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Basic Statistical Analyses of Candidate Nickel-Hydrogen Cells for the Space Station Freedom

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ABSTRACT

Nickel-Hydrogen (Ni/H_2) secondary batteries will be implemented as a power source for the Space Station Freedom as well as for other NASA missions. Consequently, characterization tests of Ni/H_2 cells from Eagle-Picher, Whittaker-Yardney, and Hughes have been completed at the NASA Lewis Research Center. Watt-hour efficiencies of each Ni/H_2 cell were measured for regulated charge and discharge cycles as a function of temperature, charge rate, discharge rate, and state of charge. Temperatures ranged from -5°C to 30°C, charge rates ranged from C/10 to 1C, discharge rates ranged from C/10 to 2C, and states of charge ranged from 20% to 100%. Results from regression analyses and analyses of mean watt-hour efficiencies demonstrated that overall performance was best at temperatures between 10°C and 20°C while the discharge rate correlated most strongly with watt-hour efficiency. In general, the cell with a back-to-back electrode arrangement, single stack, 26% KOH, and serrated zircar separator and the cell with a recirculating electrode arrangement, unit stack, 31% KOH, zircar separators performed best.

TABLE OF CONTENTS

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LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Nickel-Hydrogen secondary batteries will be implemented as a power source for the Space Station Freedom as well as for other NASA missions. Consequently, the performance of Ni/H_2 battery cells from three different vendors have been assessed. The three vendors, Eagle-Picher, Whittaker-Yardney, and Hughes have provided NASA Lewis with their respective Ni/H_2 cells for testing. This report summarizes the results and conclusions from the analyses of characterization cell tests.

Experimental Test Description

A test matrix developed by the U.S. Air Force (1) has been adopted for the NASA LeRC Ni/H_2 experiments. Watt-hour efficiencies were measured for regulated charge and discharge cycles against four control variables. The controlled variables were temperature, charge rate, discharge rate, and state of charge while the possible levels of each control variables were as follows :

Temperature	: -5°C, 0°C, 10°C, 20°C, and 30°C
Charge Rate	: C/10, C/4, C/2, and C
Discharge Rate	: C/10, C/2, C, and 2C
State of Charge	: 20%, 40%, 60%, 80%, 100%

Where C is the nameplate capacity of the cells. For example, a C/2 rate for a 65 A-hr cell equals 32.5 Amps.

Watt-hour efficiencies were used as the objective variable to be maximized and the watt-hour efficiencies of each cell were measured under selected combinations of the control variables. Five or six cells were arranged on a single cooling plate and the performance of those cells was compared, using watt-hour efficiencies as the discriminator. Watt-hour efficiencies were generally measured over a span of one cycle with a discharge voltage cut-off limit of 1.0 volt. Analyses of cell performance on two cooling plates (Cold Plate H and Cold Plate B) are reported here.

Data Analysis

All data were recorded using the ESCORT system at the NASA Lewis Research Center. The first step in the data analysis consisted of organizing, sorting, and displaying the raw data. Fortran routines were coded to read and sort the raw data while the DISSPLA graphics package was utilized to present the data graphically. All of the DISSPLA programs were written for the IBM Mainframe. The two-dimensional DISSPLA graphs were useful only for astute visual scrutiny since there were a total of five variables (including the experiment number) that affected the watt-hour efficiencies. Nonetheless, the DISSPLA programs provided a rapid means of visualizing results for a selected set of conditions.

Statistical analyses were applied to the raw data to determine and compare mean watt-hour efficiencies for the different cells and to ascertain the inter-relationships among the control variables for each cell. These analyses were accomplished by coding various Fortran routines and utilizing the routines available within the Statistical Analysis System (SAS) software package. Descriptions of the sorting, graphing, and statistical analyses follow.

Sorting and Graphing Routines

A Fortran program was coded to organize the raw data for each experiment housed on a single cold plate. An exhaustive table was generated which included all possible combinations of the control variables, and the watt-hour efficiencies were entered manually. For those conditions where watt-hour efficiencies were not measured, a "flag" of -999 was entered in place of an actual watt-hour efficiency.

A sorting algorithm was devised and implemented in Fortran to collect and store any desired sub-sets of the raw data for subsequent analyses. The sorting routine was used to isolate individual data sets which would function as input files for the statistical analysis programs. Additionally, the sorting routines provided a rapid means of inspecting any desired data sets.

The DISSPLA program is a menu driven routine which uses the entire raw data set for a single cold plate as the input file. The watt-hour efficiencies for any and all of the cells on one cold plate can be plotted as a function of any single control variable, subject to any user-selected values of the remaining control parameters. This graphics algorithm was designed to allow automatic printing of any user-selected graphs.

The Fortran programs for raw data input, for sorting, and for graphing using DISSPLA are available on the floppy disks included with this report.

Cluster Analysis

A Cluster Analysis was executed to identify combinations of the control variables which allowed for exceptionally good or poor cell performance. The IMSL Library on the NASA LeRC Scientific VAX was used for this analysis. No practical conclusions were obtained from this analysis. The cluster program is available on the floppy disks included with this report.

Analysis of Mean Watt-Hour Efficiencies

Mean watt-hour efficiencies were computed and examined for each cell on a single cold plate under specified conditions. These univariate descriptive statistics were very useful for immediate comparisons of the performance of different cells. The Statistical Analysis System (SAS) procedure called PROC MEANS was used for this analysis and the SAS program for this task is presented in Appendix II.

Correlation Analysis

A sequence of tests were performed to determine what impact each of the control variables (Temperature, Charge Rate, Discharge Rate, and State of Charge) had upon the objective variable (Watt-Hour Efficiency). The simplest of these tests was the calculation of correlation coefficients between the control variables and the objective variable. The SAS CORR procedure was implemented for this analysis. Correlation coefficients can provide an indication of the strength or weakness of a relationship between two variables. The range for the correlation coefficients is (-1,1). A correlation coefficient near unity indicates a very strong positive correlation between two variables whereby observations with high values of one variable also have high values of the other variable. Conversely, when two variables are negatively correlated, the correlation coefficient is close to -1 and high values of one variable are associated with low values of the other variable. Correlation coefficients near zero indicate a lack of any linear correlation. A sample SAS Correlation procedure is given in Appendix III.

Regression Analysis

Regression analyses were conducted to further examine what impact each control variable and couples (products) of control variables had upon the watt-hour efficiencies for each experiment. The watt-hour efficiencies of each cell were fit with a quadratic surface and critical values of the control variables were explored to obtain the factors which optimized cell performance. In addition, the significance level (or importance) of each control variable and each pair-wise combination of control variables was determined to provide an indication of which variable(s) most strongly affected performance. The SAS procedure called RSREG was implemented for the regression analyses and a sample listing of this procedure is given in Appendix IV. All variables were scaled and coded prior to the regression analysis so that the range for each independent variable was between -1 and 1, inclusive. The coefficient of determination (R^2) and the coefficient of variation (C.V.) were obtained for each experiment using the regression analyses. The coefficient of determination represents a measure of how much of the variation in the dependent variable (ie. watt-hour efficiency) is accounted for by the quadratic curve fit. The coefficient of determination ranges between 0 and 1 ($0 \leq R^2 \leq 1$) and larger values of R^2 generally indicate better model curve fits. The coefficient of variation is used to assess the degree of variation in the population. The C.V. is computed by dividing the standard deviation of the watt-hour efficiencies by the mean watt-hour efficiency, then multiplied by 100. The residual values (ie. the difference between the actual watt-hour efficiency and the watt-hour efficiency predicted by the quadratic curve fit : Residual = Actual-Predicted) were examined for outliers. If any data point exhibited a residual value which was very different from the other residuals, that data point was scrutinized for possible elimination from the regression analyses.

RESULTS FOR COLD PLATE H

The six cells on cold plate H were designated as experiments 31, 32, 33, 34, 35, and 36. The design features of each of these cells are summarized in Appendix I. All of the raw data with measured watt-hour efficiencies were used in the statistical analyses except for one or two outliers for each of the experiments. During the regression analyses, outliers for experiments 31 through 36 were discovered, where the residuals for those outliers were extremely large. Figures 1 and 2 demonstrate representative examples of residuals of the outliers, shown for experiments 31 and 32, respectively. These outliers were deleted from the data base and were not used in any of the analyses reported here, since the coefficients of determination increased dramatically when those outliers were not used in the regression analyses. Figures 3 and 4 depict the residuals from the regression analyses for experiments 31 and 32, respectively, after the outliers have been removed from the data base. Plots of the residuals for experiments 33 through 36, both with and without the outliers, are similar to the plots shown for experiments 31 and 32 in Figures 1 through 4. The corresponding conditions for the Cold Plate H outliers are shown in Table 1.

Table 1

Outliers from Regression Analysis for Cold Plate H
(These points are valid but were removed from the analyses)

Experiment Number	Temp. (°C)	Charge Rate	Discharge Rate	State of Charge	Watt-Hr Eff.
31	30	1 C	1 C	20 %	33.57 %
32	30	1 C	1 C	20 %	34.18 %
33	30	1 C	1 C	20 %	37.27 %
34	30	1 C	1 C	20 %	31.13 %
34	30	1 C	2 C	100 %	17.31 %
35	30	1 C	1 C	20 %	33.80 %
36	30	1 C	1 C	20 %	33.04 %

Note that the values listed in Table 1 are valid data points but represent outliers. The watt-hour efficiencies of these outliers in Table 1 are very low, especially for experiment 34, and these

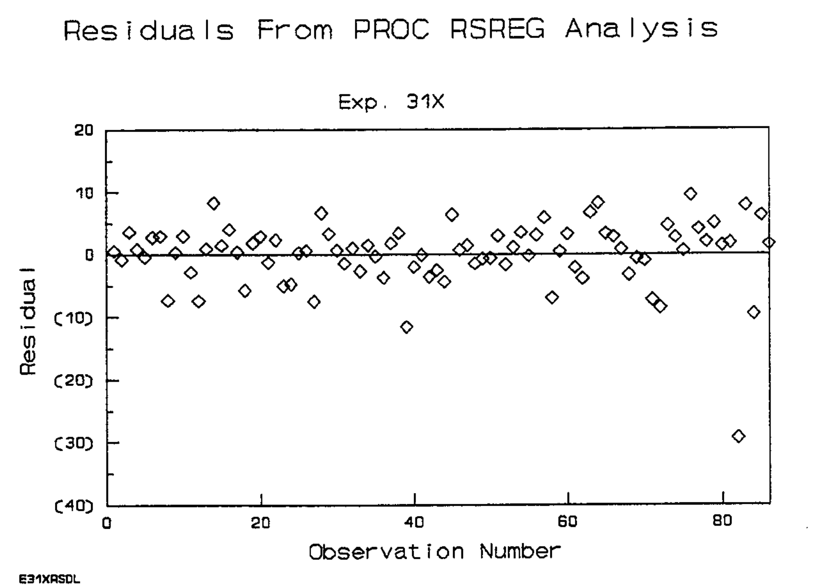

Figure 1 : Regression Analysis Residuals for Raw Data for Experiment 31

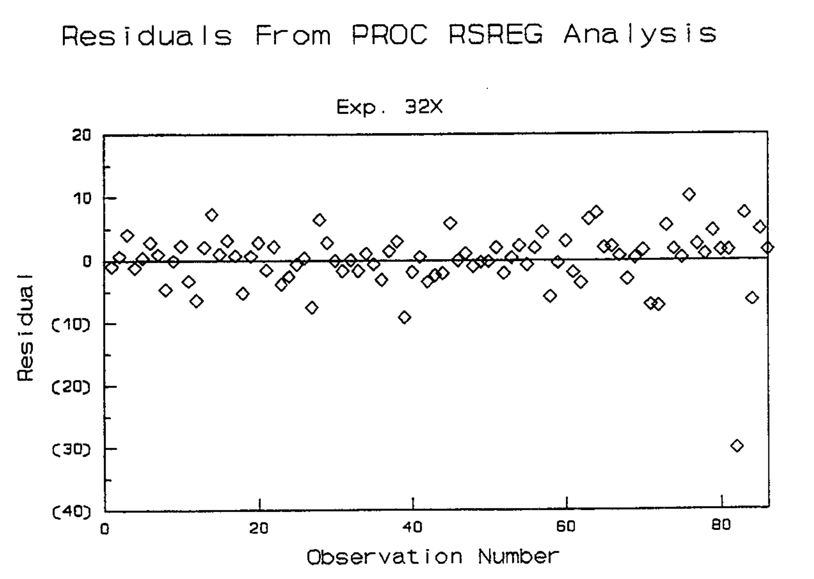

Figure 2 : Regression Analysis Residuals for Raw Data for Experiment 32

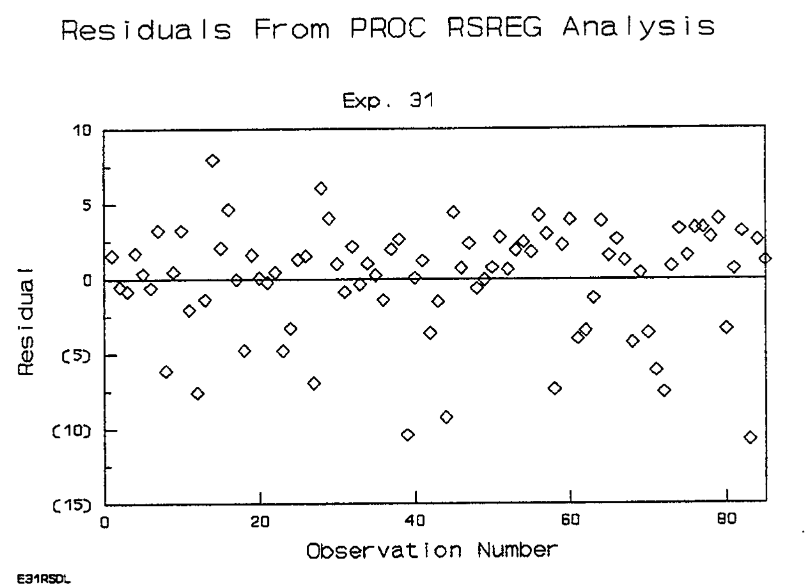

Figure 3 : Regression Analysis Residuals for the Data Utilized for Experiment 31

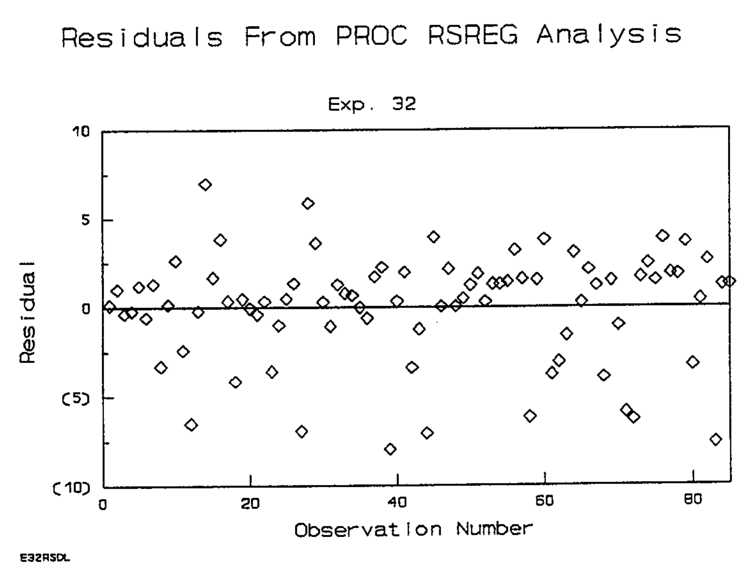

Figure 4 : Regression Analysis Residuals for the Data Utilized for Experiment 32.

data points were not used in the data analyses. This poor performance exhibited by all cells at 30°C, 1C Charge Rate, 1C Discharge Rate, and 20% State of Charge must be noted. Additionally, cell number 34 exhibited extremely poor performance at 30°C, 1C Charge Rate, 2C Discharge Rate, and 100% State of Charge.

