven hours after purge, current efficiency and transfer rates for all three cases examined were within -1% to +1.4% of pre-purge values.[2] During the 24 hours following purge only minor variations between pre- and post-purge values were observed.

- Regarding cell power (product of current and cell voltage. the cell power improvement observed immediately following nitrogen purge of cell pairs varied over a wide range (9 to 115% increase) for the three cases examined; however, after 16 - 24 hours little or no residual improvement over pre-purge power (voltage) was observed.

Figure 37 displays the same parameters as figure 36 versus time. Data was taken every fifteen minutes for a two hour period following the nitrogen purge of the non-reservoir cells. The figure shows that following a small and brief (10 to 25 minute) improvement in CO_2 transfer rate and efficiency after nitrogen purging, these two parameters show a net decrease during the next one to two hours.

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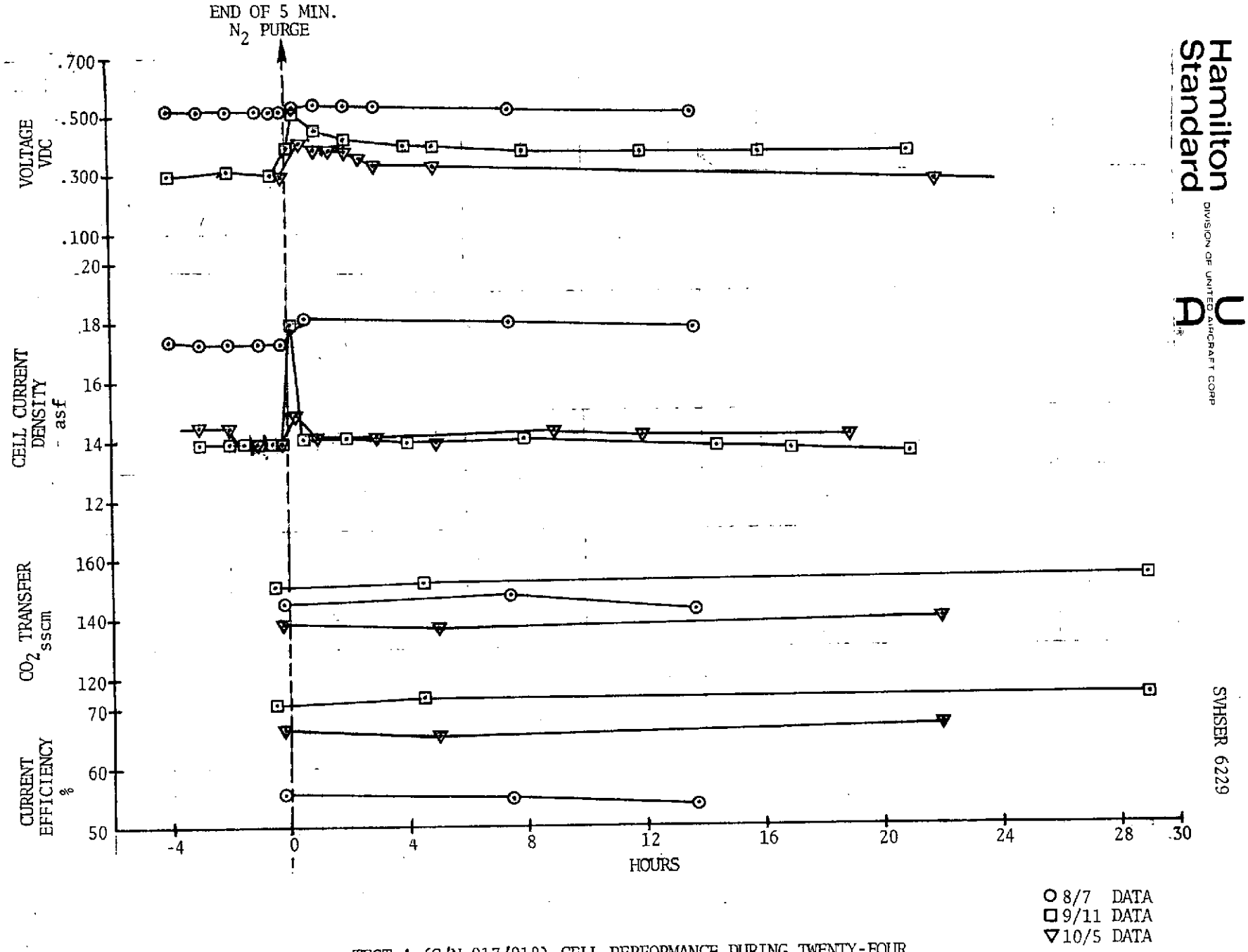
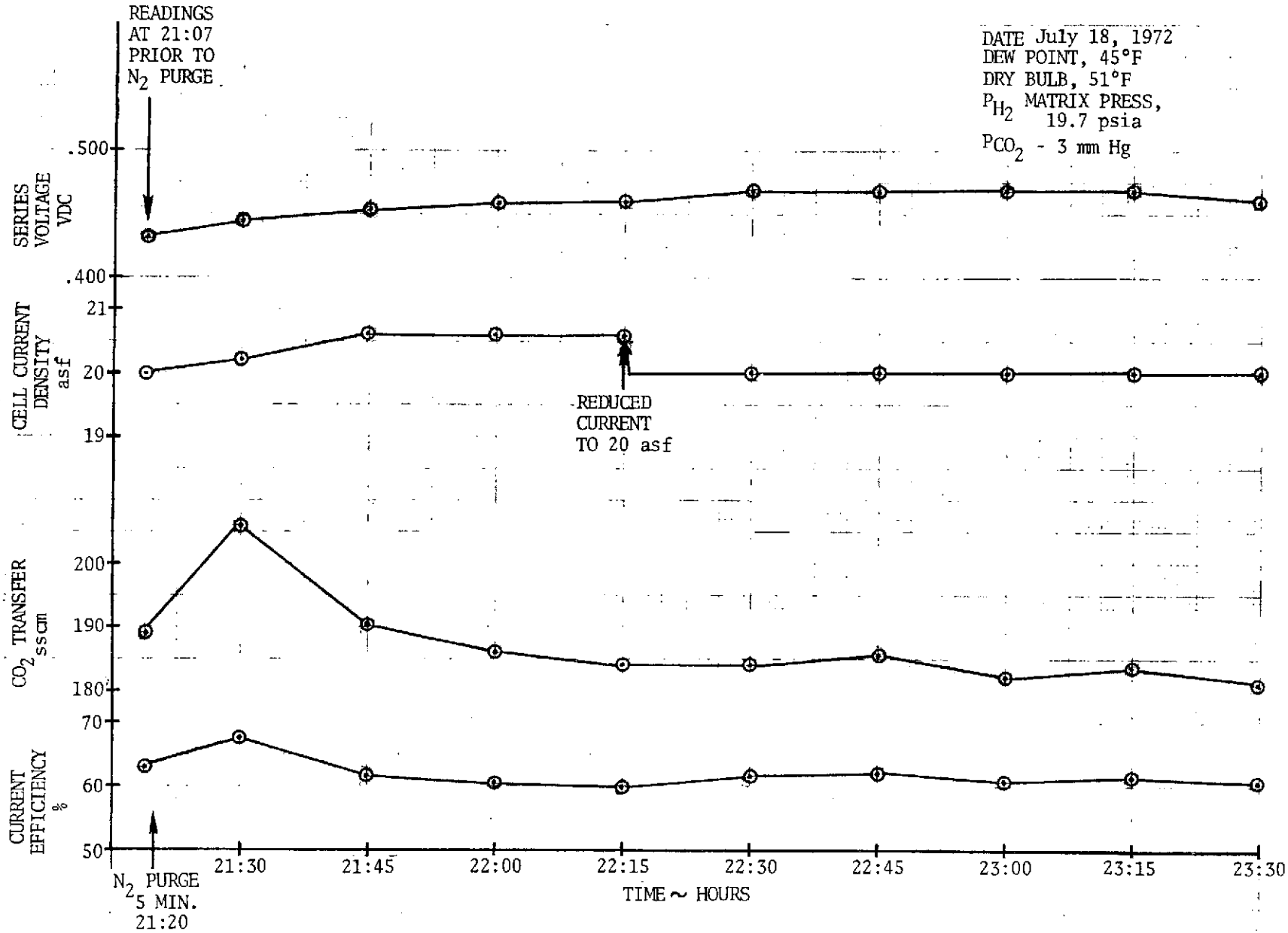
[1] Figure 35 shows that cell pair voltages, taken between "purge-to-purge" points, are typically unchanged from day-to-day.

[2] Data readings during the first five months of testing typically were taken 6 to 8 hours following purge.



TEST 4 (S/N 017/018) CELL PERFORMANCE DURING TWENTY-FOUR HOUR PERIOD FOLLOWING N_2 PURGING, AUGUST - OCTOBER 1972

FIGURE 36



TYPICAL N_2 PURGE PERFORMANCE DATA DURING THE FIRST HOUR AND 45 MINUTES AFTER PURGE CELL PAIRS S/N 015 AND S/N 016-1

FIGURE 37

Following the cessation of nitrogen purges on cell pairs 017 and 018 on October 12, 1972 (after approximately three months of daily purges), it is noted from figure 23 that each cell pair voltage level dropped by approximately 60 mv as a step change.

With reference to figure 23, although CO_2 transfer rate and CO_2 current efficiencies did drop by 4% and 5-1/2%, respectively, during the first week following the cessation of all nitrogen purging on October 12, 1972, this drop may have been associated with the air delta T being changed from 54.5°F/45.5°F to 51.3°F/45°F (dry bulb/dew point temperatures, respectively) on October 12, 1972. The subsequent return (two to three weeks later) to the 71% efficiency level achieved before stopping the purges gives evidence that periodic purging does not benefit cell efficiencies.

Conclusion - Effect of Purging on Cell Voltage

It is concluded that the periodic nitrogen purges performed daily on test cell pairs during this special test program resulted in a 50 to 60 mv per cell pair voltage improvement over the voltage which would have been achieved without the purge. No basis exists, of course, to establish whether the periodic nitrogen purges contributed to the higher than expected voltage (power) degradation rate, although no reason was initially seen to suspect that it would. It is obvious from examination of cell voltage versus time characteristics following purge cessation, that if the periodic purges did adversely affect voltage degradation rate,[1] the "purge-related" mechanism by which this occurs is irreversible.

It is emphasized that cell voltage level is not important until and unless it falls to such a low level (20 mv for a 36 cell pair Hamilton Standard subsystem) that insufficient current causes an inadequate CO_2 removal rate.

Periodic Purge Effects on CO_2 Transfer Rate and Efficiency

Only minor (1 to 2%) variation in both the CO_2 transfer rate and current efficiency resulted following each of the daily purges in this test program. From a long term standpoint, no evidence exists to show that purging improved

[1] This point is mentioned since no reason has as yet been established to explain why the degradation rates for all cell pairs used in this program exceed the rate observed in cell pair 010. Although other differences did exist which might account for this discrepancy, the periodic nitrogen purge is one of the more obvious.

CO_2 transfer rates or current efficiencies. Based upon examination of test results, it is concluded that data gathering 6 to 8 hours following the daily purges was valid, and did not result in the recording of optimistic data. In two of three cases examined closely in this section, current efficiencies calculated from 6 to 8 hour data were actually slightly lower than the efficiencies derived from data taken immediately before purge.

GAS ANALYSES

This section gives the results of chemical analyses performed by Analytical Research Laboratories, Inc., on four gas samples.

- A Hamilton Standard Electrochemical Laboratory air sample;
- An air sample from within the test chamber which housed the cell pair being evaluated;
- The cell H_2 plus CO_2 discharge stream during a purge of the cell with nitrogen; and
- Same as the third item above except not during nitrogen purge.

It had been an expressed concern of the NASA, that voltage degradation experienced by Hamilton Standard cell pairs may be caused by poisoning of the electrodes. Such poisoning, if it did exist, could give rise to voltage degradation with time and could result from any or all of the following sources:

- Contaminants built-in to the cell during assembly;
- Contaminants in the room carrying into the test chamber and subsequently poisoning the cell through adsorption at the electrodes;
- Contaminants added to the cell at the anode through impurities contained in the hydrogen gas.

Every attempt was made during the course of this special test program to eliminate those sources of cell contaminants which might detrimentally affect cell performance. The following actions were taken:

Cell Pair Assembly

(avoidance of built-in contaminants)

Electrolyte was evaluated electrochemically to verify that it was free of contaminants which might poison the electrodes.

The matrix was pre-cleaned and subsequently verified by electrochemical test to be non-poisoning to the electrodes.

Room Contaminants

Particulate and charcoal filters were incorporated within the test chambers (Note: charcoal filters subsequently were removed when it was determined that they were adversely affecting cell air inlet humidity).

An attempt was made to reduce air leakage between test chambers and the laboratory. Because of the inherent construction of the test chambers these attempts were unsatisfactory. The leakage rate of test chamber D, a relatively tight chamber, was found to be about 0.25 sccm air/second; rates of test chambers A, B and C were significantly and immeasurably higher.

