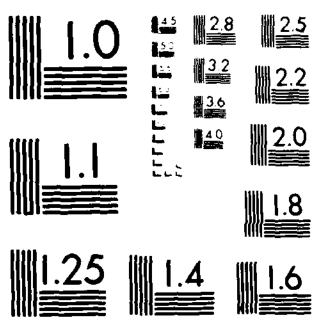
AD-A084 935 AEROSPACE CORP EL SEGUNDO CA CHEMISTRY AND PHYSICS LAB F/G 10/3
A STUDY OF AIRCRAFT NICD BATTERY STATE-OF-CHARGE MEASUREMENT BY--ETC(U)
APR 80 M R MARTINELLI, S W MAYER, C C BADCOCK F04701-79-C-0080
UNCLASSIFIED TR-0080(5970-01)-2 SD-TR-80-24 NL

1 OF 1
AD A084935

END
DATE FILMED
7-80
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

LEVEL II

ADA084935

REPORT SD-TR-80-24

A Study of Aircraft NiCd Battery State-Of-Charge Measurement by Phase Meter

M. R. MARTINELLI, S. W. MAYER (Consultant), and C. C. BADCOCK
Chemistry and Physics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, Calif. 90245

DTIC
ELECTE
JUN 2 1980
S C

30 April 1980

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

DDC FILE COPY

80 5 30 017

This interim report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-79-C-0080 with the Space Division, Contracts Management Office, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by S. Siegel, Director, Chemistry and Physics Laboratory. Gerhard E. Aichinger was the project officer for Mission-Oriented Investigation and Experimentation (MOIE) Programs.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Gerhard E. Aichinger
Project Officer

FOR THE COMMANDER

Evan R. Brossman, Chief
Contracts Management Office

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: SD-TR-80-24
2. GOVT ACCESSION NO.: AD-A084935
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): A STUDY OF AIRCRAFT NiCd BATTERY STATE-OF-CHARGE MEASUREMENT BY PHASE METER.
5. TYPE OF REPORT & PERIOD COVERED: Interim
6. PERFORMING ORG. REPORT NUMBER: TR-0080(5970-01)-2
7. AUTHOR(s): Michael R. Martinelli, Stanley W. Mayer, and Charles C. Badcock
8. CONTRACT OR GRANT NUMBER(s): F04701-79-C-0080
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The Aerospace Corporation, El Segundo, Calif. 90245
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: Space Division, Air Force Systems Command, Los Angeles, Calif. 90009
12. REPORT DATE: 30 April 1980
13. NUMBER OF PAGES: 31
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
NiCd Batteries
State of Charge
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experiments were performed to determine if the phase angle between alternating voltage and current could be used to predict, within a probable error of 5 percent, the state of charge of vented NiCd aircraft batteries. A 22 A-hr, 19-cell Gulton type MS24497-4 battery and several individual cells from that battery were tested in these experiments. The battery was charged for various lengths of time at 11 amperes to obtain a range of state of charge. Battery phase angle and individual cell phase angles were measured with a Hewlett-Packard HP-3575A gain-phase meter at frequencies of 350, →

DD FORM 1473 (FACSIMILE)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

409382

100, 35, 17.5, and 11 Hz; and the cells were discharged at 11 amperes to 0.1 V (1.9 V for the battery) to determine their state of charge in ampere-hours of capacity. The phase-angle, state-of-charge data were subjected to second-order polynomial curve fitting by means of least-squares analysis. The probable errors obtained from the least-squares analyses were used to judge the quality of the measured correlation between phase angle and state of charge. The effect of temperature on the correlation was also studied.

The results for the individual cells were, on the whole, quite poor, although two of the individual cells tested achieved the stated goal of a probable error of 5 percent for the correlation between phase angle and state of charge. The 19-cell battery gave the best results with a probable error of 3.8 percent measured at 11 Hz. Overall, better results were obtained at lower measuring frequencies. A strong temperature effect on the correlation between phase angle and state of charge was also observed.

CONTENTS

Accession For
NTIS GRA&I
DDC TAB
Unannounced
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or special
A

FIGURES

TABLES

I. INTRODUCTION

The development of a method for measuring NiCd battery state of charge has been a recognized technical need within the Air Force for more than 10 years. The importance of having a capability for measuring the residual ampere-hour capacity of aircraft NiCd batteries is apparent in view of the planned use of battery-operated fly-by-wire aircraft controls and because of the need for dependable battery-powered restarts of aircraft engines after flameouts. Consequently, several suggested procedures for determining the state of charge for NiCd batteries have been tested by others,[1] but the methods have not been found to have satisfactory dependability. Among the methods reported to be inadequate for monitoring NiCd battery charge levels were open- and closed-circuit voltage measurements, impedance determinations at several frequencies, ampere-hour measurements with coulometers, and measurements of battery voltage rise times.

The phase angle between sinusoidal voltage and current for a NiCd cell also was evaluated as a state-of-charge indicator in the past, but results were inconclusive.[1,2] Advances in instrumentation have made it possible to measure phase angles more precisely. Furthermore, preliminary work done in 1974 by E. J. Dowgiallo,[3,4] employing a Hewlett-Packard HP-3575A gain-phase meter, indicated that the phase-angle method held promise of being a reliable state-of-charge indicator for NiCd cells.

The phase angle of a NiCd cell is, moreover, a function of the electrical capacitance of the cell. In 1968 Dr. N. Latner,[5,6] through use of a Wayne-Kerr transformer ratio-arm bridge, found a dependable correlation between the state of charge of sealed 0.5 A-hr NiCd cells and their electrical capacitance. By using a similar bridge, the authors confirmed this correlation and found it to be reliable within a probable error of 5 percent. It also appeared to apply as well for up to 18 cells in series as it did for one cell. Higher-capacity NiCd cells, such as those typically found in aircraft, did not lend themselves to Latner's approach, because their capacitances (~20 F) lie outside the ranges of most commercially available capacitance bridges. Accordingly, efforts were directed toward investigating the phase angle method.