PROC MEANS Analysis for Cold Plate H

Considering all conditions with watt-hour efficiency measurements within the test matrix, experiment number 33 afforded the highest mean watt-hour efficiency (79.5%) while experiment number 34 dispensed the lowest (69.4%). Experiments 31 and 32 exhibited mean watt-hour efficiencies of 77.2% and 76.6%, respectively, while experiments 35 and 36 showed essentially equal mean watt-hour efficiencies of 75.8%. These overall means are shown in Figure 5.

The standard deviation from the mean for each experiment must be noted in accordance with the overall means. As shown in Figure 6, data for experiment number 34 imparted the lowest standard deviation, $\sigma \approx 6.5$, while the highest standard deviation was calculated for experiment number 35, $\sigma \approx 7.5$. The standard deviations for experiments 31, 32, and 33 were $\sigma \approx 7.3$, 7.0, and 6.7, respectively. For experiment 36, the standard deviation was essentially the same as that for experiment 35, $\sigma \approx 7.5$.

An examination of mean watt-hour efficiencies for each cell design at specific temperatures in Figure 7 revealed that experiment number 33 exhibited the highest mean at all

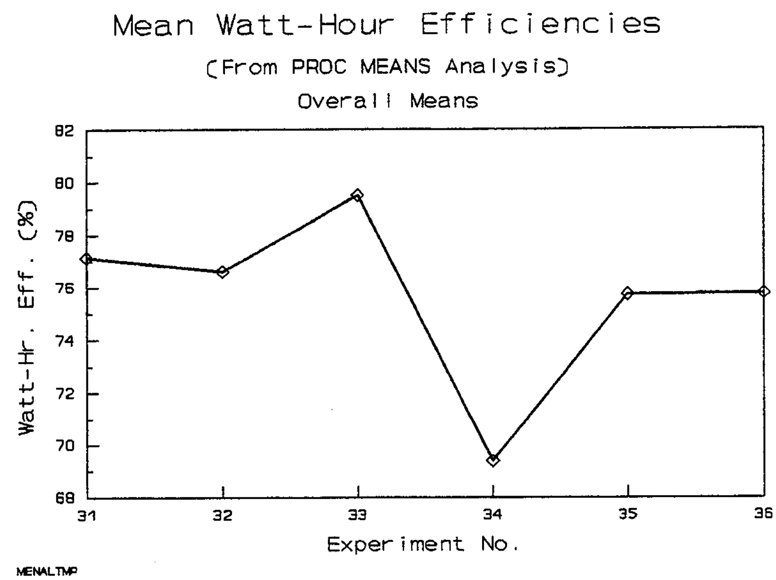

Figure 5 : Overall Mean Watt-Hour Efficiencies for each Cold Plate H Cell

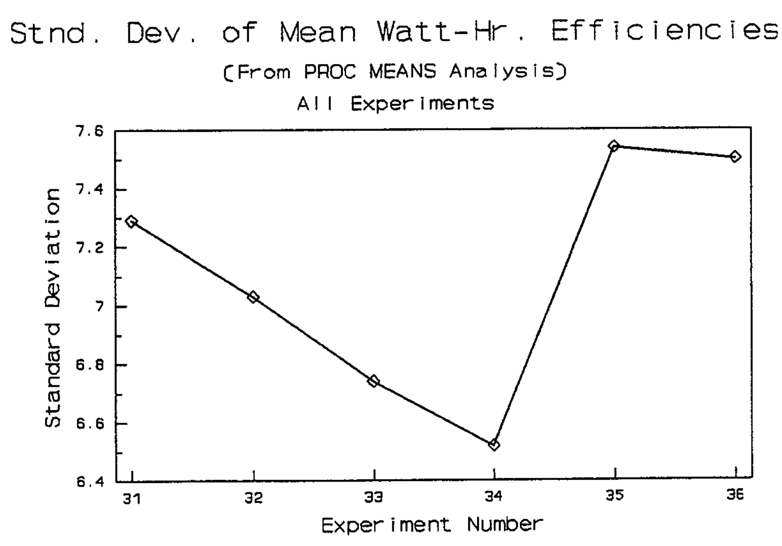

Figure 6 : Standard Deviations of the Overall Mean Watt-Hour Efficiencies for each Cold Plate H Cell

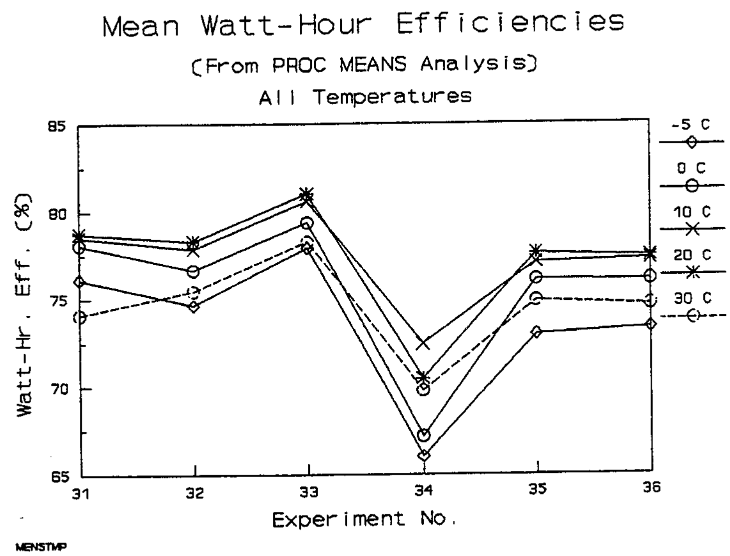

Figure 7 : Constant Temperature Mean Watt-Hour Efficiencies for each Cold Plate H Cell

temperatures while experiment number 34 exhibited the lowest mean at all temperatures (see Figure 7). Each cell achieved the maximum mean watt-hour efficiency at 20°C except for experiment 34, where the maximum was achieved at 10°C. Also, for all experiments except experiment 34, the mean watt-hour efficiencies at 10°C were only slightly less than those at the 20°C maximum. Mean watt-hour efficiencies for each experiment at 0°C were between the maximum and minimum values. Furthermore, for all experiments except number 31, the minimum mean watt-hour efficiencies occurred at -5°C and the means at 30°C were close to those minima. For experiment 31, the mean watt-hour efficiency was smallest at 30°C but the -5°C mean was close to that minimum. Finally, it should be noted that experiments 35 and 36 exhibit essentially the same mean watt-hour efficiencies at all temperatures and experiments 31 and 32 exhibit similar means at 10°C and at 20°C.

Standard deviations from the mean watt-hour efficiencies at each temperature are plotted in Figure 8 for all experiments. The constant temperature standard deviations of mean watt-hour efficiencies for all experiments were greatest at -5°C. The minimum standard deviations occurred at 20°C for experiments 32, 34, 35, and 36. For experiments 31 and 33, the minima occurred at 0°C, but the standard deviations at 20°C for each of those experiments was also relatively small and very close to those minimum values at 0°C. It was noted that the standard deviations for experiments 35 and 36 behaved similarly, with only slight differences at -5°C and at 20°C. The constant temperature standard deviations were almost constant for each cold plate H experiment for the 10°C and 30°C cases.

Maximum and minimum mean watt-hour efficiencies of each cell at every temperature level were also compared. The largest and smallest maxima were recorded as well as the largest and smallest minima. A summary of these values is presented in Table 2 and the maxima, minima, and means for all experiments at each temperature are shown in Figures 9-13. At -5°C for example, the largest maximum mean watt-hour efficiency was 90.5%, which occurred for experiment 33. The smallest maximum mean watt-hour efficiency occurred for experiment number 34 at 75.0%. All other experiments had maxima somewhere in between 75.0% and 90.5% at -5°C. The smallest minimum mean watt-hour efficiency at -5°C

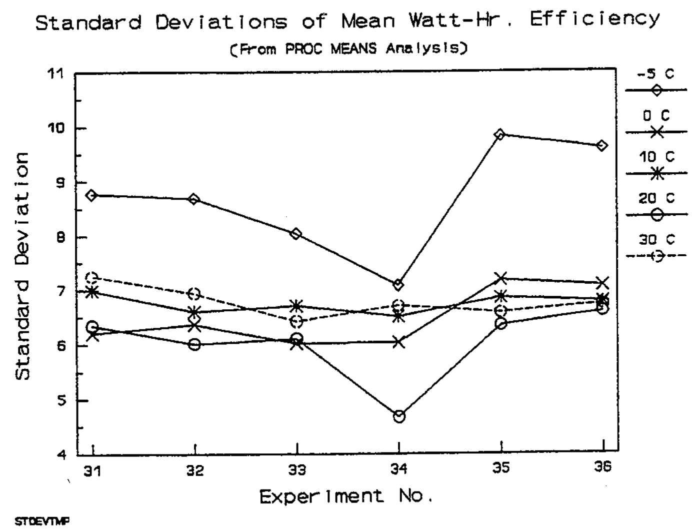

Figure 8 : Standard Deviations of the Constant Temperature Mean Watt-Hour Efficiencies for each Cold Plate H Cell

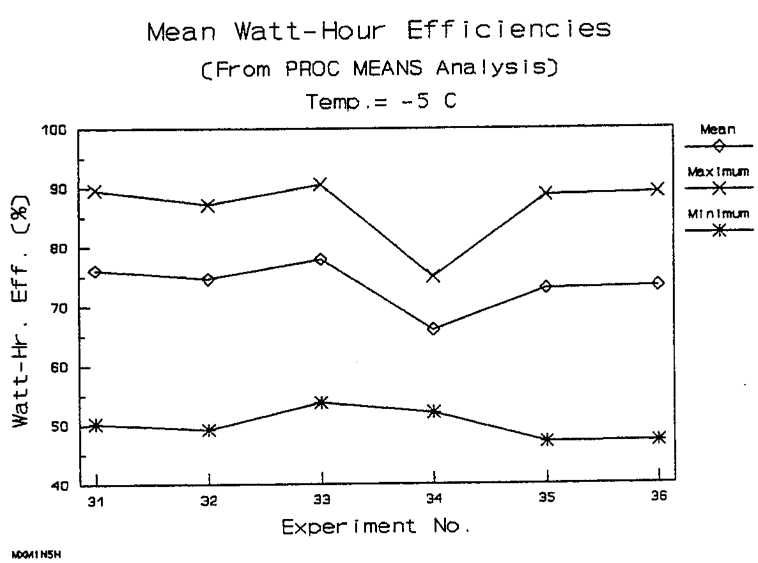

Figure 9 : Maximum, Minimum, and Mean Watt-Hour Efficiencies for Cold Plate H Cells at -5°C

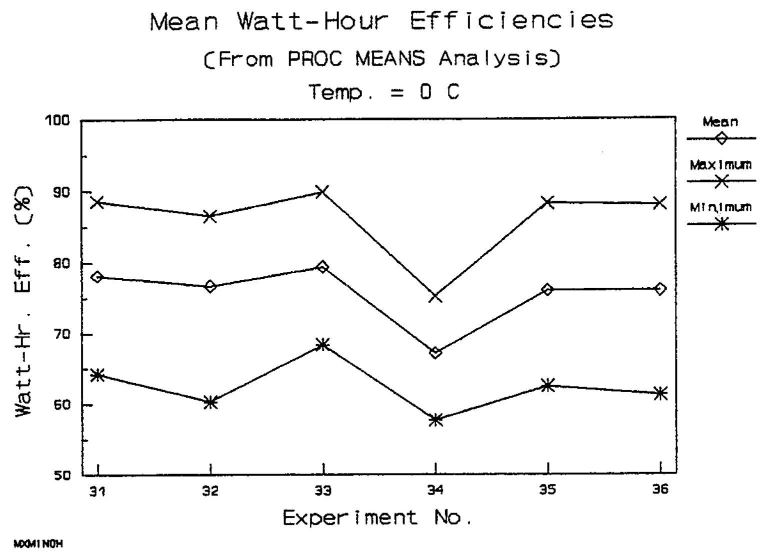

Figure 10 : Maximum, Minimum, and Mean Watt-Hour Efficiencies for Cold Plate H Cells at 0°C

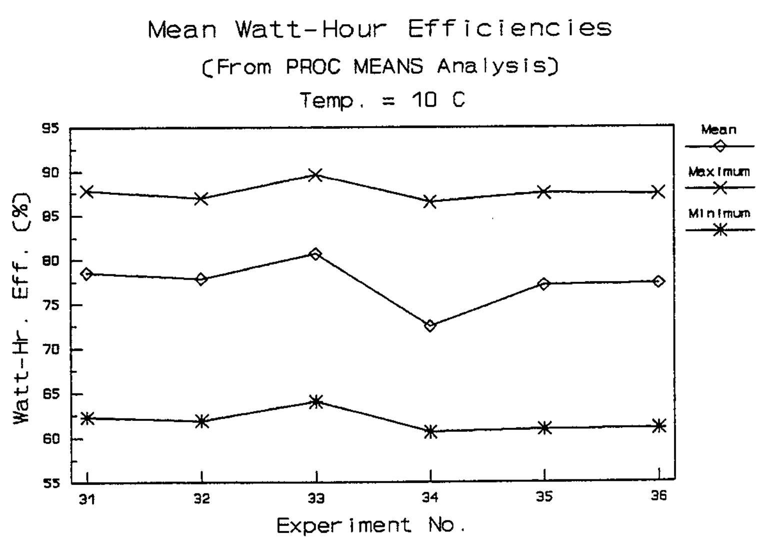

Figure 11 : Maximum, Minimum, and Mean Watt-Hour Efficiencies for Cold Plate H Cells at 10°C

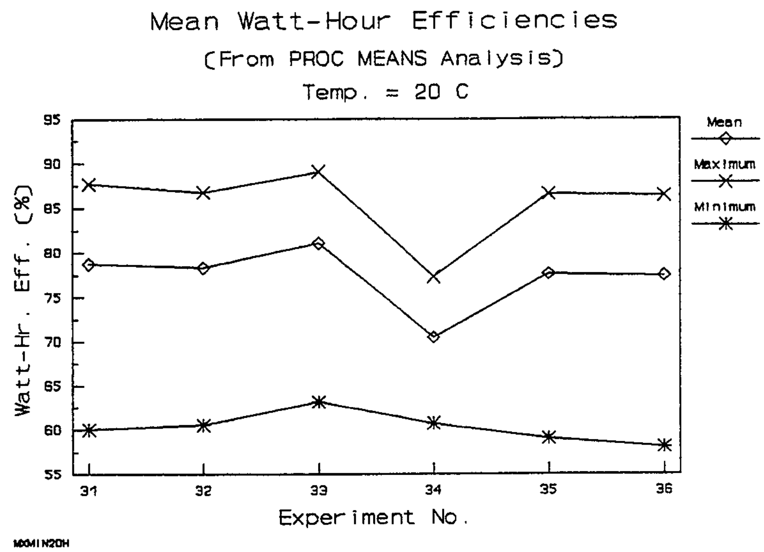

Figure 12 : Maximum, Minimum, and Mean Watt-Hour Efficiencies for Cold Plate H Cells at 20°C

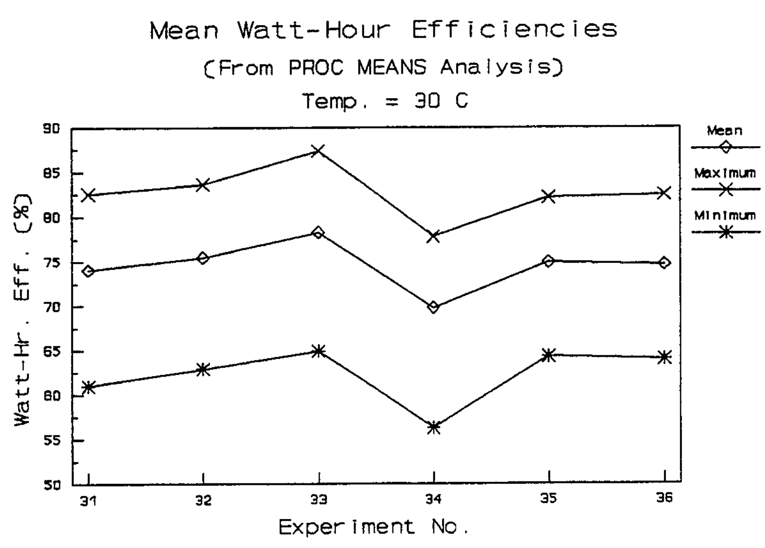

Figure 13 : Maximum, Minimum, and Mean Watt-Hour Efficiencies for Cold Plate H Cells at 30°C

occurred for experiment number 35 at 47.1% . The largest minimum occurred for experiment 33 at 53.8% .