Hydrogen Contaminant Poisoning

Because of funding restraints, NASA and Hamilton Standard jointly agreed that a chemical analysis of the hydrogen sypply gas would not be required. It was believed that sampling of each cylinder was impractical (200 - 240 scf gas cylinders of H_2 were employed by the test facility and were consumed at the approximate rate of one cylinder every 3 to 4 days) and that a review of the purity analysis from the H_2 supplier would be satisfactory. Data obtained from the supplier showed no significant percentage of any contaminant adjudged to be detrimental to cell performance. A subsequent analysis performed at United Aircraft Research Laboratory employing a Dohrmann Sulfur Analyzer, showed less than 0.05 ppm sulfur content in the Hamilton Standard H_2 supply.

Floating electrode and potential sweep electrochemical tests, performed upon cell pairs S/N 015 and S/N 016-1 (the non-reservoir cell pairs of this test program) and upon the cells during the five to six month test period, did not indicate an electrode poisoning problem. The operating characteristics of these electrodes do not appear to have degraded compared to new electrodes. However, exposure of the anode to air during cell disassembly might result in the oxidation of impurities off the anode. This type of poisoning would not have been detected in the subsequent electrochemical tests, so that anode poisoning cannot be completely ruled out.

Appendix E gives the results of the gas analysis.(1) The organic compounds present in significant amounts should be readily oxidized at the HDC electrodes, and no short term poisoning would be expected from these materials. Of the inorganic impurities sulfur dioxide (SO_2) is the one most likely to cause trouble, although it is thermodynamically unstable in the HDC environment toward oxidation to sulfate (cathode) or reduction to sulfide (anode). Even so, significant a amounts of SO_2 (SO_3^{-2}) could accumulate in the electrolyte before the rate of oxidation or reduction becomes equal to the rate of absorption from the air stream.

(1) Assorted gas analyses were taken on August 27, 1972, November 10, 1972, and December 1972. Appendix E tabulates the results of each analysis and describes where and under what conditions it was taken.

Analysis of the chamber air showed 21 ppm SO_2. Since SO_2 is an acid gas, one would expect it to be transferred from the air stream to the hydrogen stream in the HDC cell just as CO_2 is transferred. An analysis of the hydrogen stream for SO_2 during normal operation shows that 1.1% of the SO_2 in the air stream is being discharged into the hydrogen stream. From air mass transport considerations one would expect a scrubbing efficiency considerably greater than 1%, so it seems likely that SO_2 is accumulating in the electrolyte. Also, under HDC operating conditions SO_2 would be reduced to sulfur or sulfide at the anode and a closed circuit nitrogen purge at the anode chamber would oxidize the sulfur back to SO_2. This seems to be the case, since an analysis of the nitrogen purge gas showed 1980 ppm SO_2 whereas only 24 ppm SO_2 were found in the hydrogen stream during normal operation.

It is believed that if any catalyst poisoning did occur during the six months extended test, it's contribution was in fact small. Figure 38, attached to the next section of this report, shows that on November 11, 1972, the voltage on cell pair S/N 017 was restored to ~250 mv following a three minute evacuation of the hydrogen passageway of the cell and subsequent repressurization to 0 psig. The restoration of voltage level to the aforementioned level after four months of continuous operation, is felt to rule out poisoning of the electrode as a significant contributor to voltage degradation.

IR & D ACTIVITIES

A number of Hamilton Standard IR & D funded tasks were undertaken during the last half of 1972. The more significant of these tasks, together with general observations and conclusions are outlined in this section. A more detailed discussion of tasks 1, 2 and 6 below is provided elsewhere in this text.

TASK DESCRIPTION	GENERAL OBSERVATIONS OR CONCLUSIONS
1. Extend the test of cell pairs S/N 017 and S/N 018 from the period September 22, 1972 through December 31, 1972.	The additional test time provided proof, as had been characteristically observed in previous tests, that • cell current efficiency does not degrade with operating time. • cell operating voltage (or power) decay rate, decreases with time, and as with cell pair S/N 010 either approaches or reaches a point where no further decrease is observed. As is discussed, page 42 in this report, it was demonstrated that sufficient voltage did exist to accommodate the necessary CO_2 removal requirements for the SSP (for reduced current density operation).
2. Perform additional chemical analysis to establish SO_x and NO_x concentrations in the effluent H_2 + CO_2 stream, by nitrogen purging.	Whereas about 2000 ppm of SO_x was observed in the cell effluent during a nitrogen purge of the cell, only 19 to 23 ppm were observed in the effluent stream when not purged with nitrogen. This and other results of the chemical analysis are discussed in Appendix E of the report.
3. Perform mechanical pre-bending of cell pair housings to provide uniform electrode-gap, matrix compression and current density in the cell.	One set of cell pair housings was pre-bent to demonstrate that the HS cell pair configuration could be assembled per the SSP configuration to eliminate "bowing" of both the upper and lower cell housing surfaces. The aforementioned housings when assembled per print, had a "bow" of only 0.000in.- 0.005in.(instead of the customary .025in.- .035in.) when measured across the 6 inch cell width. No variation was observed as H_2 pressure was increased to 5 psig.

The procedure developed to prestress the housings, would accommodate a nearly uniform matrix compression/electrode gap, and therefore current density, over the entire cell area.

4. Evaluate specific electrode structures for further reducing cell voltage degradation rate.

Various cell assemblies were made and electrochemical tests performed to allow evaluation of the effects of

- PPF (P&W) electrodes.
- varying the electrode pretreatment options.
- varying the density of catalyst applied to the electrode.

Results of these tests permitted the definition of a cell pair (see IR & D task #5 below) which should yield a voltage decay rate lower than that which had been observed on cell pairs S/N 017 and S/N 018.

5. Build-up cell pair S/N 019R to evaluate the effectiveness of electrochemical studies (Task #4) in reducing voltage degradation rate.

To evaluate the candidate anode configuration (developed in task #4 above) designed to reduce voltage degradation rate, cell pair S/N 019R, a reservoir cell pair, was built employing a PPF anode, and "clamped" housings to provide a uniform current density/matrix compression which would not vary with operating time due to cell spacer cold flow. It was subjected to test on November 24, 1972.

Cell pair S/N 019-R was further equipped with a new cathode configuration previously untested, to allow evaluating that configuration upon current efficiency. It was thought that the new cathode configuration would not compromise the voltage degradation measurement objective of the test.

Sixty days after the test start, cell pair voltage and power were 0.275 volts and 5.0 watts, respectively under an 18 asf current density.

Although the current efficiency was low (40 to 50%), demonstrating the ineffectiveness of the new cathode, the primary test objective orientated toward achieving the reduced voltage degradation rate appeared successful. The voltage degradation rate was substantially lower, 16 microvolts/hr (μv/hr), than had been achieved on cell pairs S/N 017 and S/N 018.

Additional operating time and a post test examination of cell pair S/N 019-R will be required before firm conclusions can be reached, but it is significant that the cell, operated continuously with 5 psig H_2 back pressure and other typical SSP inlet conditions, had a relatively low voltage degradation rate.

6. Perform cell purge investigations.

As discussed within this report, various investigations were made under the HS sponsored IR & D program to determine the effectiveness of specific techniques in restoring voltages to the initial cell operating level. Among the techniques evaluated in the IR & D program were:

- open circuiting the cell for various time periods.
- nitrogen purges of various durations.
- cathode electrochemical oxidization at different voltage levels (1.6 to 2.5 volts).
- electrical driving of both cathode and anode.
- increasing the cell temperature by discontinuing air flow through the cell pair for sixty minutes; this resulted in increasing cell pair electrolyte temperature to about 100°F.

The aforementioned evaluations were made upon cell pair S/N 016-1, and are discussed in some detail on page 39 of this report. It was generally observed that once significant voltage degradation had occurred, none of the aforementioned techniques were successful in causing permanent voltage restoration to the initial operating level.

Figure 38 shows a technique which was employed on cell S/N 017 and which produced significant voltage improvement. Figure 38 shows that on November 11, 1972, cell pair S/N 017 was self evacuated (closing off H_2 flow to cell causes a reduction in that pressure below ambient), and subsequently repressurized to various pressure levels. As is noted, the cell voltage achieved at 0 psig (zero matrix ΔP), approached the initial 300 mv of the cell when first subjected to test four months earlier. Although further effort is being directed at additional investigation, the figure seems to rule out the possibility that catalyst poisoning is responsible for the voltage degradation observed during the extended duration test.

A. Self evacuation of cell - H_2 flow off; PH_2 to ~ 10.7 psia
B. 5 psig.
C. 3 psig.
D. 2 psig.
E. 0 psig.

TEST 4 (S/N 017) CELL VOLTAGE - CURRENT AFTER EVACUATING

APPENDIX A

MEASUREMENT ERROR ANALYSIS

MEASUREMENT ERROR ANALYSIS FOR HAMILTON STANDARD HYDROGEN DEPOLARIZED CELL PAIR TEST FACILITY

June 23, 1972

ERROR ANALYSIS

Chamber CO_2

A. Cal Gas

1. Absolute Accuracy	± 1%
2. Variability Due to Stratification	Negligible
3. Variability Due to No. of Cal Points	Negligible

B. Lira Analyzer

1. Accuracy Total (± 2% F.S.) at 40% F.S.	± 5% Reading
2. Readability	±1/2% Reading
3. Temperature, Humidity, Pressure, Flow	Negligible

C. Simpson Controller

1. Resolution Band ± 0.5 Part out of 40	± 1.25%

RSS = ± 5.27%

CO_2 Concentration in Effluent Stream

D. Cal Gas

Same as A.	± 1%
	Negligible

E. Lira Analyzer

1. Accuracy Total (± 2% F.S.) at 80% F.S.		± 2.5% Reading
2. Readability		± 1/2% Reading
3. Temperature (50°F to 80°F)	Estimate	± 1/2% Reading
4. Humidity, Pressure and Flow		Negligible

RSS = ± 2.78%

Flow

F. Volume Measurement

1. Vessell Readability (± 5 cc/500 cc)	± 1%
2. Temperature	± 2.5%
3. Pressure (± 1" H_2O/15 psia), Humidity	Negligible

G. Time

1.	Coordination Variability (± 1/2 sec/60 sec)	± 0.8
2.	Accuracy	Negligible
		RSS = ± 2.81%

CO_2 Transfer Rate

In order to establish the measurement error for the rate at which carbon dioxide (CO_2) is actually being transferred, it is necessary only to examine the errors associated with the mass flow rate of the total effluent stream ('F' & 'G', above) and the concentration of CO_2 in the effluent ('D' & 'E'). Accordingly,

$$\text{RSS}_{CO_2 \text{ Transfer Rate}} = \sqrt{(D + E)^2 + (F + G)^2}$$

$$= \sqrt{(2.78)^2 + (2.81)^2}$$

$$= 3.95\%$$

APPENDIX B

COMPUTER PROGRAM & PERFORMANCE PREDICTIONS

CONTENTS

[1] Performance predictions were reduced to Microfiche. One copy of the Microfiche cards was transmitted to NASA JSC and the master set plus one copy are being retained at Hamilton Standard.

DESCRIPTION OF H543 COMPUTER PROGRAM

A brief description of the Hamilton Standard Cabin CO_2 Partial Pressure Computer Program is included in this report, since the program was employed in the analytical examination of the HDC performance requirements and the relationship between these requirements and the performance of cells evaluated in this program.

H543 predicts the partial pressure of CO_2 in a one cabin compartment as a function of time. Basically, the required input is the CO_2 generation rate as a function of time, the initial CO_2 partial pressure, cabin volume, and CO_2 removal rate as a function of CO_2 partial pressure.

H543 was designed by the Space Systems Department of Hamilton Standard Division, United Aircraft Corporation for the IBM 370 system in Fortran IV language.

The computer program simulates a CO_2 collection device which is placed in a closed cabin of given volume. The cabin has an initial CO_2 partial pressure. CO_2 is generated at a variable rate which is given as a step function of up to ten different rates per day. CO_2 is removed by the collection device as a function of CO_2 partial pressure and a table of CO_2 removal rate versus CO_2 partial pressure derived from test data is input which allows interpolation of the first to third degree. A mass balance is made of CO_2 for every time step and a new partial pressure is calculated for the next time step. The program can be run at simulated cell constant current conditions, or at constant electrical load,which is more representative of the SSP system.

In addition to predicting CO_2 partial pressure, the program prints out: CO_2 removal rate; cumulative CO_2 removed for one day; O_2 use rate (the CO_2 collection device generates electrical current by combining O_2 and H_2 to form water); cumulative O_2 used for one day; H_2O generated for one day; and instantaneous H_2O generation rate. Current and voltage generated, and currency efficiency also are printed out.

RESULTS OF COMPUTER PREDICTIONS BASED UPON CELL PAIR 010 PERFORMANCE AFTER SIX AND ONE-HALF MONTHS OF OPERATION

INTRODUCTION

During the period June 14 to June 16, 1972, non-reservoir cell pair 010 was subjected to a parametric test under varying CO_2 inlet partial

pressures and varying current densities over the range of 16 to 24 amps per square foot (asf). The resulting CO_2 removal rate, shown in figure B-1, was input to the H543 Computer Program, to answer four basic questions, as follows:

1. What is the performance required of the Hamilton Standard Hydrogen Depolarized Cell (HDC) CO_2 Collection Configuration to maintain the SSP at or below P_{CO_2} = 3.00 mm Hg, considering the maximum allowable O_2 use rate? It was known that the maximum permitted number of cell pairs for the SSP application and based upon packaging limitations exceeds fifty.