Table 2

Largest and Smallest Minimum and Maximum
Mean Watt-Hour Efficiencies for Cold Plate H

Temperature	Smallest Minimum	Largest Minimum	Smallest Maximum	Largest Maximum
-5°C	Exp. 35 (47.1%)	Exp. 33 (53.8%)	Exp. 34 (75.0%)	Exp. 33 (90.5%)
0°C	Exp. 34 (57.7%)	Exp. 33 (68.4%)	Exp. 34 (75.3%)	Exp. 33 (89.9%)
10°C	Exp. 34 (60.6%)	Exp. 33 (64.0%)	Exp. 34 (86.5%)	Exp. 33 (89.6%)
20°C	Exp. 36 (58.1%)	Exp. 33 (63.2%)	Exp. 34 (77.3%)	Exp. 33 (89.1%)
30°C	Exp. 34 (56.3%)	Exp. 33 (64.9%)	Exp. 34 (77.8%)	Exp. 33 (87.4%)

In most cases, experiment number 33 showed the largest maximum and minimum watt-hour efficiencies and experiment number 34 showed the smallest.

In summary, the PROC MEANS analysis indicated that experiment number 33 exhibited the best overall performance and experiment number 34 showed the worst performance. Experiments 31, 32, 35, and 36 performed somewhere in between experiments 33 and 34 in most cases. Furthermore, experiments 35 and 36 demonstrated essentially identical behavior. The mean watt-hour efficiencies for all cold plate H cells were highest at 20°C, next highest at 10°C, and then at 0°C. The exception to this was cell 34 where best overall performance occurred for 10°C cases and the worst performance was exhibited at -5°C. The worst performance was observed at −5°C for all other cells except for cell 31 where 30°C yielded the poorest performance. Also, the standard deviations were smallest at 20°C for all cold plate H cells except cells 31 and 33 where the standard deviations for those cells were slightly smaller at 0°C than at 20°C.

PROC CORR Analysis for Cold Plate H

All of the experiments showed strongest overall correlation between the discharge rate and the watt-hour efficiency, except for number 34, where the strongest correlation was computed for state of charge and watt-hour efficiency. But for all cases, none of the correlation coefficients had absolute values greater than 0.75 . Each experiment exhibited curves of the form shown in Figure 14, except for experiment number 34 (see Figure 15). The negative correlation coefficient values for discharge rate and watt-hour efficiency imply an inverse relationship, where an increase in the discharge rate is associated with a decrease in watt-hour efficiency. Correlation coefficients between watt-hour efficiency and temperature and between watt-hour efficiency and state of charge were approximately zero for all experiments (indicating no linear correlation) except number 34 where a correlation coefficient of −0.54 was computed between state of charge and watt-hour efficiency. Correlation coefficients between charge rate and watt-hour efficiency were between −0.19 and −0.27 for all experiments except for experiment number 34,

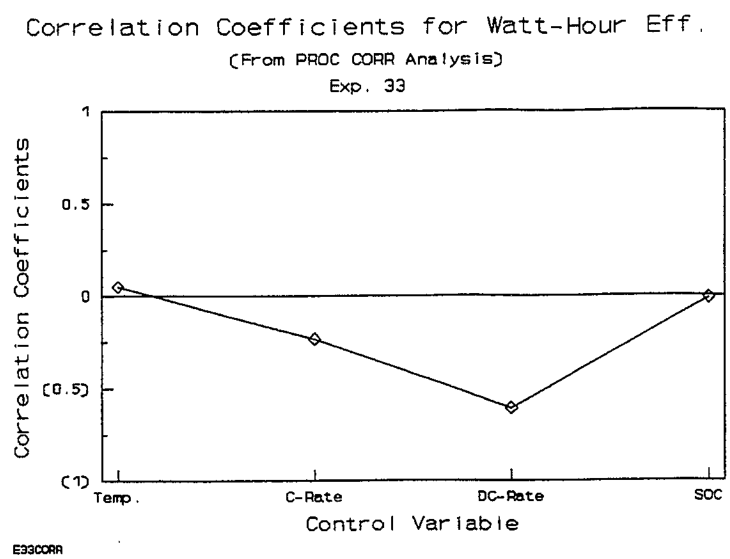

Figure 14 : Correlation Coefficients for Experiment 33 (From PROC CORR Analysis)

(Temp.=Temperature; C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

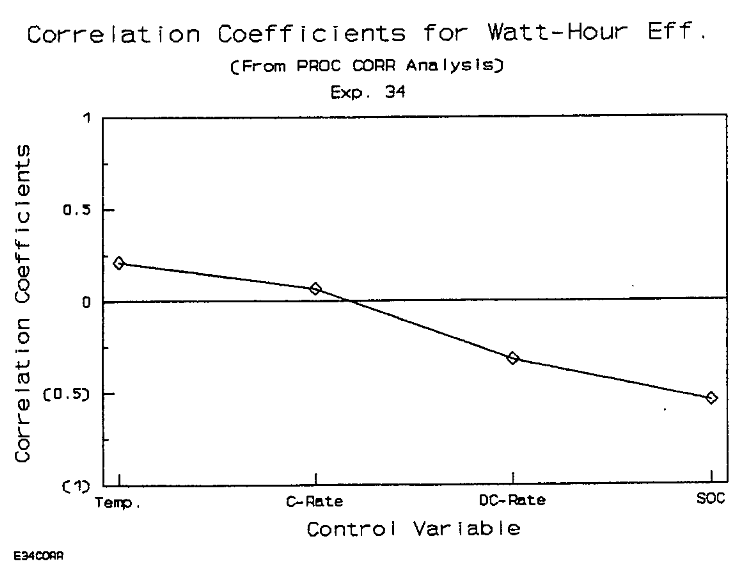

Figure 15 : Correlation Coefficients for Experiment 34 (From PROC CORR Analysis)

where a positive correlation coefficient was determined (≈ +0.07). It was noted that the correlation behavior for experiments 35 and 36 were practically identical.

Correlation coefficients between the charge rate and watt-hour efficiency, discharge rate and watt-hour efficiency, and between state of charge and watt-hour efficiency were examined for each experiment at constant temperatures. The curves behaved similarly for all experiments (except number 34) as seen in Figures 16, 17, 18, 20, and 21. For all experiments except number 34 (see Figure 19), the highest degree of linear correlation occurred between the discharge rate and watt-hour efficiency except for the 30°C cases where the correlation coefficients between state of charge and watt-hour efficiency was roughly equal to those for discharge rate and watt-hour efficiency (≈ −0.5 to −0.6). Again, the constant temperature correlation coefficients were almost identical for experiments 35 and 36. Results for experiment number 34 showed the highest degree of linear correlation between state of charge and watt-hour efficiency at all temperatures, except at 10°C where the magnitude of the correlation coefficient was greater for the discharge rate - watt-hour efficiency couple (−0.54) than for the state of charge - watt-hour efficiency couple (−0.24).

Results of the Correlation Analyses indicated that the discharge rate is most closely correlated with watt-hour efficiency for all cells except cell number 34. Results for cells 35 and 36 are especially similar and results for experiment 34 deviate substantially from those of the other cells. At 30°C,

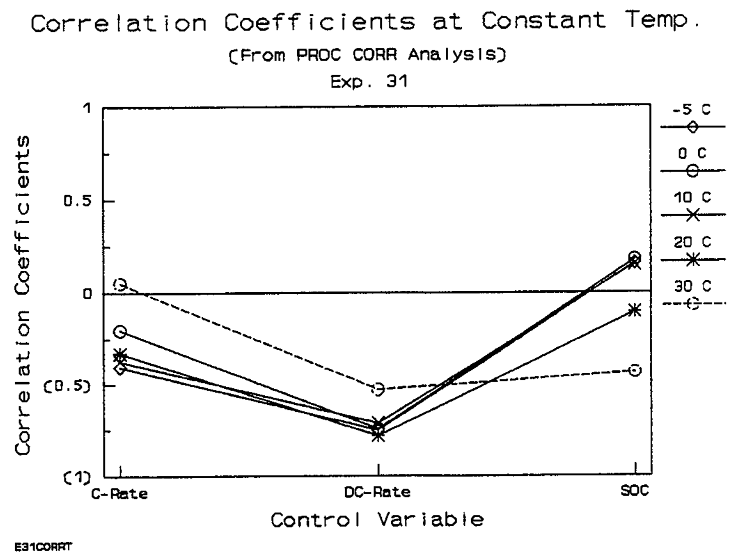

Figure 16 : Correlation Coefficients for Experiment 31 at each Temperature Level

(C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

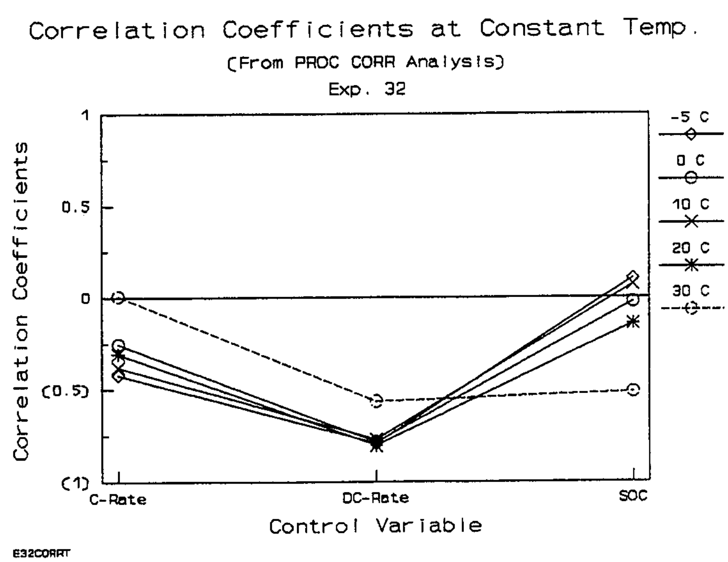

Figure 17 : Correlation Coefficients for Experiment 32 at each Temperature Level

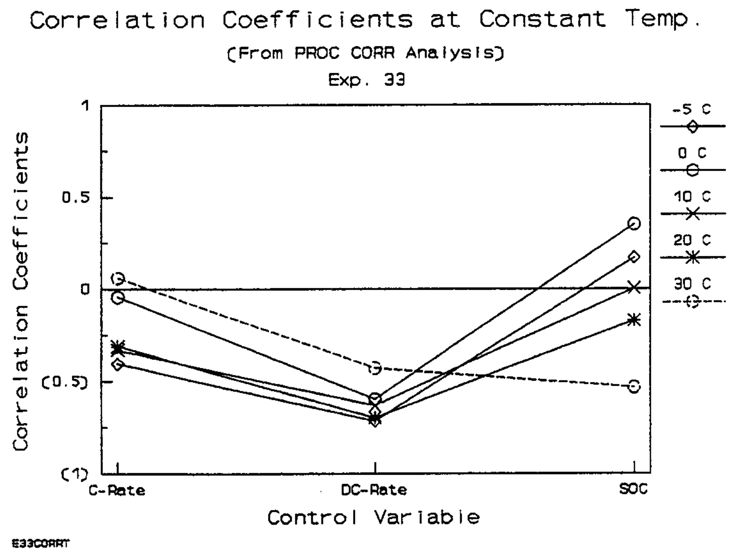

Figure 18 : Correlation Coefficients for Experiment 33 at each Temperature Level

(C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

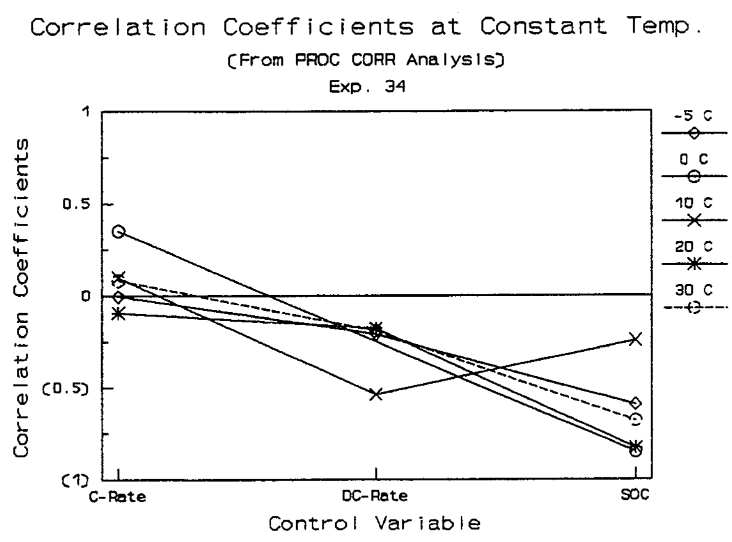

Figure 19 : Correlation Coefficients for Experiment 34 at each Temperature Level

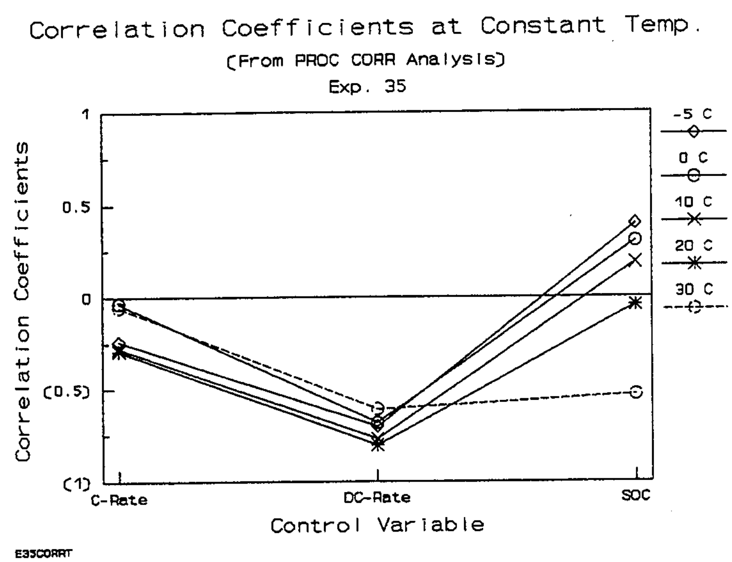

Figure 20 : Correlation Coefficients for Experiment 35 at each Temperature Level

(C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

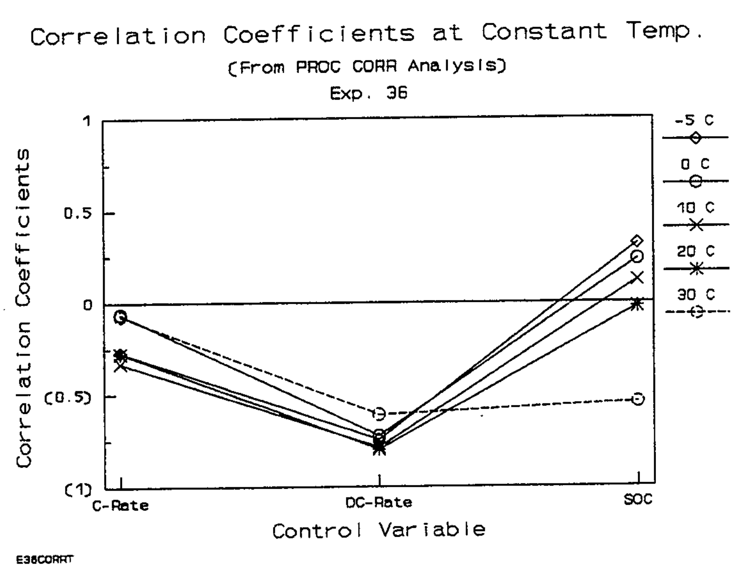

Figure 21 : Correlation Coefficients for Experiment 36 at each Temperature Level

all cells exhibited approximately zero correlation between charge rate and watt-hour efficiency. For all experiments except number 34, the correlation coefficients between charge rate and watt-hour efficiency were between -0.41 and +0.05 for all temperatures. But as seen in Figure 19, experiment number 34 exhibited correlation coefficients between -0.09 and +0.35 over the entire temperature range. Correlation coefficients between state of charge and watt-hour efficiency varied with temperature for each cell. Correlation coefficients at 30°C were approximately -0.52 for each cell except cell numbers 34 (-0.68) and 31 (-0.43). At 20°C, the range was 0 - -0.17 for all cells except cell number 34 (-0.82). The correlation coefficients at -5°C, 0°C, and 10°C were between 0 and +0.4 for all cells except number 34, where the correlation coefficients between state of charge and watt-hour efficiency were between -0.85 and -0.25 for that temperature range.