2. Using cell pair 010 performance on the aforementioned test data, what is the number of cell pairs required to maintain the cabin P_{CO_2} at or below 3.00 mm Hg.

3. What is the performance required to maintain the cabin P_{CO_2} at or below 3.00 mmHg using 33 cell pairs?

4. What is the quantity of O_2 used at 20 asf to maintain the cabin P_{CO_2} at or below 3.00 mmHg, assuming cell pair 010 performance?

Answers to questions one through four are summarized in the following paragraphs.

NOTE: Paragraph numbers correspond with questions above.

1. Maximum O_2 available for HDC (O_2) = 14.53 lb/day[1].

   Number of Cell Pairs: 43 cell pairs removing 13.2 lb/day CO_2
   46 cell pairs using 14.53 lb/day of O_2

   Current efficiency at maximum inlet P_{CO_2}:

$$48.5\% \text{ at } 2.8 \text{ mmHg} = \frac{CO_2 \text{ at 43 cell pairs}}{O_2 \text{ at 43 cell pairs}} \times \frac{16}{44}$$

   Percent of present cell pair 010 performance: 83.5% curve of CO_2 removed versus P_{CO_2} for a constant resistance at a nominal current density of 20 asf, was multiplied by 0.835.

2. a) O_2 consumed = 10.9 lb/day with 39 cell pairs at nominal 17 asf.

   Number of cell pairs: 36 cell pairs removing 13.2 lb/day CO_2.
   39 cell pairs using 10.9 lb/day O_2.

[1] See page B-5

$$0.638 \text{ at } 2.83 \text{ mmHg} = \frac{W_{CO_2} \text{ at 36 cell pairs}}{W_{O_2} \text{ at 36 cell pairs}} \times \frac{16}{44}$$

Percent of present cell pair 010 performance: 100%

b) O_2 required: 13.1 lb/day with 39 cell pairs at nominal 21 asf.

Number of cell pairs: 36 cell pairs removing 13.2 lb/day CO_2.
39 cell pairs using 13.1 lb/day O_2.

Current efficiency at maximum inlet P_{CO_2}: 0.556 at 2.68 mmHg.

Percent of present cell pair 010 performance: 100%.

3. O_2 required: 11.45 lb/day with 36 cell pairs at nominal 20 asf.

Number of cell pairs: 33 cell pairs removing 13.2 lb/day CO_2.
36 cell pairs using 11.45 lb/day O_2.

Current efficiency at maximum inlet P_{CO_2}:

$$0.63 \text{ at } 2.85 \text{ mmHg} = \frac{W_{CO_2} \text{ at 33 cell pairs}}{W_{O_2} \text{ at 33 cell pairs}} \times \frac{16}{44}$$

Percent of cell pair 010 performance: 106.75% curve of W_{CO_2} removed versus P_{CO_2} for a constant resistance at a nominal current density at 20 asf, was multiplied by 1.0675.

4. O_2 required: 12.15 lb/day with 36 cell pairs at nominal 20 asf.

Number of cell pairs: 36 cell pairs removing 13.2 lb/day CO_2.
39 cell pairs using 12.15 lb/day O_2.

Current efficiency at maximum inlet P_{CO_2}:

$$0.58 \text{ at } 2.8 \text{ mmHg} = \frac{W_{CO_2} \text{ at 36 cell pairs}}{W_{O_2} \text{ at 36 cell pairs}} \times \frac{16}{24}$$

Percent of cell pair 010 performance: 100%.

Basis for Calculations

Maximum Cabin P_{CO_2} = 3.0 mmHg

Maximum HDC Inlet P_{CO_2} = 2.85 mmHg

CO_2 generation rate 13.2 lb/day average

9.63 lb/day for 16 hours
20.3 lb/day for 8 hours

Cabin volume = 8000 ft^3

Maximum O_2 available for HDC

SSP Requirement O_2 generation for continuous operation

6 men x 1.84 lb/day	11.03 lb/day
O_2 leakage	4.11 lb/day
Contingency 10%	1.52 lb/day
Requirement	16.66 lb/day

O_2 generation subsystem design point 1.3 lb/hr = 31.2 lb/day

O_2 available from O_2 Generation Subsystem	31.20 lb/day
Less O_2 for metabolic + leakage + contingency	-16.66 lb/day
O_2 available for HDC consumption	14.53 lb/day

Discussion of Results

The performance of cell pair 010 following seven months of operation is as characterized in figure B-1. Figure B-1 depicts performance of cell pair 010 at nominal currents of 17, 21, and 23 amps/ft^2 (asf) for varying CO_2 inlet partial pressures. In view of the fact that the Hamilton Standard hydrogen depolarized cell and system is planned to operate under essentially constant external load resistance, cell current was allowed to vary during the figure B-1 tests, as CO_2 pressure was reduced below 3.0 mmHg.

To be conservative, the lower performance "leg" of the figure data was used in inputting cell performance for each of the three currents into the computer program.

A performance curve for a nominal 20 asf was obtained by interpolation of curves A, B, and C.

The maximum allowable number of cell pairs was determined from the maximum O_2 use rate (14.53 lb/day) and Faraday's Law

14.53 lb/day = .0762 gms/second.

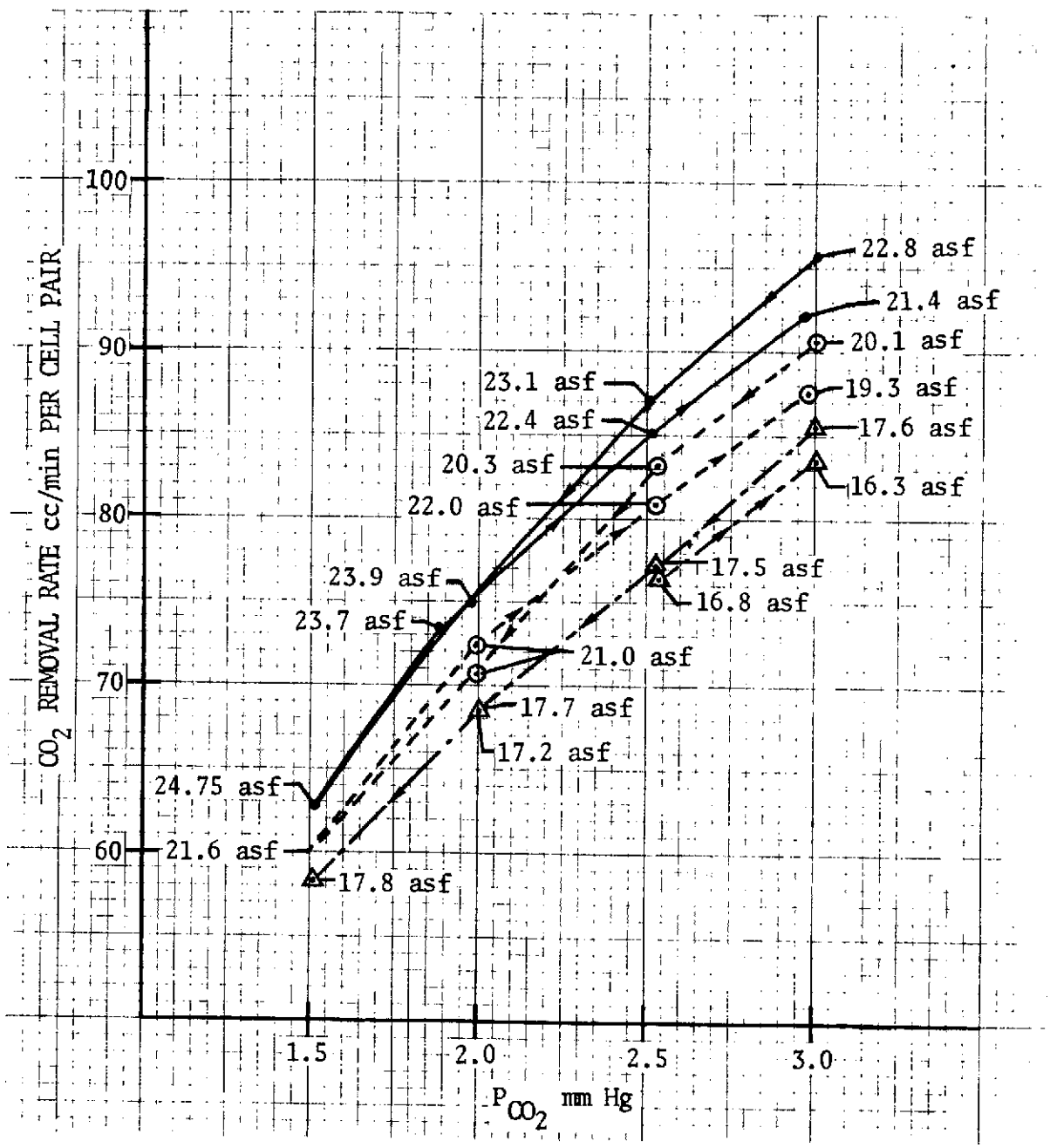

CO_2 REMOVAL RATE cc/min PER CELL PAIR
100
90
80
70
60
1.5
2.0
2.5
3.0
P_{CO_2} mm Hg
22.8 asf
21.4 asf
20.1 asf
19.3 asf
17.6 asf
16.3 asf
23.1 asf
22.4 asf
20.3 asf
22.0 asf
17.5 asf
16.8 asf
23.9 asf
23.7 asf
21.0 asf
17.7 asf
17.2 asf
24.75 asf
21.6 asf
17.8 asf

FIGURE B-1

$$I_{max} = \frac{W_{O_2} I}{e} = \frac{.0762 \quad 96500}{16/2} = 922 \text{ amps}$$

$$\text{Area allowable} = \frac{922 \text{ amps}}{20 \text{ asf}} = 46 \text{ ft}^2$$

At 1 sq ft/cell pair, = 46 cell pairs

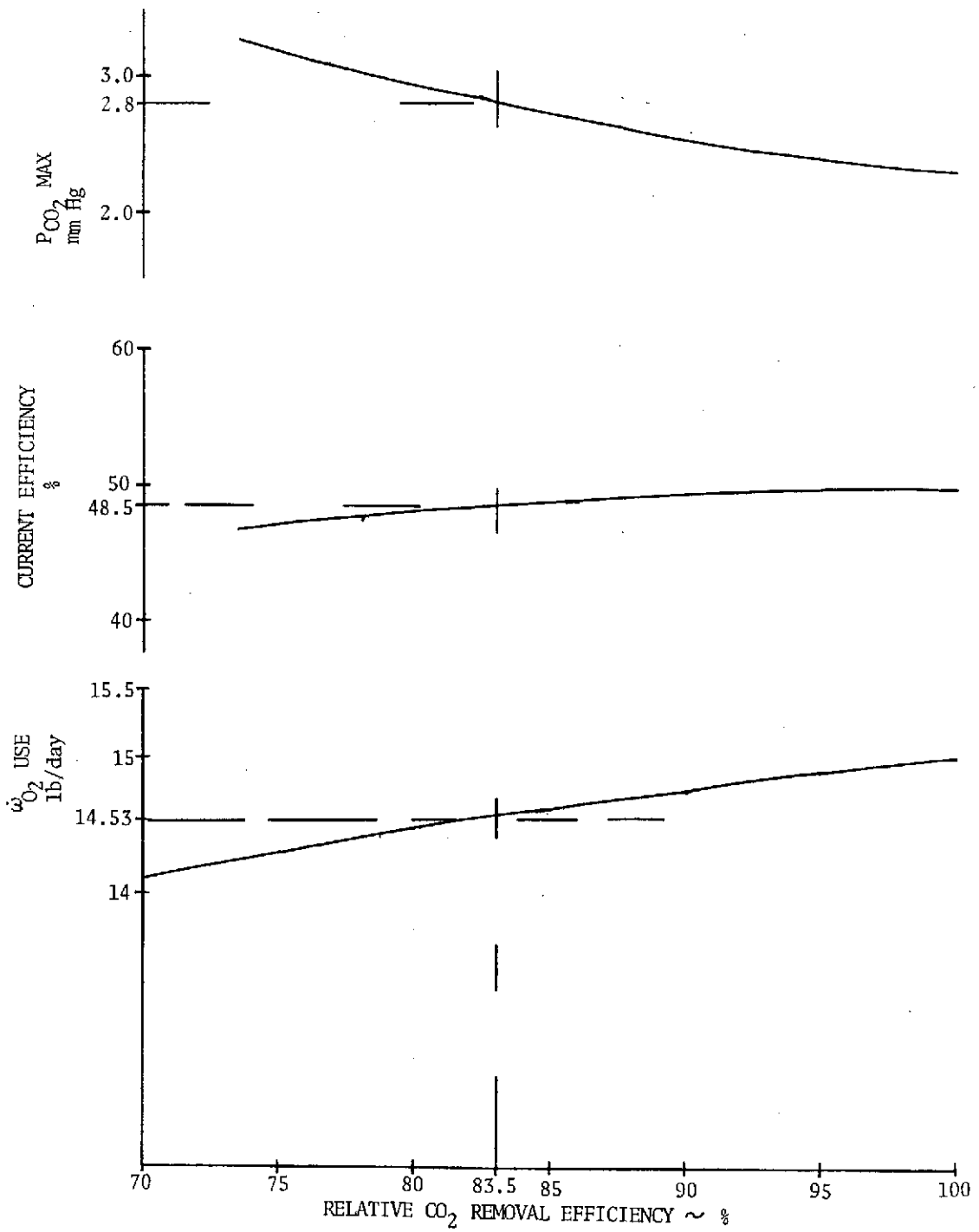
Per NASA request, three additional cell pairs should be included. Allowing three cell pair contingency, leaves CO_2 removal capability of 43 cell pairs but O_2 consumption of 46 cell pairs.

In answer to question one, runs were made at 75, 85, 90 and 100% of cell pair 010 performance. P_{CO_2}, current efficiency, and O_2 use rate were plotted. The cell efficiency requirement is determined from the curves and corresponds to that point where oxygen consumption equaled 14.53 lb/day. (See figure B-2).

In answer to question three, runs were made at 100, 105, 110 and 115% of cell pair 010 performance. P_{CO_2}, current efficiency and O_2 use rate were plotted. The cell efficiency requirement is defined as that point on the curve where P_{CO_2} = 2.85 mm Hg. (See figure B-3).

COMPUTER PERFORMANCE PREDICTIONS BASED UPON RESULTS OF THIS TEST PROGRAM

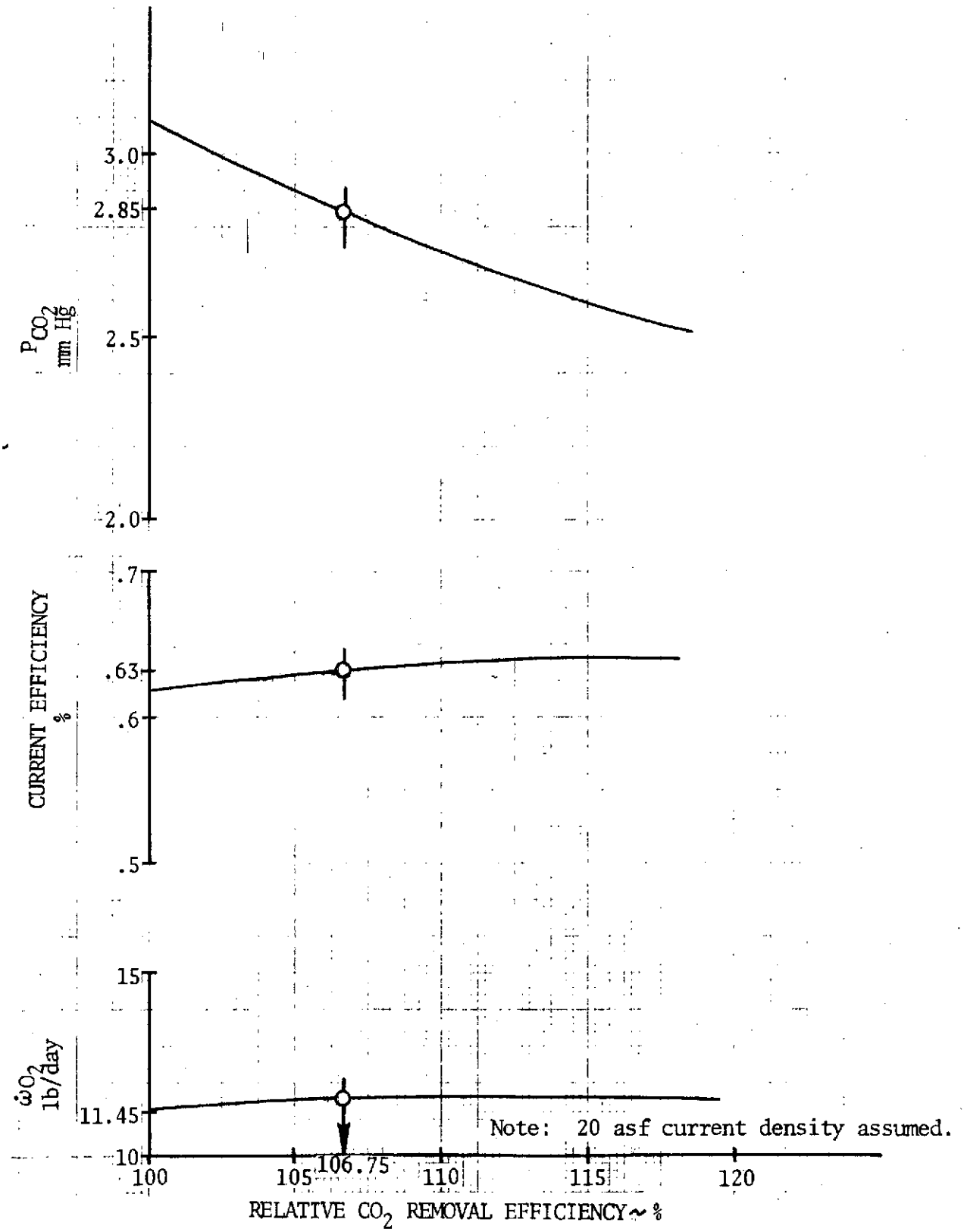
See Microfiche cards.



PERCENT OF CELL S/N 010'S PERFORMANCE REQUIRED USING
43 CELL PAIRS FOR SSP APPLICATION

108<

FIGURE B-2



PERCENT OF CELL S/N 010'S PERFORMANCE REQUIRED USING
33 CELL PAIRS FOR SSP APPLICATION

FIGURE B-3

APPENDIX C

TEST PLAN

HYDROGEN DEPOLARIZED CELL PAIR

TEST PLAN

CONTRACT NAS 9-12920

by

HAMILTON STANDARD

DIVISION OF UNITED AIRCRAFT CORPORATION

WINDSOR LOCKS, CONNECTICUT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

July 6, 1972

Written by C. R. Russell 7-6-72
Program Engineer

Approved by P. H. Greenwood
Program Manager

1.0 GENERAL INFORMATION

1.1 Scope

This plan describes the test program, including test equipment to be used, in demonstrating the operability of the Hamilton Standard designed Hydrogen Depolarized Cell. It further is intended to collect such other engineering data so as to enable the determination of the number of cells necessary to support a crew of six men for a six month mission. The test program described herein will be run under funding from NASA/MSC Contract NAS 9-12920, and will be conducted at the Hamilton Space Systems Department Test Facility.

1.2 Applicable Documents

(1) Memo, "Test Plan for Design Definition and Documentation Testing of the HSD CO_2 Concentrator Cell Pair for SSP", by C. Russell and W. Sanderson, dated 6/17/72.

(2) HDC Cell Pair Assembly SVSK 84460

1.3 Functional Requirements/Description

HDC Pair

The HDC cell pair, defined by SVSK 84460, removes CO_2 from cabin air and discharges the CO_2 thus removed into a H_2 stream. The process is electrochemical. Nominal operating conditions of a single HDC cell pair are:

Air Flow through Cell Pair, nominal	7.5 CFM
Inlet Air Temperature, nominal	T_{DP} + 6/+8°F
Inlet Humidity (Dew Point)	41 - 49°F
Hydrogen Flow Rate (at cell inlet)*	900-1200 SCCM
Ambient CO_2 level, nominal	2.5 mmHg
Current Density, nominal	20 ASF

* 3 cell pairs in series; inlet for first cell shown

2.0 TEST PLAN AND PROCEDURES

Testing described by this plan, consist of cell pair configuration tests (#1 - #3), and a parametric and endurance test (#4). All tests are described in subsequent paragraphs. Figure A shows the test and program schedule.

2.1 Test Facility Schematic and Instrumentation

Enclosure 1 is the schematic of the test facility. The facility encompasses test stations A, B, and C. Enclosure 2,[1] is the 3 σ error analysis of critical measurements (P_{CO_2} in chambers; concentration of CO_2 in H_2 discharge stream from the test articles; volumetric flow of the CO_2 + H_2 discharge stream; and, total CO_2 transport rate (removal rate). Table I presents a tabulation of the test rig instrumentation.

2.2 Configuration Tests

(Tests No. 1, 2 and 3) will be done prior to the parametric and endurance test. Data from these tests will be used to define the reservoir and non-reservoir cell configurations to be evaluated in test #4.

Specific cell configuration options, which need some additional evaluation, are:

(1) The use of sputtered vs electroplated electrodes, (to be evaluated in test #1).

(2) The validity of using those cell pair housings during this test program which were subjected to full temperature anneal during fabrication and might consequently unfavorably influence cell pair performance (to be evaluated in test #1).

Note: Through an error, subject housings were not cleaned of machine oil prior to anneal, and resulting discoloration indicated that certain hydrocarbon poisons and adverse resistivity effects could have resulted.

(3) Verification that small matrix thickness variations (+0.002") such as could arise between cells from tolerance build-up will not significantly impact cell performance. (Test #2).

(4) Demonstration that a reservoir cell all-asbestos matrix, will maintain performance under a 4°F step change in inlet temperature. (Test #3).

[1] Included in this report as Appendix A.

FIGURE A

SVHSER 6229

TEST LOCATION	CELL S/N	
A & B	15, 16	TEST 1 — HOUSING & SPLITTERED ELECTRICAL CONFIG TEST
C	19	TEST 2 — MATRIX COMPRESSION CONFIG. TEST
D	11	TEST 3 — RESERVOIR #011 CELL PAIR TEMP. REBOUND TEST.
D/B	17, 18	
A&B	15 & 16 (in series), 17 & 18 (in series)	

MOVE CELLS '15' & '16' INTO STA A ON 7-6/7-7 AT COMPLETION OF TEST #1 @ RUN @ 45°F DP/ 51°F DP UNTIL START OF TEST 4.

MOVE CELLS '17' & '18' INTO STA B ON 7-6/7-7 AT COMPLETION OF TEST #1 and RUN @ 46°F DP/ 51°F DP UNTIL START OF TEST 4.

114A

RESERVOIR CELL START-UP

CONTINGENCY

TEST 4 — 6 wk min. Time

PARAMETRIC & ENDURANCE TEST (7 wk TEST)

12 16 20 24 28 | 2 6 10 14 18 22 26 30 | 4 8 12 16 20 24 28 31

JUNE '72 — July '72 — August '72

ACTION ITEM (START ▲ COMPLETE ▲)

A. MODIFY TEST FAC.
- (a) SLIDE WIRE CURRENT ADJUST
- (b) DUST FILTER & MANIFOLD LEAKAGE
- (c) 1st order error analysis
- (d) Run P_{O_2} decay

B. TEST PLAN (PREL.) ▲ (FINAL) ▲

C. ADMIN. ROM (PREL.) ▲ CR&D PROG PLAN (PREL.) ▲ CR&D PROG PLAN (FINAL) ▲

D. PURGE DEFINITION HDC SSP SYSTEM IMPACT STUDY. COMPLETE ▲

by — NASA: W.H. Sanderson 6/27/72
IBM: C.R. [illegible] 6-17-72

FIG A

HDC CR&D TEST & PROGRAM SCHEDULE

REVISED 6-17-72

TABLE I

Instrumentation

Measurement	Instrument	Range & Readout
Temperature, cell air inlet and outlet dry bulb [°F]	Thermocouple, Cu-Con Bristol Indicator MOD 048P12G572-21	0°F to 150°F (1°F increments)
Temperature, cell air inlet, dew point [°F]	Cambridge MOD 880 Dew Point Hygrometer	-40°F to 120°F (2°F increments)
Temperature, hydrogen, inlet [°F]	Thermocouple, Cu-Con Bristol Indicator	0°F to 150°F (1°F increments)
ΔP, air, across cell pair ["H_2O]	Slant Manometer Ellison Instr, 0-2" F. W. Dwyer, 0-2"	0-2" H_2O; 0.02" increments -0.2 to 2" H_2O; 0.01" increments
Pressure, CO_2 cell inlet	MSA LIRA Gas Analyzer, MOD 300 infrared analyzer	0 to 100% (3" scale) 2% increments
Pressure, P_{CO_2} in H_2 stream (cell discharge)	MSA LIRA Gas analyzer	0 to 100% (3" scale) 2% increments
Pressure, H + CO_2 discharge (matrix) (PSIA)	Pressure gauge, Heise, absolute, 8"	0-30 psia, 0.1 psia increments
Flow, H_2 + CO_2 cell effluent (CC/Min	0-1000 CC burette	0-100C CC 10 CC increments
Voltage, cell pair (volts)	Digitec, D. C. Voltmeter, MOD 214	0.4V; 4 V; 400 V; 1 KV; 1 MV accuracy
Current, cell pair (Amps)	Digitec, D. C. Voltmeter MOD 214	"
Detector, combustible gas [% LEL (H_2)]	Combustible Gas Alum J-W CD-506-060 w/modifications Gas Tech, MOD 1020	0 to 100% ($2\frac{1}{2}$" scale), 2% increments 0 to 100% (2" scale) 2% increments

Clock, digital (seconds)	Precision Scientific Cat #69230	0-9999.9 sec 0.1 sec incr.
Analyzer, chamber P_{O_2}	Beckman, oxygen analyzer, MOD D2 Data Logger, 75 point, B&F Instrument Inc. MOD Sy-133	0-100% (0-760 mmHg) 0.2% & 1o mm incr. 75 point; 4 PLCS each

2.2 (Continued)

Note: One or more layers of Tissuquartz is normally included with the asbestos in HSD cells equipped with an electrolyte reservoir. A simplified all-asbestos cell is proposed for SSP, but testing must be performed to determine adequacy. In the event that Tissuquartz is found necessary reservoir cells will be built-up and after a start run-in period, will be used directly in test #4.