In summary, the discharge rate is most strongly correlated (negative correlation) with the watt-hour efficiency for all cells at all temperatures except 30°C. Again, results for experiment number 34 differed substantially from results of the other cells and cells 35 and 36 behaved similarly. Additional information regarding pair-wise correlations is analyzed next in the regression analysis section.

PROC RSREG for Cold Plate H

A quadratic surface was fit to all of the data for each cold plate H experiment. The estimated curve-fit parameters are given in Appendix V. Coefficients of determination of the quadratic fit (also called R^2 coefficients) are plotted in Figure 22 for each cell and the coefficients of variation for each experiment are plotted in Figure 23. The coefficient of determination was best for experiment 34 (≈0.85) and worst for experiment 33 (≈0.67). As seen in Figure 22, R^2 for experiments 31, 32, 35, and 36 were between 0.74 and 0.82 and R^2 for experiments 35 and 36 were the same. The coefficient of variation was smallest for experiment 34 (≈4.1) while experiment 33 exhibited the largest coefficient of variation (≈5.3). Coefficients of variation for the other experiments were between 4.2 and 5.2 and the values for experiments 35 and 36 were similar. The R^2 values for experiments 31, 32, 34-36 (above 0.74) are adequate while the R^2 value for experiment 33 (0.67) was relatively low, but acceptable.

Significance levels for each term in the quadratic fit (except the intercept) were plotted for each experiment in Figures 24-29. Significance levels below 0.05 indicate that the probability of having a zero coefficient is small, thereby implying that the term is significant and has an impact upon predicted watt-hour efficiencies. The charge rate was significant for all data sets (although only marginally significant for experiment 34). Temperature was not significant for experiments 31 and 33. State of charge was significant only for experiment number 34. Since the correlation analyses suggested strongest correlations between discharge rate and watt-hour efficiency for all experiments except 34, low significance

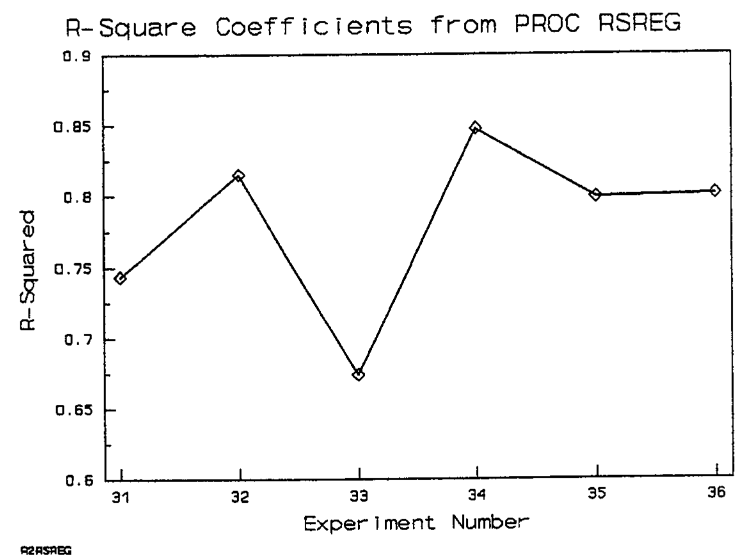

Figure 22 : Coefficients of Determination from Regression Analysis for all Cold Plate H Experiments

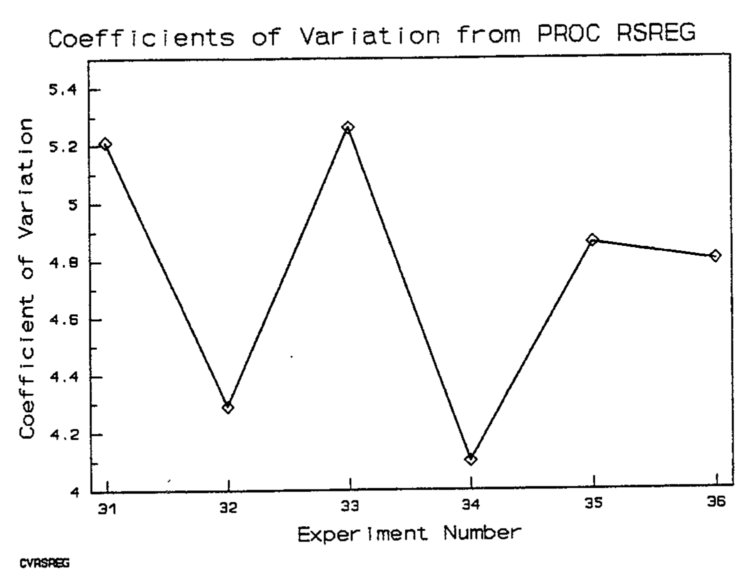

Figure 23 : Coefficients of Variation from Regression Analysis for all Cold Plate H Experiments

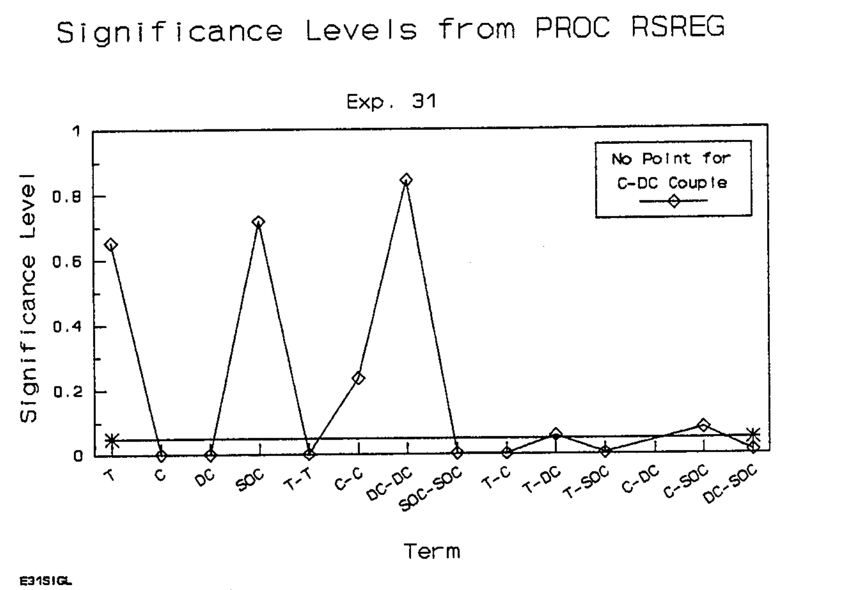

Figure 24 : Significance Levels from Regression Analysis for Experiment 31

(T=Temperature; C=Charge Rate; DC=Discharge Rate; SOC=State of Charge)

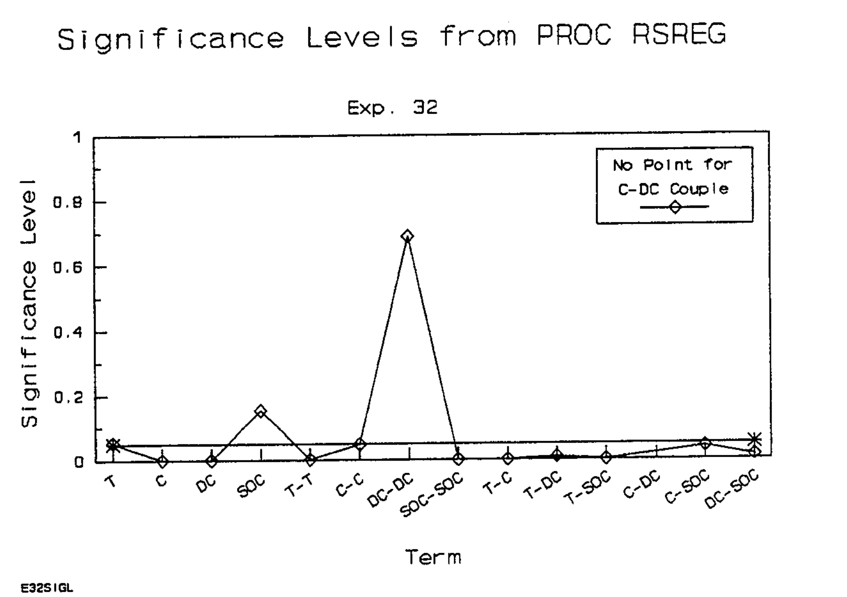

Figure 25 : Significance Levels from Regression Analysis for Experiment 32

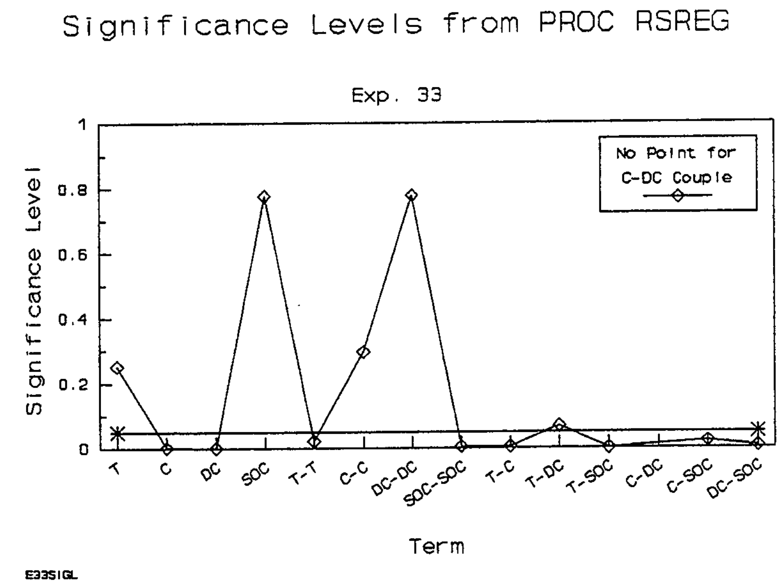

Figure 26 : Significance Levels from Regression Analysis for Experiment 33

(T=Temperature; C=Charge Rate; DC=Discharge Rate; SOC=State of Charge)

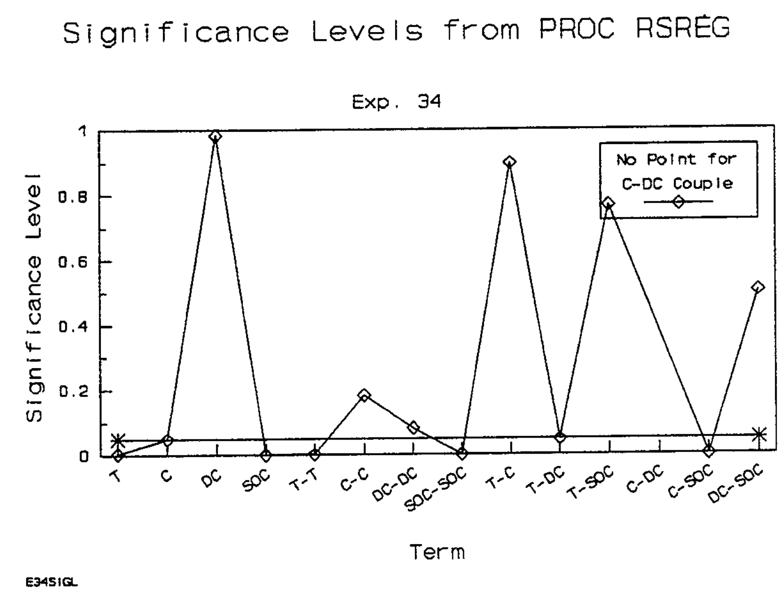

Figure 27 : Significance Levels from Regression Analysis for Experiment 34

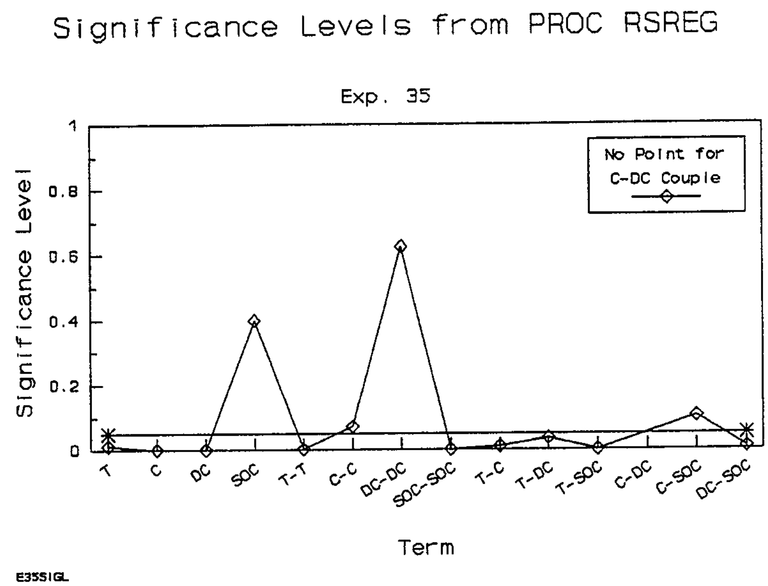

Figure 28 : Significance Levels from Regression Analysis for Experiment 35

(T=Temperature; C=Charge Rate; DC=Discharge Rate; SOC=State of Charge)

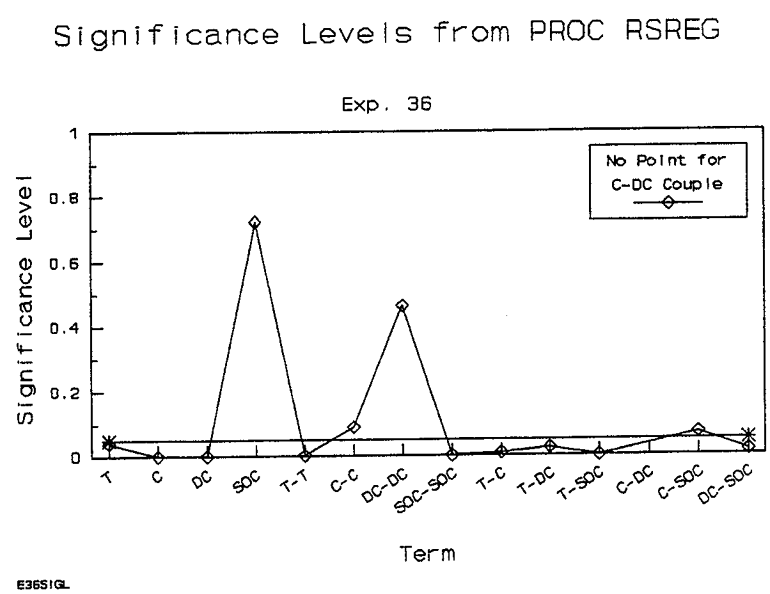

Figure 29 : Significance Levels from Regression Analysis for Experiment 36

levels were expected for the discharge rate from the regression analyses. All experiments except number 34 did indeed exhibit significance for the discharge rate. The temperature-charge rate couple was significant for all experiments except number 34 while the temperature-discharge couple was at least marginally significant for all experiments. The temperature-state of charge couple was significant for all experiments except experiment number 34. (This is interesting since the temperature and state of charge terms alone both exhibited significance only for experiment 34.) Charge rate-state of charge couples were significant for experiments 32, 33, and 34 but not for experiments 31, 35, and 36. Discharge rate-state of charge couples were significant for all experiments except 34. Once again, the significance levels for experiments 35 and 36 were very similar.