Table II, defines configuration tests #1 - #3, which address necessary evaluations 2.2 (1) to 2.2 (4) above.

TABLE II

HDC TESTS

Test No.:	1
Test Objective:	1. Estab. adequacy of oily housings.
	2. Estab. adequacy of sputtered electrodes.
Cell S/N:	15
Hardware Config.:	Sputtered electrodes; oily housings; non-reservoir; SWEF asbestos; 3 layers 0.020"; 65% Cs_2CO_3 loading; manual fill; condition 45 DP/49 DB; 9-11 mg/cm^2 electrodes.
Cell S/N:	16
Hardware Config.:	Sputtered electrodes; clean housings; non-reservoir; SWEF asbestos; 3 layers 0.020"; 65% Cs_2CO_3 loading; manual fill; conditioned 45 DP/49 DB; 9-11 mg/cm^2 electrodes.
Test Duration:	7 - 9 Days Test 1st Day Run-in cell pairs. Install each cell pair separately in chamber 'A' and 'B' respectively; Purge 5 minutes at end of 24 hours operation with N_2; Data Logger set at 15 min. read-out; chamber conditions or shown; 2nd-end 7th day Purge every 24 hours for 5 minutes; same as above.
Success Criteria:	Time '0' is initial cell start-up at T_o + 48 hours Success Criteria = 5 watts @ 20 ASF @ 3 mmHg and efficiency 65% after T_o + 168 hours (7 days) 4.5 watts @ 20 ASF @ 3 mmHg and efficiency $\geq$ 65%.
Remarks:	Case 1: If both cells meet success criteria oily housings are OK for use in test program and sputtered electrodes are acceptable and will be used subsequently. Case 2: Cell 'a' fails...don't use oily housings. Case 3: Both cells fail...don't use sputtered electrodes If performance of both cells similar oily housings OK to use.
Schedule:	See Fig. A

Table II (Continued)

Test No.:	2
Test Objective:	Verify adequacy of matrix compression range.
Cell S/N:	14
Hardware Config.:	Electroplated electrodes*; oily** housings; SWEF asbestos 3 layers 0.020"; 65% Cs_2CO_3 loading; manual fill; condition 45/49° DP/DB respectively; 9-11 mg/cm^2 electrodes. [.026"/0.024"/0.022" spacers in tests 2A, 2B, 2C, respectively,]
Test Duration:	6 - 8 Day testing total
Test Description:	Test 2A - 2B - 2C Test 2A: (3 Days); start test with new electrodes on cell 'C'; use spacers totaling 0.026" installed in way to enable tests 2B and 2C w/o requiring complete cell disassembly. Test 2B: Following performance determination @ T_o + 72 hours on test 2A, remove cell from chamber and remove 0.002" spacer w/o disassembly cell and retorque housing bolts. Initiate 3 day test as in Test 2A. Same performance 'success' criteria as in 2A. Test 2C: Same as 2B except remove additional 0.002 spacer (0.022" spacer remaining).
Success Criteria:	Time 'O' is initial cell start-up. At T_o + 72 hours determine if performance meets following criteria: 4.5 watts @ 3 mmHg CO_2 @ 20 ASF with current efficiency $\geq$ 60%.
Remarks:	* If test #1 is unacceptable ** Clean housings if test #1 shows oily housings Purpose of test: matrix compression and thickness not so much orientated to optimization as to document sensitivity of matrix thickness around design thickness 0.024".
Schedule:	See Fig. A

Table II (Continued)

Test No.:	3
Test Objective:	Determine if reservoir cell accomodates step Δ T change w/o use of tissuquartz in matrix.
Cell S/N:	11
Hardware Config.:	Cell #011 as presently built and operating (no rebuild).
Test Duration:	11-13 day addl. testing.
Test Description:	Transfer cell #011 ('d') to test sta. D. decrease Δ T by $4^{\circ}F$ (step change); observe over 4-5 days for sign of matrix flooding; increase Δ T by $4^{\circ}F$ (step change) and establish no dryout;
Success Criteria:	No flooding observed; no dryout observed.
Remarks:	Provides definition of reservoir cell configuration to be evaluated in Test 4.
Schedule:	See Fig. A

Tabel II (Continued)

Test No.:	4
Test Objectives:	1. Determine performance of two (2) reservoir and two (2) non-reservoir cells under varying inlet CO_2 concentrations, varying current densities, and varying inlet dew point & dry bulb air temperatures. 2. Provide extended duration performance data.
Cell S/N:	#015 & #016 (Non-reservoir cells). #017 & #018 (Reservoir cells).
Hardware Config:	Non-Reservoir Cells.... contingent upon results of test #1, with regard to sputtered or electroplated electrodes & the use of annealed vs non-annealed housings. Reservoir Cells.... the inclusion of Tissuquartz in matrix contingent upon results of test #3.
Test Duration:	6 weeks (minimum)to 7 weeks.
Remarks:	Parametric curves generated in early & late portion of 6-7 week test to be used to generate six (6) month operating parametric data. Data from projected parametric curves will be used to support subsystem computer program.
Schedule:	See Fig. B

2.2.1 Test #1

Test Article ---------- Two HDC non-reservoir cell pairs

Article Configuration

Cell S/N 15 — Annealed housings, sputtered electrodes special cleaned matrix and 65 wt-% CS_2 CO_3 electrolyte

Cell S/N 16 — Non-annealed housings, electrodes special cleaned matrix and 65 wt-% CS_2 CO_3 electrolyte

Set Parameters:		
	Inlet Temperature	50°F
	Inlet Dew Point	45°F
	Inlet CO_2 Pp	3 mm Hg
	H_2 In Flow	500 scc/min
	Back Pressure of H_2 Discharge	5 psig
	Air Flow	7.5 SCFM
	Constant Current Operation	20 ASF

The above test will be conducted until the units have been conditioned and valid comparison data can be obtained. Data will be recorded per paragraph 2.4.

2.2.2 Test #2

Test Article ---------- One HDC non-reservoir cell pair

Article Configuration

Cell S/N 19 — Annealed housings, sputtered electrodes special cleaned matrix PCB #3018 (P&W), variable spacers .030", .025", .022", and 65 wt-% CS_2 CO_3 electrolyte

Set Parameters:		
	Inlet Temperature	50°F
	Inlet Dew Point	45°F
	Inlet CO_2 Pp	3 mm Hg
	H_2 Inflow	500 scc/min
	Back Pressure of H_2 Discharge	5 psig
	Air Flow	7.5 SCFM
	Constant Current Operation	18 ASF

The above test will be conducted until steady state conditions have been obtained for each matrix compression. Data will be recorded per paragraph 2.4.

2.2.3 Test #3

Test Article ---------- One HDC reservoir cell pair

Article Configuration

Cell S/N 11	Annealed housings, electroplated electrodes, special cleaned matrix, tissuquartz in reservoir only, reservoir on inlet side of unit, and 65 wt-% electrolyte.	
Set Parameters:	Inlet Temperature	50-50-54°F
	Inlet Dewpoint	45°F
	Inlet CO_2 Pp	3 mm Hg
	H_2 Inflow	500 scc/min
	Back Pressure of H_2 Discharge	5 psig
	Air Flow	7.5 SCFM
	Constant Current Operation	20 ASF

NOTE: This cell pair currently under test (no rebuild is anticipated). Cell pair will be transferred to Test Station "D", dry bulb temperature will be decreased by 4°F (step charge) and observed over 4-5 day period for sign of matrix flooding. Dry-bulb temperature will be increased to 54°F (~9°F▲T), and it will be established whether matrix "dry-out" occurs. If the cell responds to both a decrease and the step increase of 4°F, it will be concluded that tissue quartz is not required for the SSP application.

2.3 Parametric and Endurance Test (Test #4)

Test Articles ---------- Two non-reservoir cell pairs and two reservoir cell pairs

Article Configuration

Cell S/N 15 (Non Reservoir)	Annealed housings, sputtered electrodes , 9-11 mg/cm^2 P_T-P_T loading. Special cleaned matrix 65 wt-% Cs_2CO_3 electrolyte, manual electrolyte loading
Cell S/N 16 (Non Reservoir)	Non annealed housings, sputtered electrodes , 9-11 mg/cm^2 P_T-P_T loading, special cleaned matrix, 65 wt % Cs_2CO_3 electrolyte, manual electrolyte loading

2.3 (Continued)

Cell S/N 17 (Reservoir)	Annealed housings, sputtered electrodes*, 9-11 mg/cm^2 P_T-P_T loading, special cleaned matrix, 65 wt % Cs_2CO_3 electrolyte, manual electrolyte loading	
Cell S/N 18 (Reservoir)	Same as Cell S/N 17	
Set Parameters:	Inlet Temperature	47 - 55°F (T_{DP}+6°F nominal)
	Inlet Dew Point	41 - 49°F
	Inlet P_{CO_2}	1.5-3.0 mmHg
	H_2 inflow (2 cells in series)	950 - 1200 SCCM
	Back pressure of H_2 + CO_2 at cell outlet	5 psig
	Air Flow	7.5 CFM/cell pair
	Current Density	12 - 24 ASF

Figure C-2 shows a time plot of the cell input conditions and environments for the four cells during test #4.

2.4 Data

Test data taken for all tests will be compiled on data sheets similar to Figure C. Reduced data will be presented by various curves as shown in figures D-1 through D-3.

2.5 Other Considerations

2.5.1 All Tests

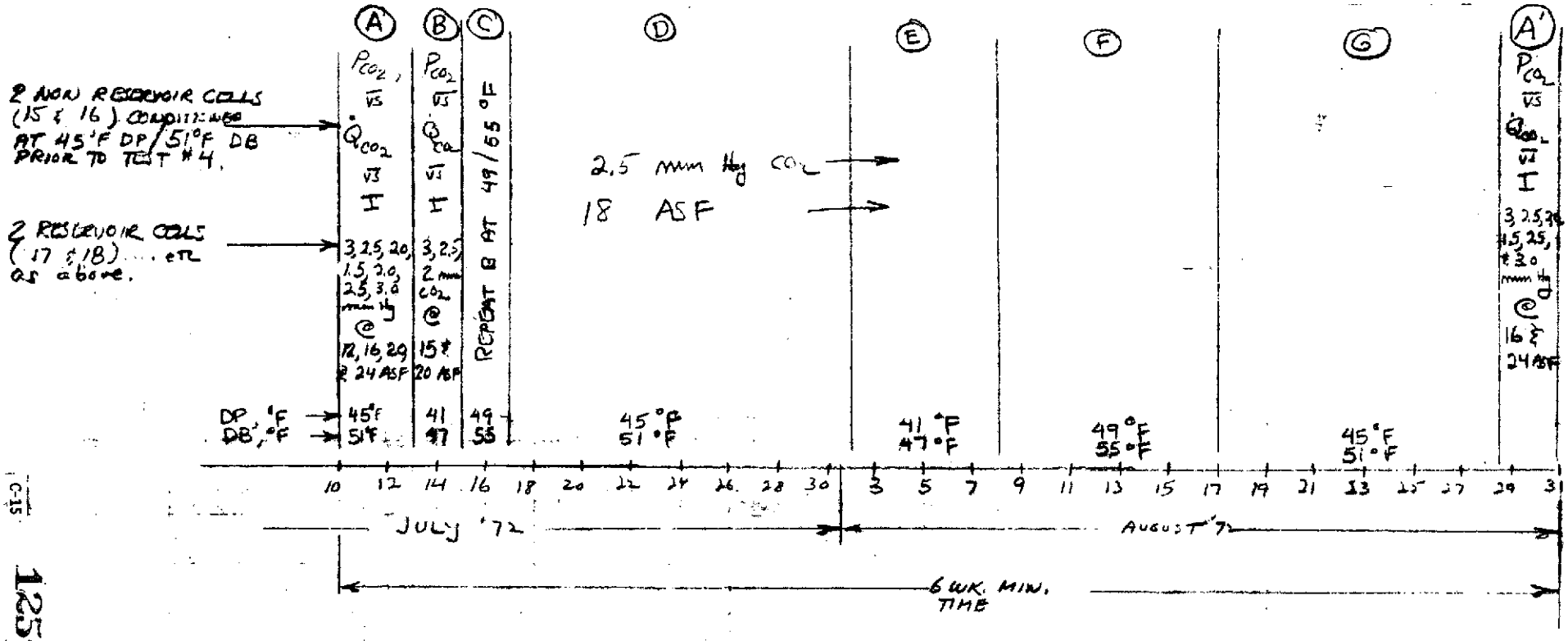
(a) The conditioning period of any cell pair may be shorter than the forty-eight hour period stated in applicable documents #1, if evidence exists to show that electrolyte concentration gradients and cell 'run-in' have/have not been achieved.

(b) All CO_2 partial pressure instrumentation will be calibrated every 48 hours.

(c) During conditioning of cell pairs, any device may be employed to hasten the conditioning of the cell pairs which would or might be employed during factory run-in following assembly.

FIGURE B

SVHSER 6229



C-15

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NOTE 1: RESERVOIR CELLS IN CHAMBER B, NON RESERVOIR CELLS IN STATION A.

2. 5 MIN PURGE (OR ALTERNATIVE METHOD ... SEE FIG A, ACTION ITEM D) WILL BE PERFORMED PERIODICALLY DURING ALL TESTS.

3. CONDITIONS OF TEST
   (a) 1200 SCCM $H_2 + CO_2$ AVERAGE EFFLUENT FLOW
   (b) 2 RESERVOIR CELLS IN EACH H_2 FLOW SERIES; DITTO NON-RESERVOIR CELLS
   (c) P_{O_2} 20 - 22 %
   (d) Current Density, where shown to be maintained constant.

FIG B

HDC PARAMETRIC & END-URANUS TEST (TEST 4)

REVISED 6-17-72

by

NASA: W.H. Sanderson 6/17/72 HSD: C.R. Russell 6-17-72

-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: REF- TEST PLAN PARA
TEST ENGINEER:
NAME OF RIG: CELL PAIR S/N & TEST STATION
PROJECT & ENG. ORDER NO.:

SHEET OF
TEST PLAN NO.:
MODEL NO.:
PART NO.:
SERIAL NO.:
OPERATORS:

SVHSER 6229

TIME	FAN ΔP		CHAMB TEMP.		AIR TEMP OUT	H_2 TEMP IN	D.P. IN	LIRA IN	H_2 FLOW	P_{H_2} MATRIX	H_2+CO_2 FLOW OUT	H_2 LIRA	CURRENT	VOLTAGE		COMB GAS	POWER	EXT RES.	CELL AERF	I	ACT CO_2	CHAMB. O_2
	"H_2O		°F		°F	°F	°F	%SCALE	%SCALE	PSIA	SCCM	%SCALE	AMPS	VDC		%LEL	WATTS	mΩ	%		SCCM	%
	ΔP ACROSS CELL PAIR IN TEST FIXTURE - USING THIS AND A CALIBRATION CURVE, THE AIR FLOW IS DETERMINED		INLET AIR TEMP. TO UNIT		OUTLET AIR TEMP FROM UNIT	INLET HYDROGEN GAS TEMP.	INLET AIR DEWPOINT TO UNIT	THIS DETERMINES THE CO_2 PARTIAL PRESSURE IN TEST CHAMBER	INLET HYDROGEN GAS FLOW	HYDROGEN GAS BACK PRESSURE	ACTUAL HYDROGEN + CO_2 OUTLET FLOW	THIS DETERMINES THE AMOUNT OF CO_2 IN THE OUTLET H_2+CO_2 GAS FLOW	CELL PAIR CURRENT	CELL PAIR VOLTAGE		COMBUSTABLE GAS DETECTOR - INDICATES IF H_2 IS PRESENT IN CHAMBER	CALCULATED POWER OF UNIT	CALCULATED EXTERNAL RESISTANCE	CALCULATED CURRENT EFFICIENCY		CO_2 REMOVAL RATE	% OF OXYGEN IN CHAMBER

REMARKS:

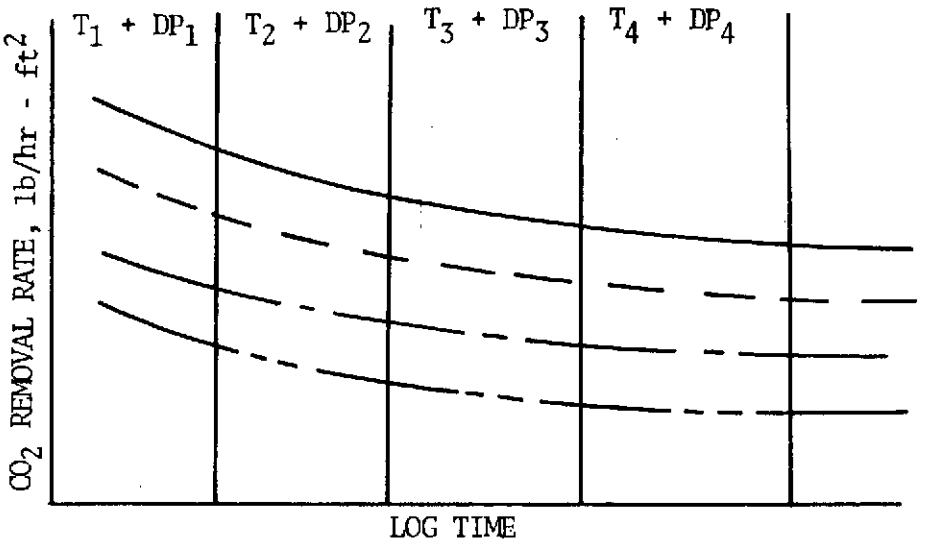
C-16

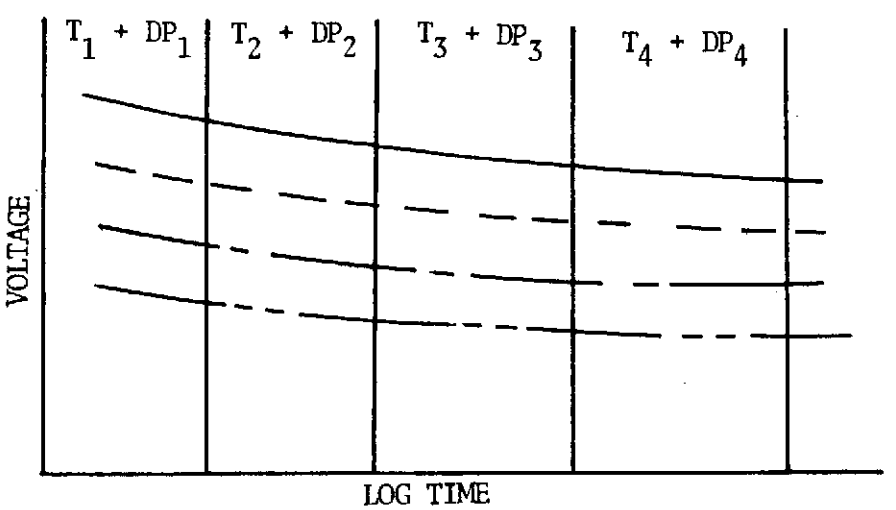
>821 128<

SAMPLE DATA LOG SHEET

FIGURE C

4322

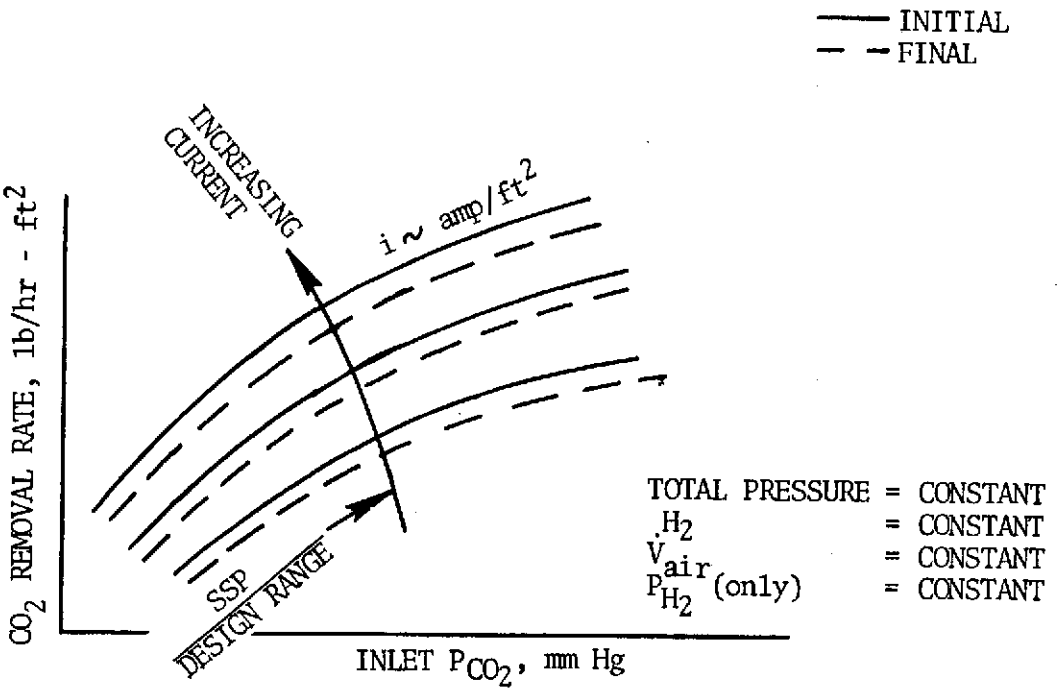




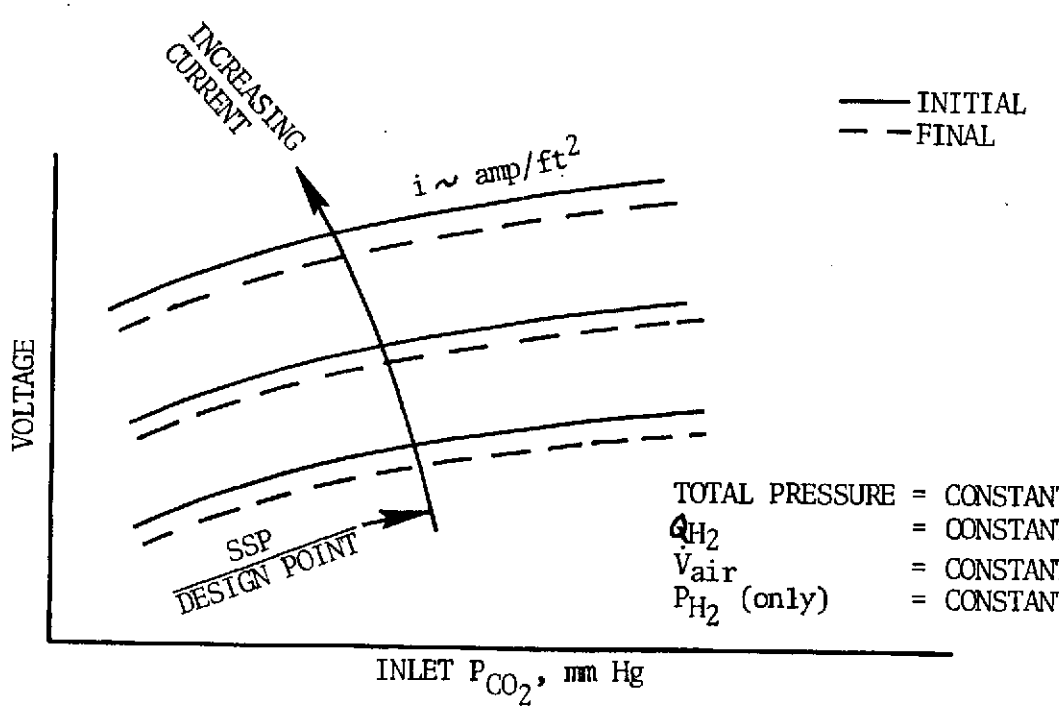
FOR BOTH PLOTS:
- TOTAL PRESSURE = CONSTANT
- P_{CO_2} = CONSTANT
- i = CONSTANT
- Q = CONSTANT
- P_{H_2} (only) = CONSTANT

——— CELL 1
— — CELL 2
— · — CELL 3
— ·· — CELL 4

FIGURE D-1



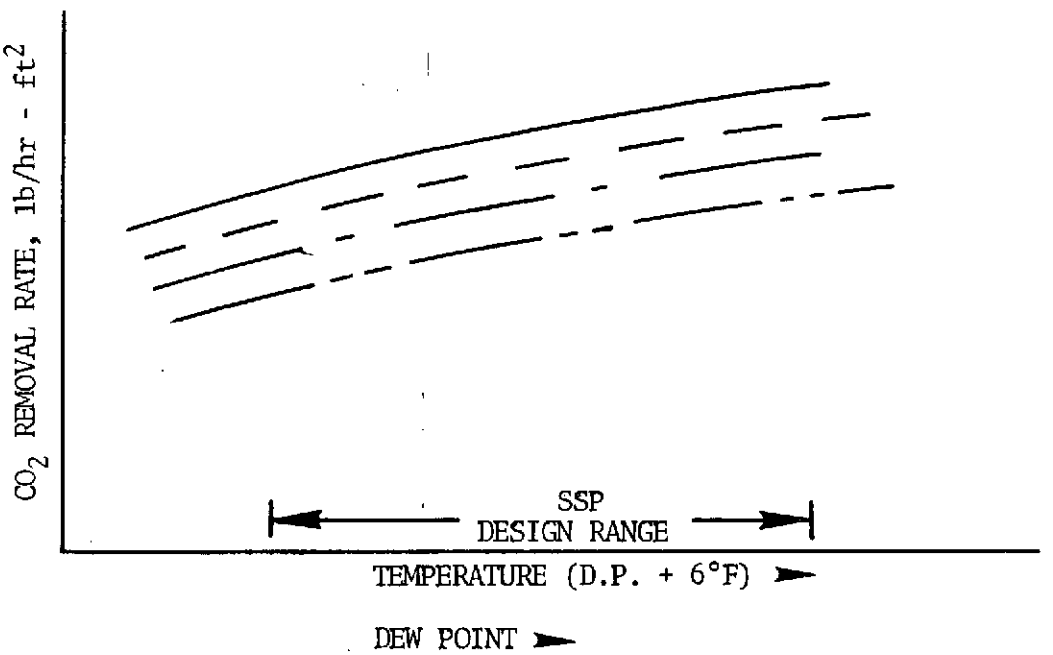
(Repeat for every cell pair)