Note that the curve-fit parameters (Appendix V) estimated for the charge rate - discharge rate couples for all cold plate H experiments were zero. This means that the effect of the charge rate - discharge rate cross-product is a linear combination of some of the other factors. For this case, the degree of freedom for the charge rate - discharge rate couple is zero, therefore, the coefficient for that couple is zero. This is not surprising since the levels for the charge rate are 0.1C, 0.25C, 0.5C, and 1C while the levels for the discharge rate are 0.1C, 0.5C, 1C, and 2C. For the data utilized in the analyses, many of the charge rate - discharge rate cross-product terms were duplicated (ie. charge rate=1C x discharge rate=1C ; charge rate=0.5C x discharge rate=2C both equal unity) such that the influence of this cross-product is diminished.

For all PROC RSREG analyses, the critical values which were determined for temperature, charge rate, discharge rate, and state of charge represented a saddle point, therefore, no interior optima were detected. This indicates that the optimum conditions lie along at least one of the parameter boundaries. These optima were not determined.

PLATE H CONCLUSIONS AND SUMMARY

In general, results from the PROC MEANS analysis indicated that experiment number 33 exhibited the best overall performance and experiment number 34 exhibited the worst overall performance. All cold plate H cells performed best at 20°C, then performance dropped only slightly at 10°C, then further at 0°C. In all cases, operation at -5°C and at 30°C allowed for poor performance. Results from the PROC CORR and PROC RSREG analyses suggested that the discharge rate is the control variable that has the greatest impact upon cell performance. In conclusion for the cold plate H analyses, cell number 33, operated between 10°C and 20°C would perform better than cells 31, 32, 34, 35, and 36. Furthermore, results for experiments 35 and 36 were very similar and it can be concluded that these two cell designs exhibit equivalent performance.

RESULTS FOR COLD PLATE B

The five cells on cold plate B were designated as experiments 13, 14, 15, 16, and 18. The design features of each of these cells are summarized in Appendix I. All of the raw data with measured watt-hour efficiencies were used in the statistical analyses except for a small number of suspect data points for experiments 13, 14, and 18. During the regression analyses, outliers for experiments 13, 14, and 18 were discovered, where the residuals for those outliers were extremely large. Figure 30 is a representative example of residuals of the outliers, shown here for experiment 13. The outliers were deleted from the data base and were not used in any of the analyses reported here. Figure 31 depicts the residuals from the regression analyses for experiments 13 after the outliers have been removed from the data base. Plots of the residuals for experiments 14 through 18, both with and without the outliers, are similar to the plots shown for experiment 13 in Figures 30 and 31. The corresponding conditions for the Cold Plate B outliers are shown in Table 3.

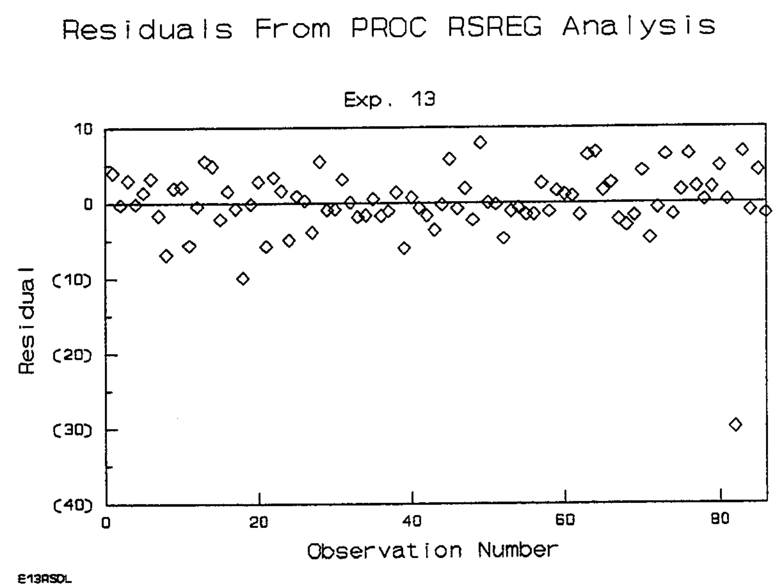

Figure 30 : Regression Analysis Residuals for Raw Data for Experiment 13

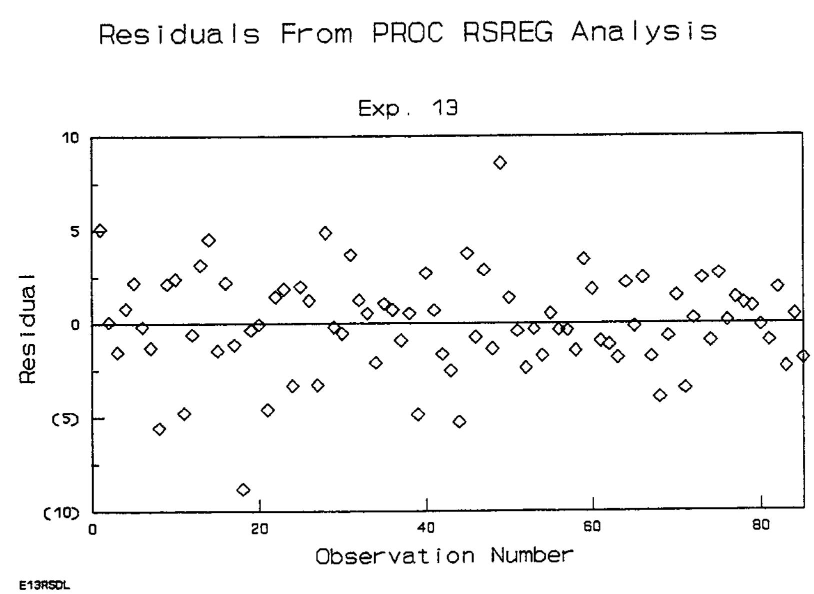

Figure 31 : Regression Analysis Residuals for the Data Utilized for Experiment 13

Table 3

Outliers from Regression Analysis for Cold Plate B
(These points are valid but were removed from the analyses)

Experiment Number	Temp. (°C)	Charge Rate	Discharge Rate	State of Charge	Watt-Hr Eff.
13	30	1 C	1 C	20 %	38.28 %
14	-5	1 C	2 C	100 %	34.94 %
14	30	1 C	1 C	20 %	28.19 %
18	-5	1 C	2 C	60 %	37.24 %
18	-5	1 C	2 C	100 %	27.82 %
18	0	1 C	2 C	100 %	30.39 %
18	10	1 C	2 C	100 %	37.76 %
18	30	1 C	1 C	20 %	38.76 %

Note that the values listed in Table 3 are valid data points but represent outliers. The watt-hour efficiencies of these outliers in Table 3 are very low and these data points were not used in the data analyses. The poor performance exhibited by cells 13, 14, and 18 at 30°C, 1C Charge Rate, 1C Discharge Rate, and 20% State of Charge must be recognized, as well as the poor performance exhibited by cells 14 and 18 under the conditions outlined in Table 3.

PROC MEANS Analysis for Cold Plate B

Examination of the watt-hour efficiency measurements for all of the experiments on cold plate B under the selected test conditions disclosed that experiment number 16 afforded the highest overall mean watt-hour efficiencies (82.2%) and experiment 18 dispensed the lowest (71.9%). Experiment 15 exhibited an overall mean watt-hour efficiency of 81.5% while experiments 13 and 14 exhibited overall mean watt-hour efficiencies of 78.3% and 73.7%, respectively. These overall means are shown in Figure 32.

The standard deviation from the mean for each experiment was also noted. As shown in Figure 33, data for experiments 15 and 16 imparted the lowest standard deviations, both approximately $\sigma \approx 5.1$, while the highest standard deviation was calculated for experiment number 14, where $\sigma \approx 9.0$. The standard deviations for experiments 13 and 18 were $\sigma \approx 6.5$ and $\sigma \approx 6.9$, respectively.

An examination of mean watt-hour efficiencies for each cell design at specific temperatures revealed that experiment number 16 exhibited the highest means at all temperatures, as seen in Figure 34. Mean watt-hour efficiencies for experiment 15 were only slightly less than those means for experiment 16. Experiment number 18 exhibited the lowest mean watt-hour efficiencies at all temperatures and the means for experiment 14 were almost as low.

As seen in Figure 34, each cell on cold plate B achieved the maximum mean watt-hour efficiency at 10°C, except for experiment 18, where the maximum mean occurred at -5°C. The smallest mean watt-hour efficiencies were observed at 30°C for all experiments, but the overall means at -5°C were close to the 30°C means for experiments 13 and 15. In general, the overall means were best at 10°C and the means became progressively smaller as the temperature changed from 10°C to 20°C to 0°C to

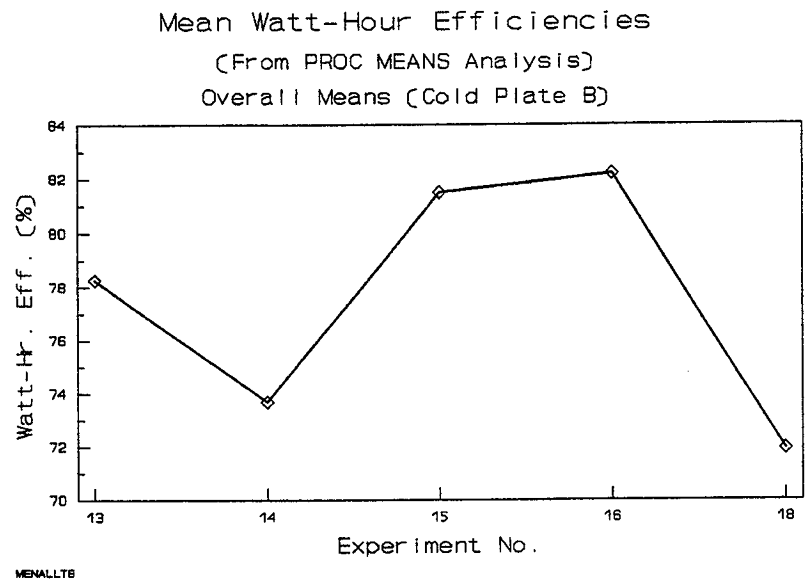

Figure 32 : Overall Mean Watt-Hour Efficiencies for Each Cold Plate B Cell

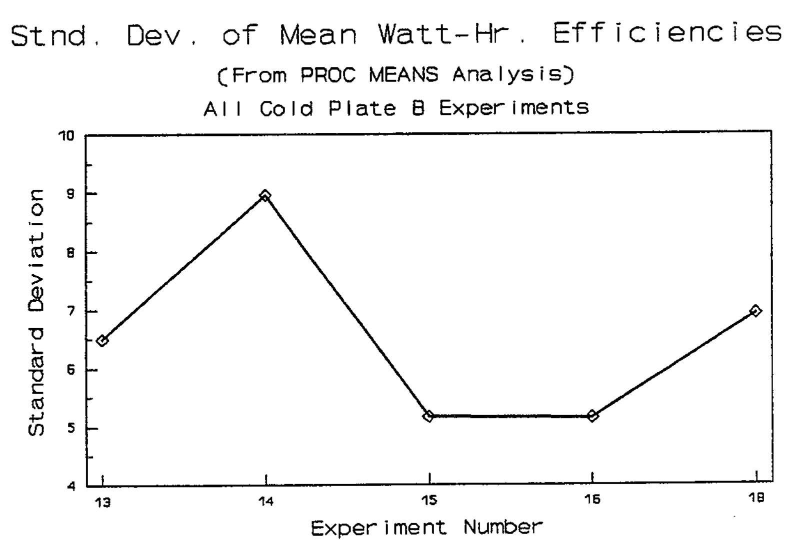

Figure 33 : Standard Deviations of the Overall Mean Watt-Hour Efficiencies for each Cold Plate B Cell

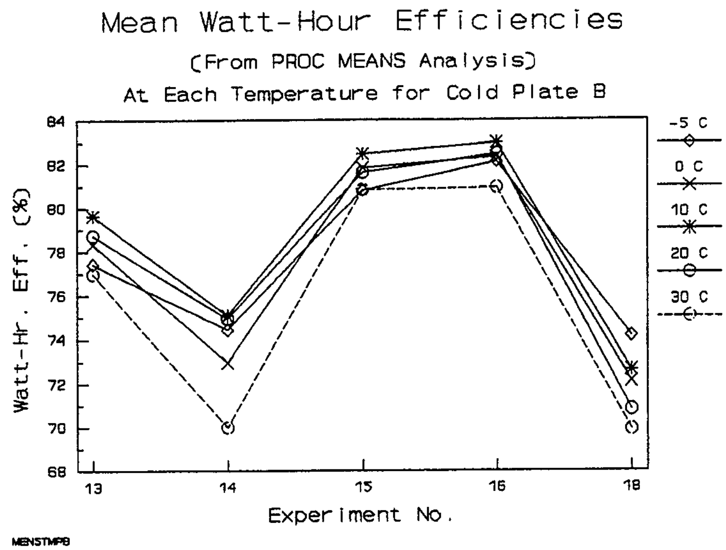

Figure 34 : Constant Temperature Mean Watt-Hour Efficiencies for all Cold Plate B Cells

-5°C and finally to 30°C. Lastly, it should be noted that experiments 15 and 16 exhibited similar mean watt-hour efficiencies at all temperatures with only a slight discrepancy at -5°C, as seen in Figure 34.

Standard deviations from the mean watt-hour efficiencies at each temperature are plotted in Figure 35 for all cold plate B experiments. The constant temperature standard deviation of mean watt-hour efficiencies for experiments 13, 15, and 16 were greatest at -5°C and relatively small at the other temperatures. For experiment 14, the smallest standard deviation was calculated for the 20°C case and the largest for the 0°C case. For experiment 18, the smallest standard deviation occurred at 0°C and the largest occurred at 20°C. Again, the results for experiments 15 and 16 were very similar. Considering all

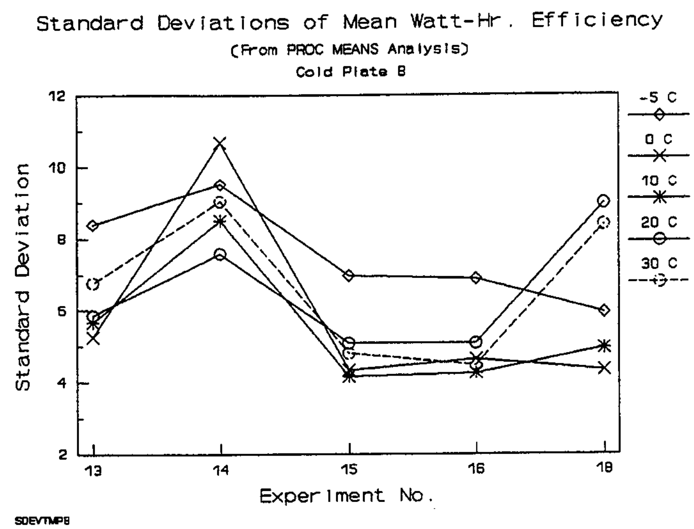

Figure 35 : Standard Deviations of the Constant Temperature Mean Watt-Hour Efficiencies for all Cold Plate B Cells

temperatures, the smallest standard deviations were exhibited by experiments 15 and 16 and the largest standard deviations were exhibited by experiment 14, as observed in Figure 35.