(Repeat for every cell pair)

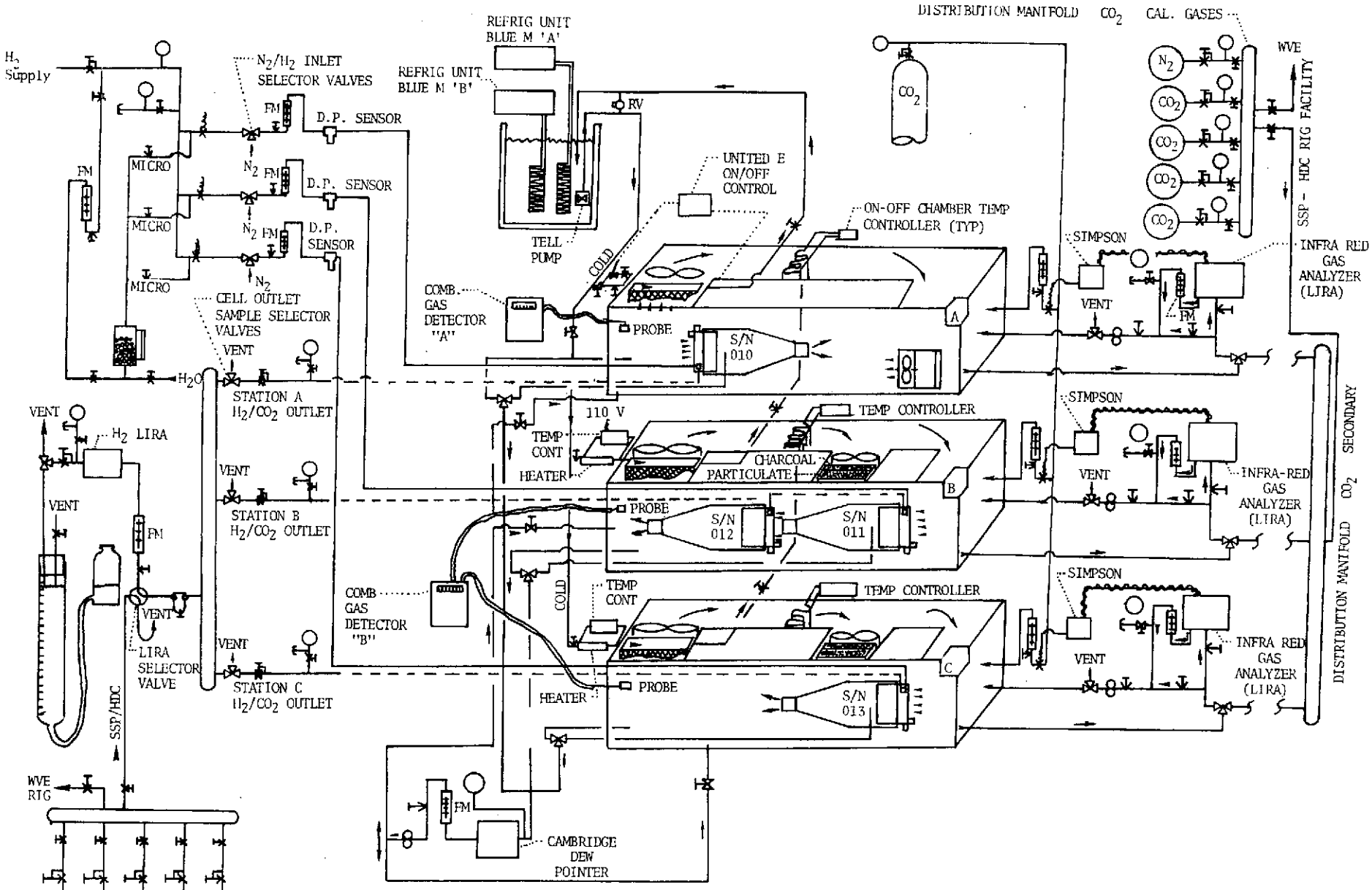
FIGURE D-2

TOTAL PRESS = CONSTANT
$\dot{Q}_{H_2}$ = CONSTANT
V_{air} = CONSTANT
P_{H_2} (only) = CONSTANT



—— CELL PAIR 1
– – CELL PAIR 2
–·– CELL PAIR 3
–··– CELL PAIR 4

FIGURE D-3



MECHANICAL FLOW DIAGRAM AND SCHEMATIC OF THE HDC TEST FACILITY

TEST PLAN - ENCLOSURE 1

APPENDIX D

BASIC HDC CELL PAIR DETAILED DESIGN CONFIGURATION DEFINITION

INTRODUCTION

This appendix defines the configuration of the cell pairs tested. The cell pair definition given herein, defines changes in the reservoir and non-reservoir configurations with respect to Hamilton Standard drawing SVSK 84460. Figure D-1 describes the geometry of the Tissuquartz layer, employed within the matrix of reservoir cell pairs #017 and #018.

HYDROGEN DEPOLARIZED CELL PAIR CONFIGURATION DEFINITION

(Reference HS drawing SVSK 84460)

1. Sheet 1 - Assembly
2. Sheet 2 - Upper Housing
3. Sheet 3 - Center Housing
4. Sheet 4 - Lower Housing
5. Sheet 5 - Reservoir Revision B
6. Sheet 6 - Kel-F Spacers

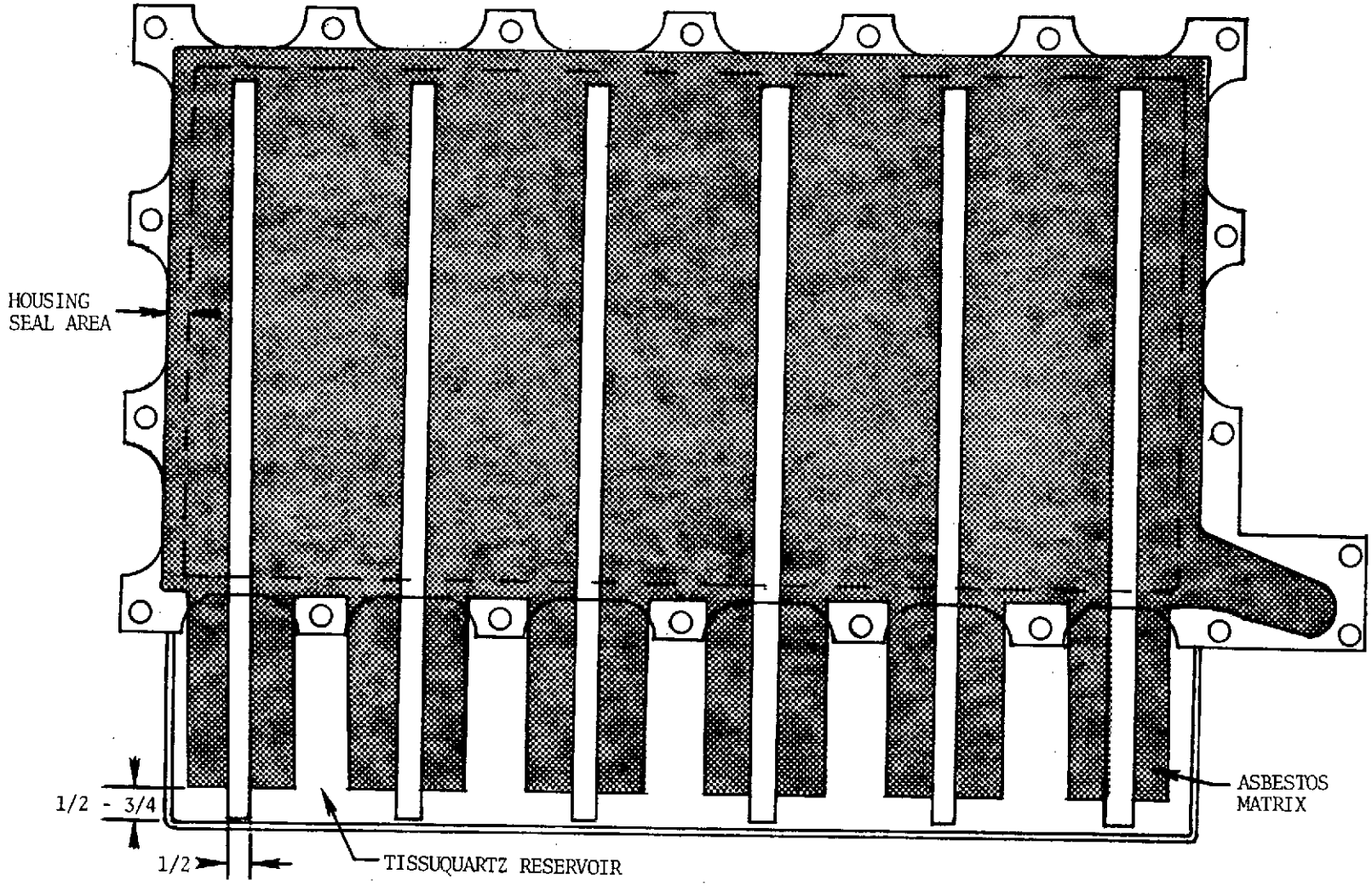
Basic Configuration

Electrochemical Cell Assembly, with upstream electrolyte reservoir; overall dimensions of assembly 17.5" long x 11.5" deep x 11/16" thick; dry weight 5.0 lb., wet (w/electrolyte) 6.0 lb. Electrode area 1.0 ft^2; Electrodes Pratt & Whitney Aircraft No. PCB3019 on platinum electroplated expanded tantalum metal, 0.007" thick, 20 x 35 mesh; asbestos matrix per Pratt & Whitney Aircraft No. PCB3018 manufactured using distilled water; 0.025" Tissuquartz Pallflex.

Design Configuration for SSP

Design configuration for SSP is as indicated on reference drawing (SVSK 84460) with certain changes as follows:

Item No.	Reference Sheet No.	Comment
-12, -27	1	Matrix - Revision needed on Sheet 1 to define: a. Different shape asbestos for upstream reservoir location b. Different Pratt & Whitney Aircraft manufacturing procedure using distilled water. c. Incorporation of 1 sheet of 0.025" Tissuquartz, sandwiched between asbestos, to facilitate greater electrolyte wicking rate. Attached figure D-1 describes Tissuquartz.



.025 thick Tissuquartz strips inserted between the 1st and 2nd sheets of asbestos matrix from the air side of each cell. (Note 3 sheets of .020 in. thick asbestos/cell for the matrix.)

TISSUQUARTZ CONFIGURATION ON CELL PAIRS
S/N 017 AND S/N 018

FIGURE D-1

Item No.	Reference Sheet No.	Comment
-30	5	Reservoir - Revision B of drawing shows upstream reservoir configuration.
-4	1	Electrodes - Reference Note 15. Sheet 1 revised per Revision B to reflect Pratt & Whitney Aircraft Part No. for electrodes on electroplated platinum expanded metal. See Basic Configuration Paragraph above.
-5/-23	1	Asbestos - Reference Note 13. Sheet 1 revised per Revision B to reflect Pratt & Whitney Aircraft Part No. for asbestos processed with distilled water.
-16	1	Hydrogen Probe - Tests used the test configuration probe to reduce costs.
-1	1	Upper Housing - Test configuration included H_2 probe tab...also included an extended electrical tab not used on SSP configuration.
-2	1	Center Housing - Test configuration used more complicated H_2 passageway configuration and extended electrical connector tab.
-3	1	Lower Housing - Minor changes in improving electrical connector tab used on SSP.

NOTE: CR&D Test Cells to use:

- upstream reservoir (on reservoir tests);
- purified asbestos matrix (Pratt & Whitney Aircraft No. PCB3018/ with distilled water option);
- electrodes per Pratt & Whitney Aircraft No. PCB3019, with electroplated platinum expanded tantalum metal 0.007" and 20 x 35 mesh;

all per SSP design configuration.

APPENDIX E

GAS SAMPLE ANALYSES

As discussed in the text of this report, gas samples were collected and analyses made at various times during this test program. The tabulation below gives the date and the particular conditions and sources of each of the samples, and refers to one of several tables in this appendix which shows the results of each analysis. All of the analyses were performed by the Analytical Research Laboratories, Inc., of Monrovia, California.

KEY TO GAS ANALYSES

SAMPLE	DATE TAKEN	WHERE TAKEN	REFER TO
1 A	8-27-72	HS Laboratory Room Air, Electrochemical Test Laboratory	Table E-I Table E-IV
1 B	8-27-72	HS Test Station A, which contained cell S/N 016-1	Table E-II Table E-IV
1 C	9-28-72	The effluent from cell S/N 016-1 H_2 + CO_2 cavity (anode) taken during the nitrogen purge of the cell over a five minute period	Table E-III Table E-IV
2 A	11-10-72	HS Laboratory Room Air, Electrochemical Test Laboratory	Table E-V
2 B	11-10-72	HS Test Station A, which contained cell S/N 017	Table E-V
2 C	11-10-72	The effluent from cell S/N 017 H_2 + CO_2 cavity (anode) taken during the nitrogen purge of the cell over a five minute period.	Table E-V
3 A	12-12-72	The effluent from cell S/N 017 H_2 + CO_2 cavity (anode) taken at approximately 1015 hours over 3 minutes without nitrogen purging cell.	Table E-VI
Sample 3 A corrected by factoring out helium.	12-12-72	Same as above except corrected by factoring out helium	Table E-VII

TABLE E-I

RESULTS OF ANALYSIS - SAMPLE 1 A
(LABORATORY AIR)

COMPOUND	mg/m^3	ppm
Freon 113	0.25	0.032
trichloroethylene	0.0004	<0.0001
dichlorobenzene	0.00003	<0.0001
toluene	0.0079	0.0021
ethyl alcohol	0.23	0.12
isopropyl alcohol	0.007	0.0028
n-butyl alcohol	0.31	0.10
acetone	4.0	1.7
methyl ethyl ketone	0.69	0.23
methyl isobutyl ketone	0.00008	<0.0001

TABLE E-II

RESULTS OF ANALYSIS - SAMPLE 1 B
(TEST STATION A)

COMPOUND	mg/m^3	ppm
Freon 11	0.12	0.022
Freon 113	0.44	0.057
chloroform	0.008	0.0017
methyl chloroform	0.0001	<0.0001
1.2 dichloroethane	0.0002	<0.0001
trichloroethylene	0.0021	0.0004
dichlorobenzene	0.0065	<0.0011
n-hexane	0.25	0.072
propylene	0.052	0.030
2 butene	0.087	0.038
methyl cyclopentane	0.078	0.023
benzene	0.37	0.11
toluene	0.034	0.0091
indene	0.059	0.021
methyl alcohol	0.61	0.47
ethyl alcohol	0.87	0.46
n-propyl alcohol	0.40	0.16
isopropyl alcohol	0.019	0.0075
n-butyl alcohol	0.42	0.14
acetone	11.0	4.5
methyl ethyl ketone	1.1	0.36
methyl isobutyl ketone	0.029	0.007
furan	0.059	0.021

TABLE E-III

RESULTS OF ANALYSIS - SAMPLE 1 C
(CELL EFFLUENT)

COMPOUND	mg/m^3	ppm
Freon 113	0.19	0.025
1, 2 dichloroethane	0.0027	0.0001
benzene	0.20	0.062
toluene	0.46	0.12
furan	0.074	0.026
methyl alcohol	0.18	0.14
ethyl alcohol	0.18	0.14
n-propyl alcohol	0.11	0.045
isopropyl alcohol	0.17	0.070
n-butyl alcohol	0.13	0.041
acetone	5.2	2.2
methyl ethyl ketone	0.68	0.23

TABLE E-IV

RESULTS OF MASS SPECTROMETRY ANALYSIS
SAMPLES 1 A - 1 B - 1 C

SAMPLE	LOCATION	H_2	N_2	O_2	A	CO_2
1 A	Laboratory Air	0.0	78.2	20.8	0.91	0.13
1 B	Test Chamber	0.50	78.0	20.6	0.91	0.41
1 C	Cell Effluent During Nitrogen Purge	0.39	99.3	0.06	0.01	0.20

TABLE E-V

RESULTS OF ANALYSIS FOR SO_x, NO_x, AND NH_3

		ANALYSES		
SAMPLE	WHERE TAKEN	NO_x	SO_x	NH_3
2 A	Laboratory Air	0.4 ppm	11 ppm	30 ppm
2 B	Test Station A	0.5 ppm	21 ppm	56 ppm
2 C	Effluent from cell #017 (anode during nitrogen purge	3.1 ppm	1980 ppm	72 ppm

NOTE: The analysis also determined that the aqueous wash solution was turbid and also contained considerable dissolved carbonate.

The hydrogen effluent sample was split for multiple analytical disciplines. The results are as follows:

TABLE E-VI

RESULTS OF ANALYSIS - SAMPLE 3 A
(CELL S/N 017 H_2 + CO_2 EFFLUENT w/o N_2 PURGE)

			µg/l	ppm
Hydrogen	70.4 Mol. %			
Helium	19.6 Mol. %	Methyl alcohol	1.63	1.24
Nitrogen	2.24 Mol. %	Ethyl alcohol	0.032	0.017
Oxygen	0.60 Mol. %	Isopropyl alcohol	0.14	0.057
Argon	0.03 Mol. %	Acetone	0.23	0.095
Carbon dioxide	7.07 Mol. %	Methylene chloride	0.13	0.037
Methane	0.6 ppm	Freon 113	2.62	0.34
NO_2	0.2 ppm			
SO_2	19 ppm			
NH_3	25 ppm			

NOTE: The above values have been corrected for content of evacuated bottle. The control bottle contained all of the above compounds plus Freon 11, which was not found in the submitted sample.

TABLE E-VII

CORRECTED RESULTS OF ANALYSIS - SAMPLE 3 A
(CELL S/N 017 EFFLUENT w/o N_2 PURGE)

Hydrogen	87.70 Mol. %
Nitrogen	2.68 Mol. %
Oxygen	.72 Mol. %
Argon	.03 Mol. %
Carbon Dioxide	8.80 Mol. %
Methane	0.75 ppm
NO_2	0.25 ppm
SO_2	23 ppm
NH_3	31 ppm

NOTE: Helium, concentration show in Table E-VI, factored out in Table E-VII.

APPENDIX F

CO_2 TRANSFER MEASUREMENT TECHNIQUE

Figure F-1 diagrams that portion of the test facility wherein the CO_2 transfer rate of the cell pair(s) within any one of the four test stations (A - D) was measured. The CO_2 transfer rate from only one station at a time could be measured. If the station contained one cell pair, the transfer rate of that cell pair would be measured but if two cell pairs were contained in series within that station, the measurement configuration shown would produce the collective transfer.

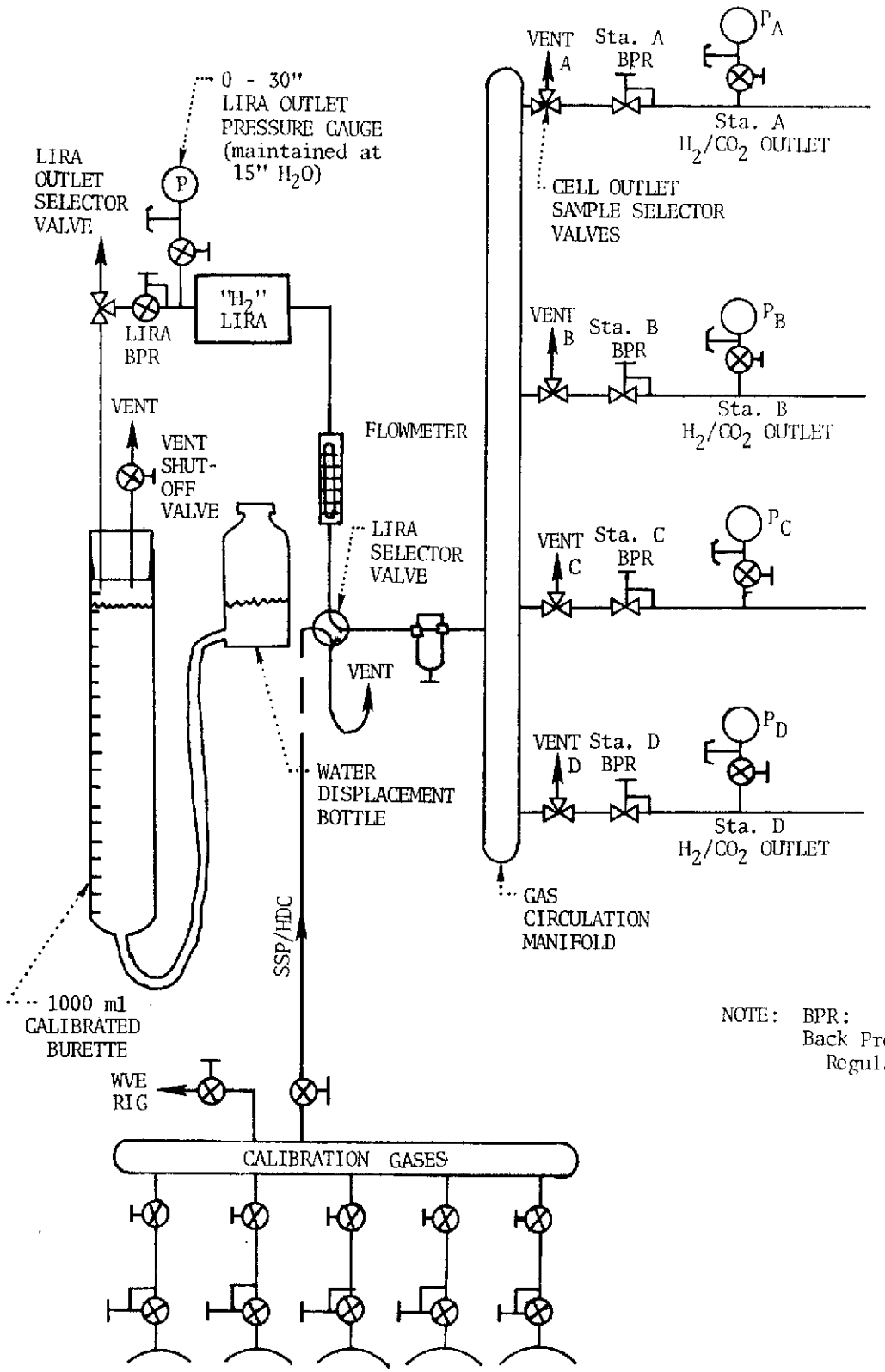
Referring to figure F-1, the procedure employed for determining the flow rate of cell pairs #017 and #018, installed in series hydrogen flow within station B, is described as follows:

Vent selector valves A, C, and D would all be placed in the "vent" position. Vent selector valve B would be opened to permit the flow of the H_2 plus CO_2 effluent from cell pairs #017 and #018 (in chamber B) to flow in both directions around the 1/4" tubing loop of the gas circulation manifold, through the H_2 LIRA and discharged to atmosphere above the roof of the laboratory through the LIRA outlet selector valve (vent position). Sufficient time would be allowed for the H_2 LIRA reading to stabilize (typically 3 to 6 minutes), during which time small adjustments would be made as necessary on the "LIRA BPR" (back pressure regulator) to maintain the outlet pressure of that instrument at 15 ± 0.2" H_2O gauge pressure. When the LIRA had reached a steady state condition the LIRA reading was read and recorded, and the LIRA outlet selector valve repositioned to cause all of the H_2 plus CO_2 effluent from station B to flow into the 1000 ml calibrated burette (burette outlet shutoff valve closed). The water displacement bottle had sufficient volume to accommodate the water displaced from the burette, and was moved vertically downward at such a rate as to maintain a 15" H_2O head at the LIRA outlet. A finger-tip controlled digital clock was used to determine the time required to displace a volume of 500 to 800 ml of water within the burette. During this entire measurement period, considerable emphasis was placed on maintaining the LIRA outlet pressure gauge at 15" ± 0.5" H_2O.

The H_2 plus CO_2 flow rate was calculated by the straight forward technique of multiplying the total displaced water volume obtained in "X" seconds by $\frac{60}{X}$, and entering the flow rate in sccm on the data sheet.

CO_2 transfer rate, was established by multiplying CO_2 volume percent (determined from the LIRA reading five minutes earlier) by the H_2 plus CO_2 flow rate, and entering the transfer rate thus determined on the test data sheet.

The LIRA was calibrated at frequent intervals (typically once a day) to guard against drift. The calibration procedure used maintained the same 15" H_2O at the LIRA outlet, at a standardized norminal flow rate through the instrument, as during test.



NOTE: BPR: Back Pressure/ Regulator

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FIGURE F-1

outlet, at a standardized nominal flow rate through the instrument, as during test.

Cell current efficiency was calculated by multiplying the cell current by the constant 7.5 (for one cell pair; 15.0 for two cell pairs) and determining the percentage of this theoretical CO_2 efficiency actually achieved.

A considerable degree of confidence exists in the accuracy of the foregoing technique. The procedure described was always used by each of the engineers and technicians in making these critical measurements. On several occasions the repeatability and human error evaluation of the procedure were cross checked by having two or three test operators take consecutive readings to determine variations. On these occasions it was generally determined that the readings agreed within a fraction of one percent.

Checks were frequently made to compare the LIRA reading recorded, with the reading taken immediately following the completion of the flow measurement and thereafter over the next several minutes. No variation would be observed between the three LIRA readings, showing that the measurement had no effect upon cell pair flow conditions.

An additional crude but worthwhile check was randomly made during the test series by noting that the flow meter reading taken during the water displacement check agreed with the recorded value taken earlier, thereby showing that flow rate in fact was maintained constant.

APPENDIX G

TEST DATA SHEETS

The data sheets compiled during all tests, were reduced to Microfiche. One copy of the Microfiche cards was transmitted to NASA JSC, and the master set, plus one copy, was retained at Hamilton Standard.

APPENDIX H

DATA LOGGER TABULATIONS

In addition to the test data sheets (Appendix G) certain key test data was automatically printed out every fifteen minutes during the entire test period. Because of the large volume of the data collected, the Data Logger tape has been reduced to Microfiche. One copy of the Microfiche cards was transmitted to NASA JSC, and the master set plus one copy retained at Hamilton Standard.