Maximum and minimum mean watt-hour efficiencies of each cell at every temperature level were compared. The largest and smallest maxima were recorded as well as the largest and smallest minima. A summary of these values is presented in Table 4 and the maxima, minima, and means for all experiments at each temperature are shown in Figures 36-40. At -5°C for example, the largest maximum mean watt-hour efficiency was 89.2%, which occurred for experiment 16. The smallest maximum mean watt-hour efficiency occurred for experiment number 14 with a value of 85.3%. All other experiments had maxima somewhere in between

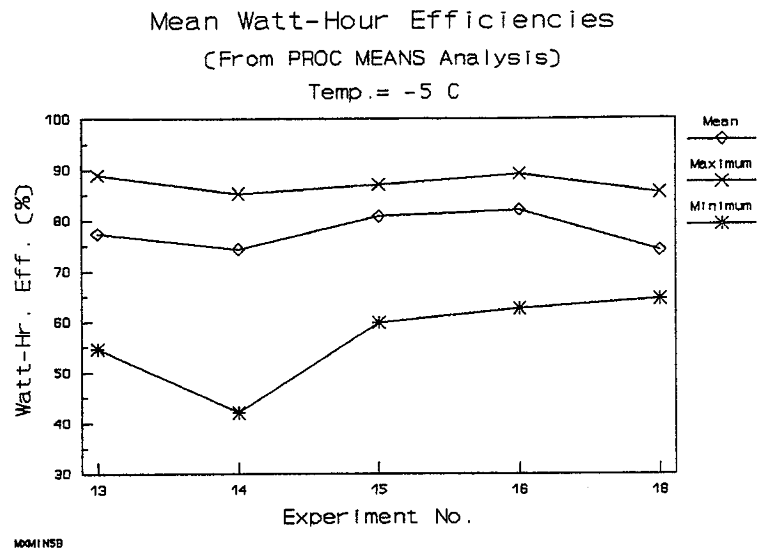

Figure 36 : Maximum, Minimum, and Mean Watt-Hour Efficiencies at −5°C for all Cold Plate B Cells

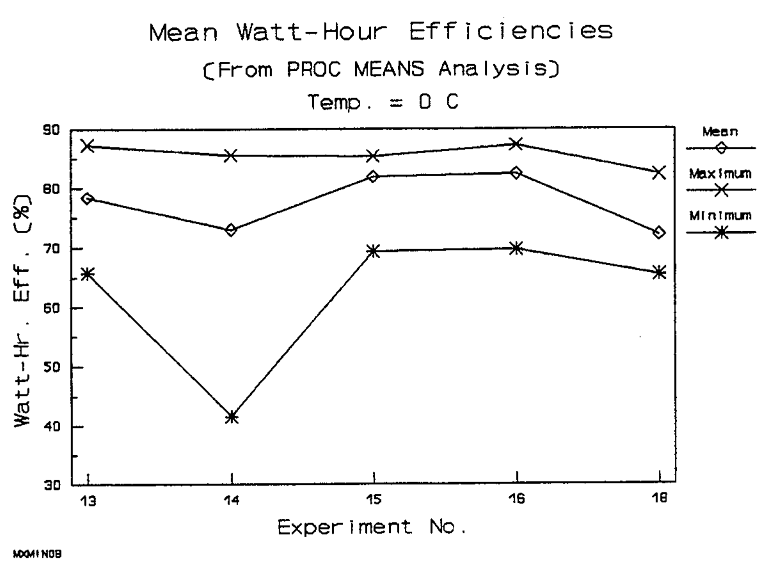

Figure 37 : Maximum, Minimum, and Mean Watt-Hour Efficiencies at 0°C for all Cold Plate B Cells

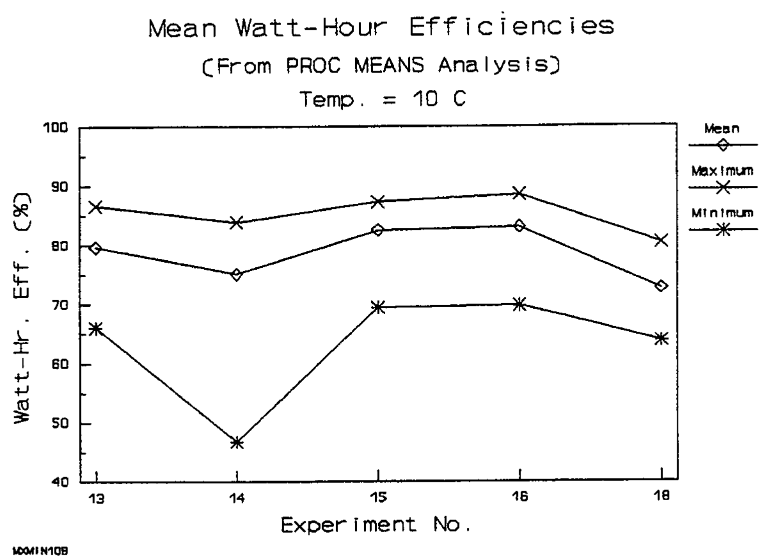

Figure 38 : Maximum, Minimum, and Mean Watt-Hour Efficiencies at 10°C for all Cold Plate B Cells

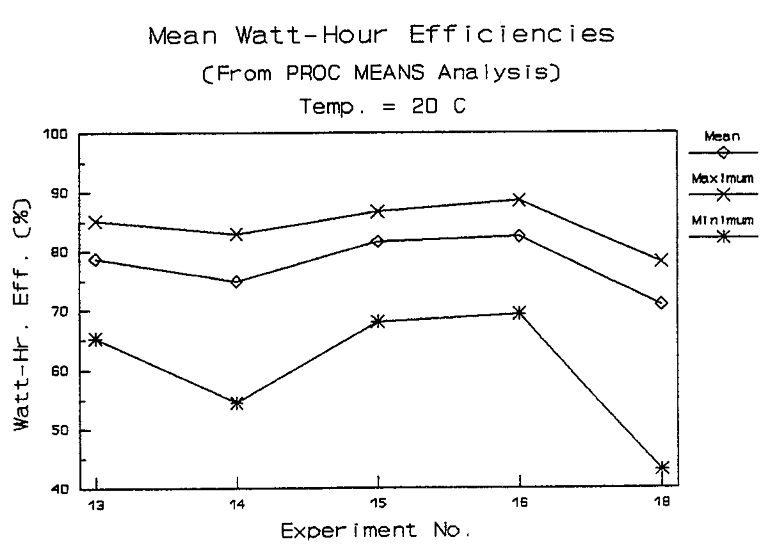

Figure 39 : Maximum, Minimum, and Mean Watt-Hour Efficiencies at 20°C for all Cold Plate B Cells

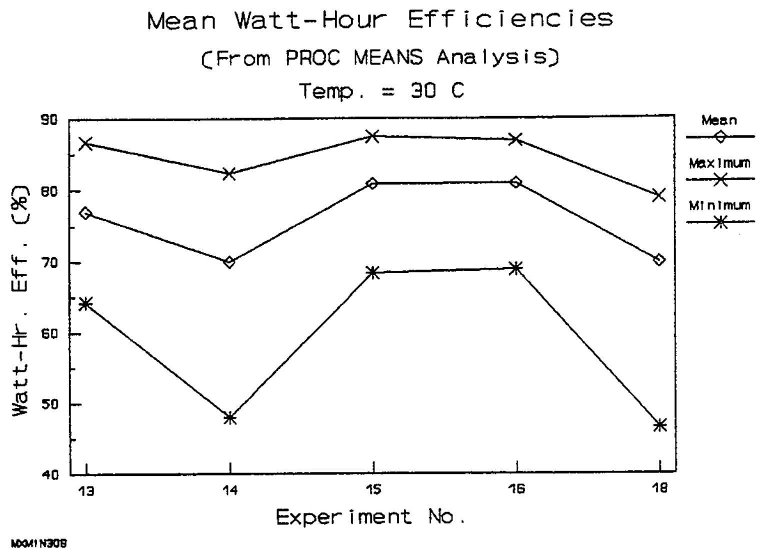

Figure 40 : Maximum, Minimum, and Mean Watt-Hour Efficiencies at 30°C for all Cold Plate B Cells

85.3% and 89.2% . The smallest minimum watt-hour efficiency at -5°C occurred for experiment number 14 at a value of 42.1% . The largest minimum occurred for experiment 18 at 64.6% . For most of the cases, experiments 14 and 18 showed the smallest minimum and maximum mean watt-hour efficiencies at all temperatures while experiment 16 showed the largest.

In summary, the PROC MEANS analysis indicated that experiment numbers 15 and 16 exhibited the best overall performance with experiment 16 performing slightly better than experiment 15. Experiment numbers 14 and 18 generally showed the worst performance and experiment 13 performed somewhere in between the best and worst cases. Furthermore, experiments 15 and 16 demonstrated similar behavior.

TABLE 4

Largest and Smallest Minimum and Maximum
Mean Watt-Hour Efficiencies for Cold Plate B

Temperature	Smallest Minimum	Largest Minimum	Smallest Maximum	Largest Maximum
-5°C	Exp. 14 (42.1%)	Exp. 18 (64.6%)	Exp. 14 (85.3%)	Exp. 16 (89.2%)
0°C	Exp. 14 (41.6%)	Exp. 16 (69.7%)	Exp. 18 (82.2%)	Exp. 13 (87.3%)
10°C	Exp. 14 (46.8%)	Exp. 16 (69.8%)	Exp. 18 (80.3%)	Exp. 16 (88.5%)
20°C	Exp. 18 (43.1%)	Exp. 16 (69.3%)	Exp. 18 (78.1%)	Exp. 16 (88.5%)
30°C	Exp. 18 (46.6%)	Exp. 16 (68.9%)	Exp. 18 (78.9%)	Exp. 15 (87.4%)

PROC CORR Analysis for Cold Plate B

All of the experiments showed strongest overall correlation between the discharge rate and the watt-hour efficiency, however none of the correlation coefficients had absolute values greater than 0.71 . Each experiment exhibited curves of the general form shown in Figure 41. The negative correlation coefficient values for discharge rate and watt-hour efficiency imply an inverse relationship, where an increase in the discharge rate is associated with a decrease in watt-hour efficiency. Correlation coefficients between watt-hour efficiency and temperature were very close to zero for all experiments, except number 18 where the coefficient was approximately -0.2 . Correlation coefficients between charge rate and watt-hour efficiency were between -0.22 and -0.44 for all cold plate B experiments whereas

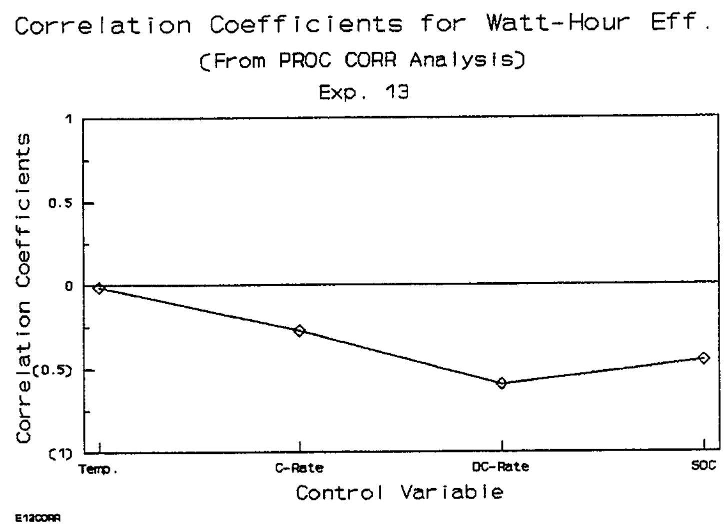

Figure 41 : Correlation Coefficients for Experiment 13

(Temp.=Temperature; C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

the correlation coefficients between state of charge and watt-hour efficiency were between -0.3 and -0.45 .

Correlation coefficients between the charge rate and watt-hour efficiency, discharge rate and watt-hour efficiency, and between state of charge and watt-hour efficiency were examined for each experiment at constant temperatures. The curves are plotted in Figures 42-46. The highest degree of linear correlation at each temperature (except 30°C) occurred between the discharge rate and watt-hour efficiency for all Cold Plate B cells. For the 30°C cases, the correlation coefficients between state of charge and watt-hour efficiency were greatest in magnitude for all experiments, as shown in Figures 42-46. In addition, the correlation coefficients for the discharge

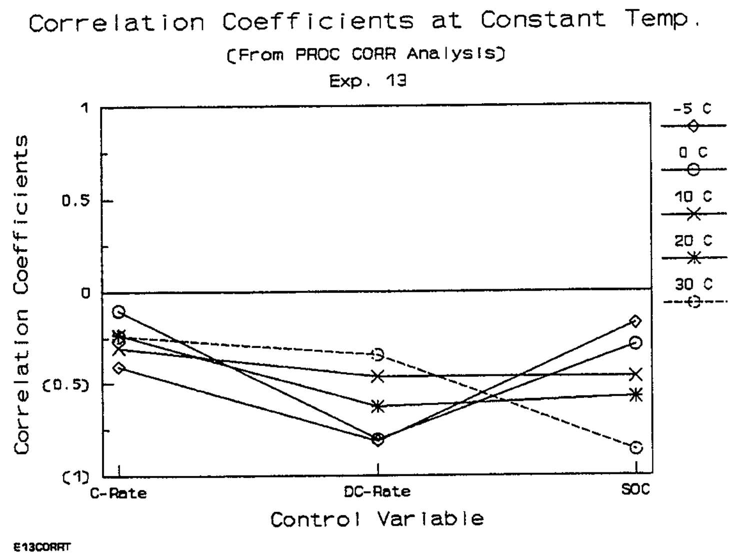

Figure 42 : Correlation Coefficients for Experiment 13 at each Temperature Level

(C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

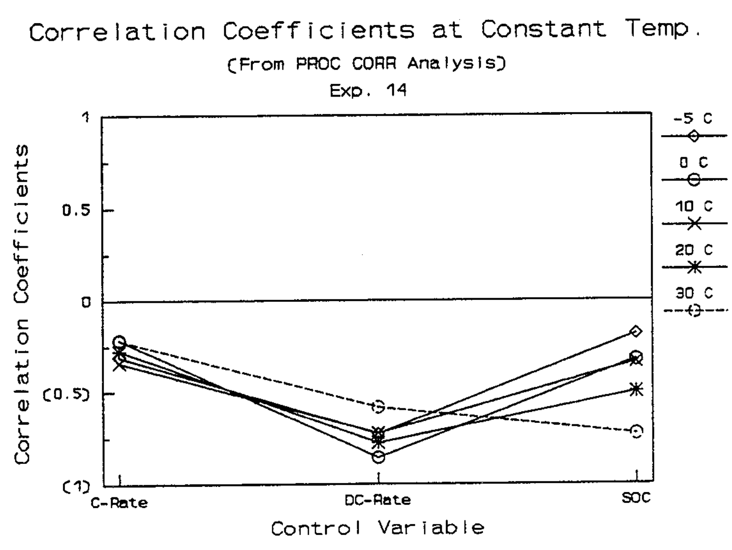

Figure 43 : Correlation Coefficients for Experiment 14 at each Temperature Level

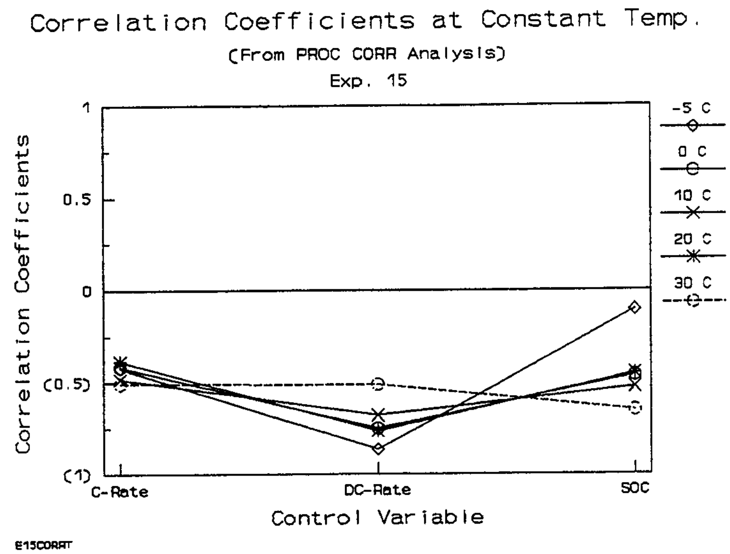

Figure 44 : Correlation Coefficients for Experiment 15 at each Temperature Level

(C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

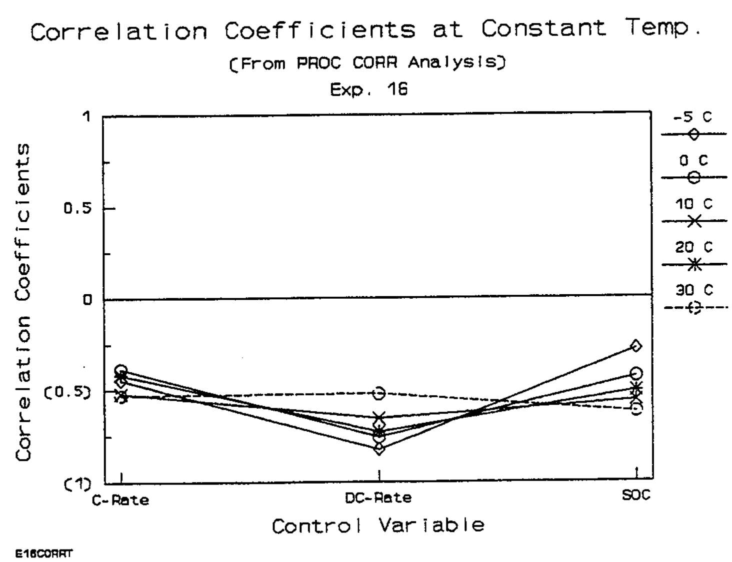

Figure 45 : Correlation Coefficients for Experiment 16 at each Temperature Level

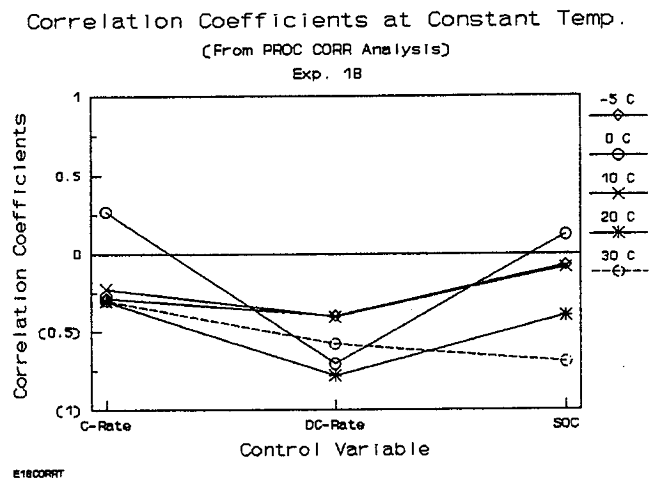

Figure 46 : Correlation Coefficients for Experiment 18 at each Temperature Level

(C-Rate=Charge Rate; DC-Rate=Discharge Rate; SOC=State of Charge)

rate-watt-hour efficiency couple and the state of charge-watt-hour efficiency couple were approximately the same for experiment 13 at 10°C and 20°C. The only positive correlation coefficients were computed for the charge rate - watt-hour efficiency couple and the state of charge - watt-hour efficiency couple for experiment 18 at 0°C.

Results of the Correlation Analyses for plate B indicate that the discharge rate is most closely correlated with watt-hour efficiency for all cells at all temperatures except at 30°C, where state of charge is most strongly correlated.

PROC RSREG for Cold Plate B

A quadratic surface was fit to all of the data for each cold plate B experiment. The estimated curve-fit parameters are given in Appendix V. Coefficients of determination of the quadratic fit (also called R^2 coefficients) are plotted in Figure 47 for each cell and the coefficients of variation for each experiment are plotted in Figure 48. The largest coefficient of determination was computed for experiment 16 (≈0.93) and the smallest coefficients were computed for experiments 13 and 18 (both ≈0.83). The regression analyses for experiments 14 and 15 produced coefficients of determination of roughly 0.90 and 0.92, respectively. As seen in Figure 48, the coefficient of variation was smallest for experiment 16 (≈1.8) and largest for experiment 18 (≈4.3). The coefficients of variation for experiments 13, 14, and 15 were 3.7, 4.2, and 2.0, respectively.

Significance levels for each term in the quadratic fit (except the intercept) were plotted for each cold plate B experiment in Figures 49-53. Significance levels below 0.05 imply that particular term of the quadratic fit is significant. The charge rate, discharge rate, and state of charge were found to be significant for all experiments but temperature was marginally significant for experiments 16 only. These results do not contradict those results from the plate B Correlation Analyses where the watt-hour efficiency was determined to be most strongly correlated with the discharge rate. Furthermore, the temperature-charge rate couple, the temperature-discharge rate couple, and the temperature-state of charge couple are significant for experiments 13, 14, and 15, however, only the temperature-state of charge couple is significant for

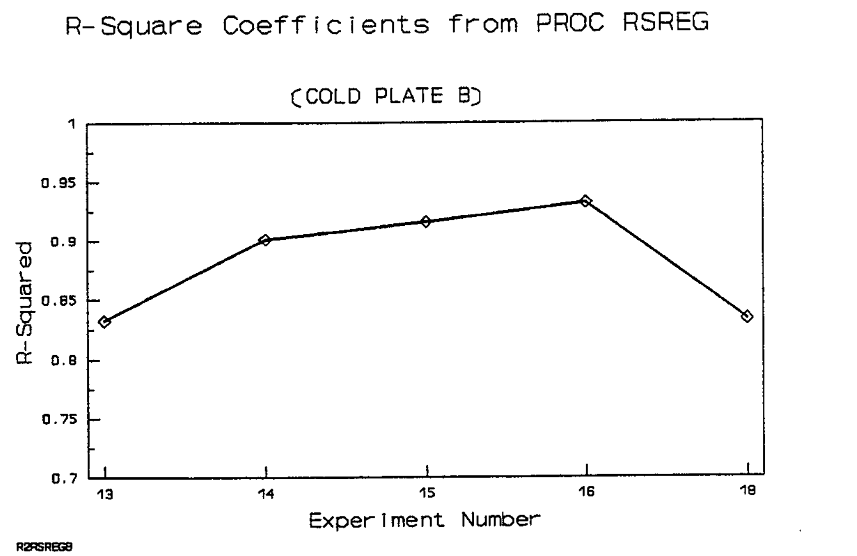

Figure 47 : Coefficients of Determination from Regression Analysis for all Cold Plate B Experiments

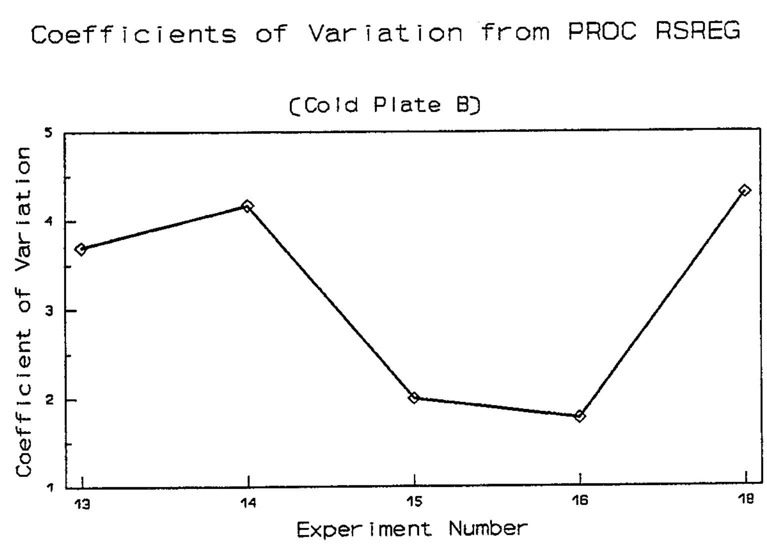

Figure 48 : Coefficients of Variation from Regression Analysis for all Cold Plate B Experiments

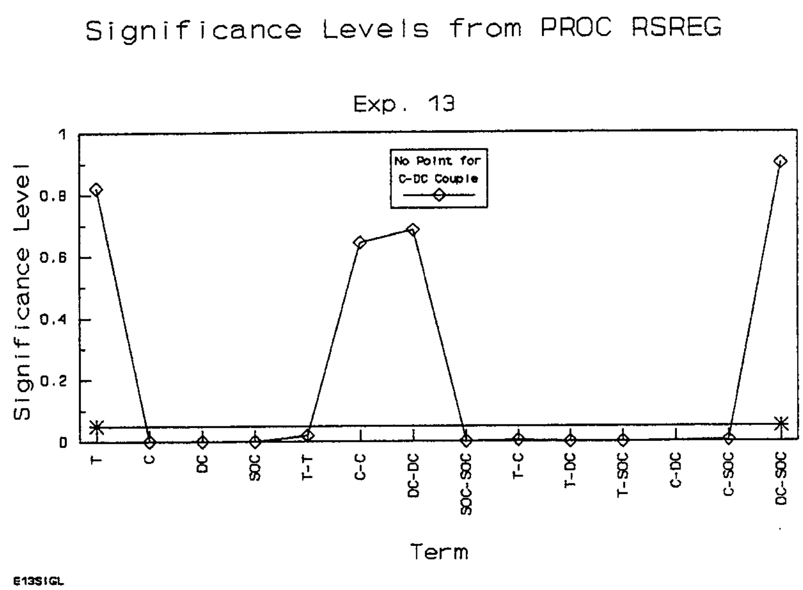

Figure 49 : Significance Levels from Regression Analysis for Experiment 13

(T=Temperature; C=Charge Rate; DC=Discharge Rate; SOC=State of Charge)

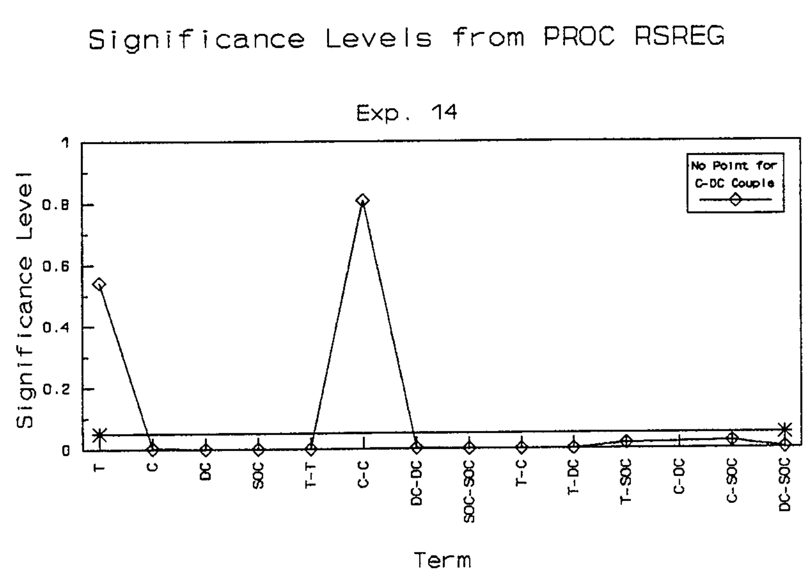

Figure 50 : Significance Levels from Regression Analysis for Experiment 14

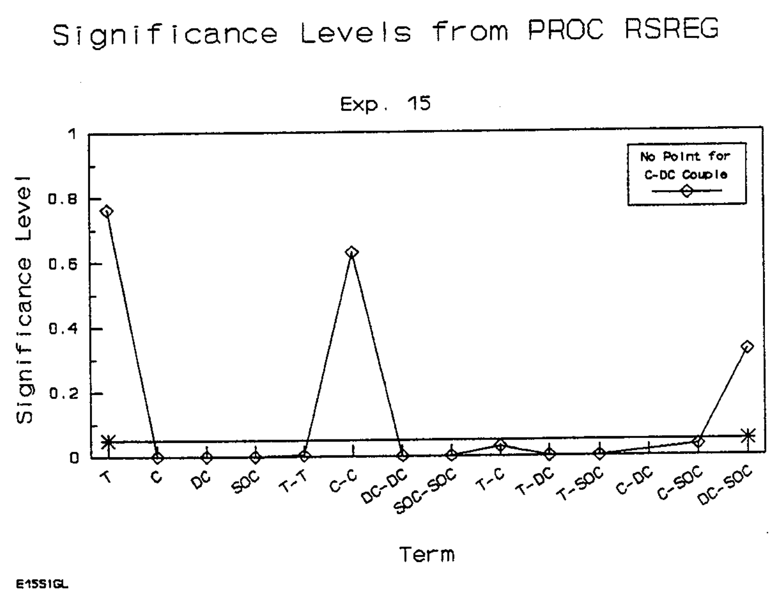

Figure 51 : Significance Levels from Regression Analysis for Experiment 15

(T=Temperature; C=Charge Rate; DC=Discharge Rate; SOC=State of Charge)

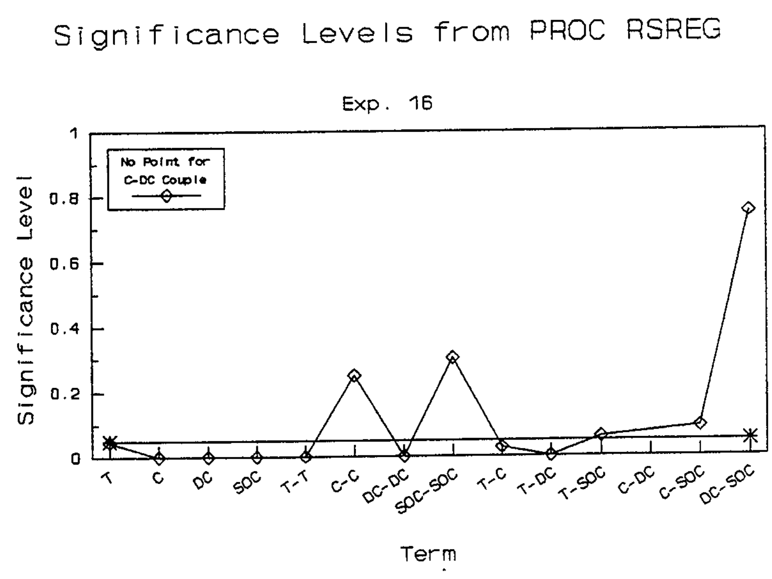

Figure 52 : Significance Levels from Regression Analysis for Experiment 16

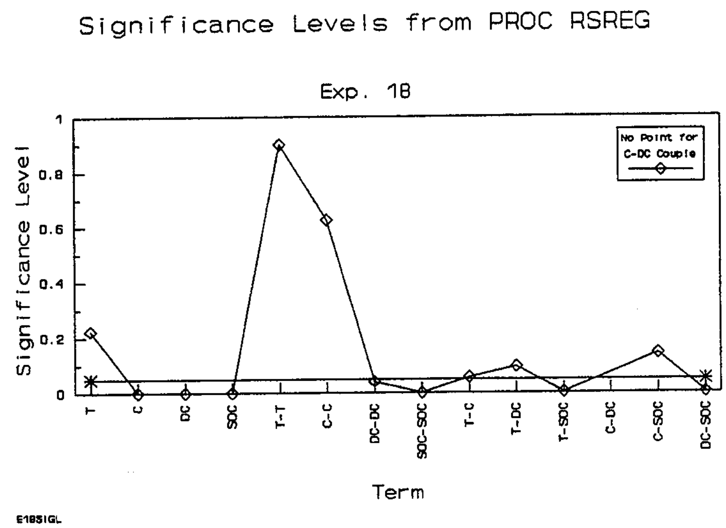

Figure 53 : Significance Levels from Regression Analysis for Experiment 18

(T=Temperature; C=Charge Rate; DC=Discharge Rate; SOC=State of Charge)

experiment 18 and only the temperature-charge rate and temperature-discharge rate couples are significant for experiment 16. The charge rate - state of charge couple was significant for experiments 13, 14, and 15 while the discharge rate - state of charge couple was significant for experiments 14 and 18 only.

As was the case for the cold plate H data, the curve-fit parameters (Appendix V) estimated for the charge rate - discharge rate couples for all cold plate B experiments were zero. This means that the effect of the charge rate - discharge rate cross-product is a linear combination of some of the other factors. For this case, the degree of freedom for the charge rate - discharge rate couple is zero, therefore, the coefficient for that couple is zero. This is not surprising since the levels for the charge rate are 0.1C, 0.25C, 0.5C, and 1C while the levels for the discharge rate are 0.1C, 0.5C, 1C, and 2C. For the data utilized in the analyses, many of the charge rate - discharge rate cross-product terms were duplicated (ie. charge rate=1C x discharge rate=1C ; charge rate=0.5C x discharge rate=2C both equal unity) such that the influence of this cross-product is diminished.

PLATE B CONCLUSIONS AND SUMMARY

In general, experiment number 16 exhibited the best overall performance and experiment numbers 14 and 18 exhibited the worst overall performance. Results for experiments 15 and 16 were somewhat similar, however, it was not concluded that the cell designs for experiments 15 and 16 manifest equivalent results. Overall, each cold plate B cell performed best at 10°C except for cell number 18, which performed better at -5°C. For all experiments except number 18, the 20°C performance was only slightly worse than the 10°C performance. In all cases, the worst cell performance was noted at 30°C but the -5°C performance was almost as poor for experiments 13 and 15. Performance for all cells at 0°C was between the maximum and minimum performance. In addition, the discharge rate appears to be the control variable that has the greatest impact upon cell performance.

In conclusion for the cold plate B analysis, cell number 16, operated between 10°C and 20°C, would perform better than cells 13, 14, and 18. Cell number 15 exhibited performance comparable to cell 16 in most cases, but cell 16 performed slightly better in most cases.

For all PROC RSREG analyses, the critical values which were determined for temperature, charge rate, discharge rate, and state of charge represented a saddle point, therefore, no interior optima were detected. This indicates that the optimum conditions lie along at least one of the parameter boundaries. These optima were not determined.

OVERALL CONCLUSIONS AND RECOMMENDATIONS

From the preliminary statistical analyses that were performed, it was concluded that experiment number 33 performed better than all other cold plate H experiments and experiment number 16 performed better than all other cold plate B experiments. Overall performance was determined to be best at temperatures between 10°C and 20°C for both cold plates and the discharge rate correlated most strongly (negative correlation) with the watt-hour efficiency.

Future work should focus on analyzing the voltages of the cells on each cold plate and sensitivity analyses may provide more information regarding cell behavior.

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APPENDIX I

DESCRIPTION OF THE DESIGN FEATURES OF THE Ni-H_2 CELLS THAT WERE TESTED.

$Ni-H_2$ Cell Design Features

COLD PLATE B

Experiment #	Design Features
13	Back-to-Back Electrode Arrangement, Dual Stack, Serrated Asbestos/Zircar Separator, 26% KOH, Pt Catalyzed Wall Wick
14	Back-to-Back Electrode Arrangement, Dual Stack, Serrated Asbestos/Zircar Separator, 31% KOH, Pt Catalyzed Wall Wick
15	Back-to-Back Electrode Arrangement, Single Stack, Serrated Zircar Separator, 31% KOH
16	Back-to-Back Electrode Arrangement, Single Stack, Serrated Zircar Separator, 26% KOH
18	Back-to-Back Electrode Arrangement, Single Stack, Serrated Asbestos/Zircar Separator, 26% KOH, Pt Catalyzed Wall Wick

COLD PLATE H

Experiment #	Design Features
31	Recirculating Electrode Arrangement, Dual Stack, Zircar Separators, 31% KOH
32	Back-to-Back Electrode Arrangement, Dual Stack, Asbestos Separator, 26% KOH, Pt Catalyzed Wall Wick
33	Recirculating Electrode Arrangement, Unit Stack, Zircar Separators, 31% KOH
34	Back-to-Back Electrode Arrangement, Unit Stack, Asbestos Separator, 26% KOH, Pt Catalyzed Wall Wick
35 & 36	Back-to-Back Electrode Arrangement, Unit Stack, Asbestos Separator, 26% KOH, Pt Catalyzed Wall Wick

Note : All cells are 65 A-hr capacity except for cell numbers 33 and 34 which are 50 A-hr capacity.

APPENDIX II

SAMPLE SAS PROCEDURE FOR ANALYSIS OF MEANS (PROC MEANS)

```
/* ***************************************************** */
/* FILE : MEANS.SAS                                      */
/*                                                       */
/* MEANS PROCEDURE FOR EXPERIMENT NUMBERS 31-36 ON COLD  */
/* PLATE H FOR TASK 8606-01.                             */
/*                                                       */
/* ***************************************************** */
/*                                                       */
/*                                                       */
/* INPUT RAW DATA                                        */
/*                                                       */
DATA RAWDATA;
   INFILE 'EXP36.DAT';
   INPUT X0 X1-X4 Y;
     LABEL X0='EXP. NO.'
           X1='TEMPERATURE'
           X2='CHARGE RATE'
           X3='DISCHARGE RATE'
           X4='STATE OF CHARGE'
           Y='WATT-HOUR EFFICIENCY';
/*                                                       */
/*                                                       */
/* SORT DATA AND CALL MEANS PROCEDURE                    */
PROC SORT DATA=RAWDATA ; BY X1-X4 ;
/* PROC PRINTTO NAME='EXP36.MEN' NEW;   */
PROC PRINTTO;
/*                                                       */
PROC MEANS;
PROC MEANS;
   BY X1;
PROC SORT DATA=RAWDATA ; BY X2-X4 ;
PROC MEANS;
   BY X2;
PROC SORT DATA=RAWDATA ; BY X3-X4 ;
PROC MEANS;
   BY X3;
PROC SORT DATA=RAWDATA ; BY X4 ;
PROC MEANS;
   BY X4;
RUN;
```

APPENDIX III

SAMPLE SAS PROCEDURE FOR

CORRELATION ANALYSIS

(PROC CORR)

```
/* ***************************************************** */
/* FILE : CORR.SAS                                        */
/*                                                        */
/* CORR PROCEDURE FOR EXPERIMENT NUMBERS 31-36 ON COLD    */
/* PLATE H FOR TASK 8606-01.                              */
/*                                                        */
/* ***************************************************** */
/*                                                        */
/*                                                        */
/* INPUT RAW DATA                                         */
/*                                                        */
DATA RAWDATA;
   INFILE 'EXP36.DAT';
   INPUT X0 X1-X4 Y;
     LABEL X0='EXP. NO.'
           X1='TEMPERATURE'
           X2='CHARGE RATE'
           X3='DISCHARGE RATE'
           X4='STATE OF CHARGE'
           Y='WATT-HOUR EFFICIENCY';
/*                                                        */
/*                                                        */
/* SORT DATA AND CALL MEANS PROCEDURE                     */
PROC SORT DATA=RAWDATA ; BY X1-X4 ;
/* PROC PRINTTO NAME='EXP36.COR' NEW;   */
PROC PRINTTO;
/*                                                        */
PROC CORR;
PROC CORR;
   BY X1;
PROC SORT DATA=RAWDATA ; BY X2-X4 ;
PROC CORR;
   BY X2;
PROC SORT DATA=RAWDATA ; BY X3-X4 ;
PROC CORR;
   BY X3;
PROC SORT DATA=RAWDATA ; BY X4 ;
PROC CORR;
   BY X4;
RUN;
```

APPENDIX IV

SAMPLE SAS PROCEDURE FOR REGRESSION ANALYSIS

(PROC RSREG)

```
/* ***************************************************** */
/* FILE : OBSRESID.SAS                                   */
/*                                                       */
/* RSREG PROCEDURE FOR EXPERIMENT NUMBERS 31-36 ON COLD  */
/* PLATE H FOR TASK 8606-01.                             */
/*                                                       */
/* ***************************************************** */
/*                                                       */
/*                                                       */
/* INPUT RAW DATA                                        */
/*                                                       */
DATA RAWDATA;
   INFILE 'EXP31.DAT';
   INPUT X0 X1-X4 Y;
     LABEL X0='EXP. NO.'
           X1='TEMPERATURE'
           X2='CHARGE RATE'
           X3='DISCHARGE RATE'
           X4='STATE OF CHARGE'
           Y='WATT-HOUR EFFICIENCY';
/*                                                       */
PROC PRINT DATA=RAWDATA;
/* STANDARDIZE (NORMALIZE) THE RAW DATA & SORT           */
/*                                                       */
DATA STANDATA;
   SET RAWDATA;
   RENAME X0=SX0;
   RENAME X1=SX1;
   RENAME X2=SX2;
   RENAME X3=SX3;
   RENAME X4=SX4;
   RENAME Y=SY;
PROC STANDARD DATA=STANDATA MEAN=0 STD=1 OUT=STANDATA;
     VAR SX1-SX4;
PROC SORT DATA=STANDATA; BY SX1-SX4;
/*                                                       */
/*                                                       */
/* ECHO PRINT RAW DATA AND STANDARDIZED DATA TO CONSOLE  */
/*                                                       */
/* PROC PRINT DATA=RAWDATA;  */
/* PROC PRINT DATA=STANDATA; */
/*                                                       */
/*                                                       */
/* PRINT RAW DATA AND STANDARDIZED DATA TO OUTPUT FILE   */
/*                                                       */
PROC PRINTTO NAME='OBRSD31.OUT' NEW;
PROC PRINT DATA=RAWDATA;
PROC PRINTTO NAME='OBRSD31.OUT';
PROC PRINT DATA=STANDATA;
/* PROC PRINTTO ;  */
PROC PRINT DATA=STANDATA;
/* PROC RSREG DATA=STANDATA; */
PROC RSREG DATA=STANDATA OUT=RSREGOUT;
    MODEL SY=SX1-SX4 / LACKFIT PREDICT RESIDUAL
                       U95M L95M U95 L95 ;
```

```
PROC PRINT DATA=RSREGOUT;
/*  */
/* set up graphics data file */
PROC PRINTTO NAME='OBRSD31.PLT' NEW;
PROC RSREG DATA=STANDATA OUT=OBSRESID ;
    MODEL SY=SX1-SX4 / LACKFIT RESIDUAL ;
PROC PRINT DATA=OBSRESID;
PROC PRINTTO ;
PROC PRINT DATA=OBSRESID;
/*  */
RUN;
```

APPENDIX V

REGRESSION COEFFICIENTS

FROM PROC RSREG ANALYSIS

REGRESSION PARAMETERS FROM THE PROC RSREG ANALYSES
COLD PLATE H EXPERIMENTS

The Regression Fit is of the Form :

$$Y = I + a_1T + a_2C + a_3DC + a_4SOC + a_5T*T + a_6C*C + a_7DC*DC + a_8SOC*SOC$$
$$+ a_9T*C + a_{10}T*DC + a_{11}T*SOC + a_{12}C*DC + a_{13}C*SOC + a_{14}DC*SOC$$

Where : Y = Watt-Hour Efficiency (%) ; T = Temperature (Coded)
C = Charge Rate (Coded) ; DC = Discharge Rate (Coded)
SOC = State of Charge (Coded)

The Coded Parameters are Estimated by :

	Subtract This	Then Divide By
Temperature (°C)	12.5	17.5
Charge Rate (Fraction of Nameplate)	0.55	0.45
Discharge Rate (Fraction of Nameplate)	1.05	0.95
State of Charge (%)	60.0	40.0

Example for Experiment 31 :
Temp.=10°C ; 1C Charge Rate ; 1C Discharge Rate ; 60% State of Charge
Coded Values : T=-0.1429 ; C=1 ; DC=-0.0526 ; SOC=0 ;
$Y_{REGRESS}$=78.39 % ; (Y_{ACTUAL}=79.11 %)

Parameter Estimates	Exp. 31	Exp. 32	Exp. 33	Exp. 34	Exp. 35	Exp. 36
Intercept (I)	81.76	81.64	83.39	75.72	81.53	81.32
a_1	-0.75	0.60	0.52	-1.12	1.41	1.05
a_2	-2.31	-1.97	-2.08	-1.01	-1.71	-1.79
a_3	-15.21	-14.57	-13.80	-7.10	-15.41	-15.29
a_4	0.56	-0.01	0.45	-3.08	1.74	1.28
a_5	-3.63	-2.89	-2.59	-3.02	-3.26	-3.27
a_6	-1.54	-2.12	-1.41	-1.25	-2.17	-2.01
a_7	0.35	-0.58	0.52	4.33	-0.79	-1.18
a_8	-3.31	-3.43	-3.17	-3.47	-4.73	-4.35
a_9	2.61	2.58	2.37	-0.09	1.84	-3.27
a_{10}	2.57	2.95	2.58	2.84	2.62	2.79
a_{11}	-3.19	-2.92	-3.50	-0.20	-4.55	-4.06
a_{12}	0.0	0.0	0.0	0.0	0.0	0.0
a_{13}	1.42	1.38	1.97	4.26	1.22	1.34
a_{14}	6.03	4.78	6.75	-1.75	5.77	5.22

REGRESSION PARAMETERS FROM THE PROC RSREG ANALYSES
COLD PLATE B EXPERIMENTS

The Regression Fit is of the Form :

$$Y = I + a_1T + a_2C + a_3DC + a_4SOC + a_5T*T + a_6C*C + a_7DC*DC + a_8SOC*SOC$$
$$+ a_9T*C + a_{10}T*DC + a_{11}T*SOC + a_{12}C*DC + a_{13}C*SOC + a_{14}DC*SOC$$

Where : Y = Watt-Hour Efficiency (%) ; T = Temperature (Coded)
C = Charge Rate (Coded) ; DC = Discharge Rate (Coded)
SOC = State of Charge (Coded)

The Coded Parameters are Estimated by :

	Subtract This	Then Divide By
Temperature (°C)	12.5	17.5
Charge Rate (Fraction of Nameplate)	0.55	0.45
Discharge Rate (Fraction of Nameplate)	1.05	0.95
State of Charge (%)	60.0	40.0

Example for Experiment 13 :
Temp.=-5°C ; 1/2 C Charge Rate ; 1C Discharge Rate ; 80% State of Charge
Coded Values : T=-1.0 ; C=-0.1111 ; DC=-0.0526 ; SOC=0.5 ;
$Y_{REGRESS}$=79.85 % (Y_{ACTUAL}=81.88 %)

Parameter Estimates	Exp. 13	Exp. 14	Exp. 15	Exp. 16	Exp. 18	
Intercept (I)	82.18	77.92	83.96	84.38	74.91	
a_1	0.11	0.69	0.11	-0.49	-0.29	
a_2	-1.94	-1.93	-1.84	-1.73	-2.58	
a_3	-9.43	-11.43	-8.57	-7.74	-9.48	
a_4	-3.67	-4.90	-1.93	-2.40	-3.55	
a_5	-1.81	-3.66	-1.29	-1.33	0.11	
a_6	-0.43	0.24	-0.25	-0.54	0.49	
a_7	0.51	-4.45	-2.56	-2.76	-3.71	
a_8	-4.09	-3.13	-1.50	-0.39	-6.18	
a_9	1.62	2.12	0.66	0.61	1.27	
a_{10}	3.87	5.56	2.96	2.91	2.85	
a_{11}	-2.71	-1.59	-1.32	-0.56	-2.20	
a_{12}	0.0	0.0	0.0	0.0	0.0	
a_{13}	1.74	1.46	0.68	0.49	0.95	
a_{14}	0.21	-5.80	0.91	0.27	-7.29	

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13. ABSTRACT ***(Maximum 200 words)***

Nickel-Hydrogen (Ni/H_2) secondary batteries will be implemented as a power source for the Space Station Freedom as well as for other NASA missions. Consequently, characterization tests of Ni/H_2 cells from Eagle-Picher, Whittaker-Yardney, and Hughes have been completed at the NASA Lewis Research Center. Watt-hour efficiencies of each Ni/H_2 cell were measured for regulated charge and discharge cycles as a function of temperature, charge rate, discharge rate, and state of charge. Temperatures ranged from −5°C to 30°C, charge rates ranged from C/10 to 1C, discharge rates ranged from C/10 to 2C, and states of charge ranged from 20% to 100%. Results from regression analyses and analyses of mean watt-hour efficiencies demonstrated that overall performance was best at temperatures between 10°C and 20°C while the discharge rate correlated most strongly with watt-hour efficiency. In general, the cell with back-to-back electrode arrangement, single stack, 26% KOH, and serrated zircar separator and the cell with a recirculating electrode arrangement, unit stack, 31% KOH, zircar separators performed best.

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