The relationship between the electrical capacitance of a battery and its phase angle θ (given the commonly used equivalent circuit for a battery[2,3,4] in Fig. 1, where R_L is the resistance of the cell terminal leads, L is the inductance of the cell terminal leads, R_S is the electrolyte resistance, C is cell capacitance, and E is the cell potential) is

$$\theta = \arc\tan \frac{X_L (X_C^2 + R_S^2) + R_S^2 X_C}{R_L (X_C^2 + R_S^2) + R_S X_C^2} \qquad (1)$$

where $X_C = 1/2\pi fc$, $X_L = 2\pi fL$, and f = frequency (Hz).

Reported herein is a preliminary study of the correlation between phase angle and state of charge for NiCd aircraft cells and batteries. The objectives were to determine if the state of charge could be predicted within a probable error of 5 percent and to briefly examine the effect of temperatures on the phase-angle measurement.

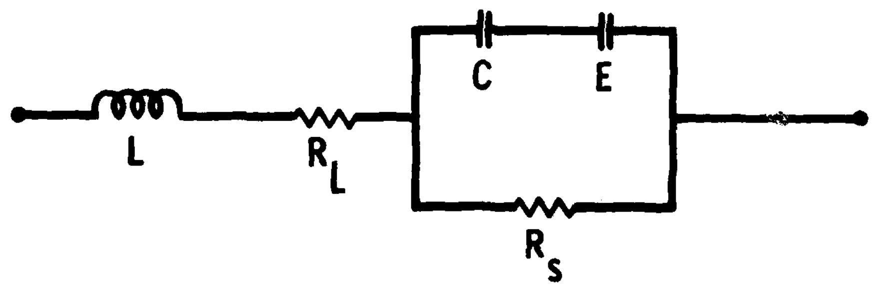


Figure 1. Battery Equivalent Circuit

II. EXPERIMENTAL DATA

A 22 A-hr 19-cell Gulton type MS24497-4 battery was obtained from the Air Force Logistics Command in Sacramento. It was checked and reconditioned, in accordance with Air Force T.O. 8D2-3-1,[7] for use in this study. The cells in this battery were arranged as shown in Fig. 2. The individual cells from this battery that were used for these experiments are referred to by their number in the battery sequence, starting with the cell that has the positive terminal for the battery.

The phase angles of the cells and the battery tested in this study were measured using the circuit shown in Fig. 3. The Hewlett-Packard HP-3575A phase-gain meter measures the phase angle between the ac voltage developed across the cell or battery being monitored and the 8 ohm reference resistor. To reduce the effects of lead impedance, the cells are monitored with a four-lead arrangement in which the ac-current-carrying leads are separated from the voltage-measuring leads. The quadruple-pole eight-throw high-wattage switch enables the experimenter to shift the four-lead arrangement from one cell to another, or to monitor several cells in series. The ac signal needed for the measurement originates with the Hewlett-Packard HP-204C oscillator and is amplified by the McIntosh 75 power amplifier to produce an ac current of from 1.5 to 2 amperes rms in the circuit. At this ac current, the signal developed across the battery is sufficiently large to be detected by the phase-gain meter without amplification. The 200 MFD blocking capacitor is used to prevent the cells from discharging through the amplifier.

A Hewlett-Packard HP-6267B dc power supply was used to maintain constant current for charging and discharging the cells and the battery tested in this study.

An Associated Testing BK-1100 environmental chamber was used to heat and cool the battery during the temperature effects experiments.

PRECEDING PAGE BLANK-NOT FILMED

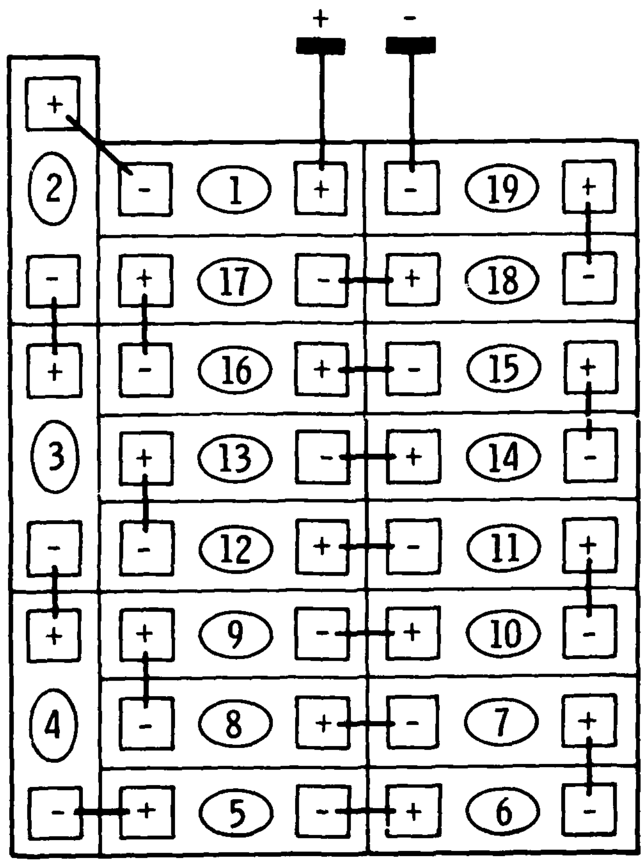


Figure 2. Cell Layout for a Gulton MS24497-4, 19-Cell, 22 A-hr Battery

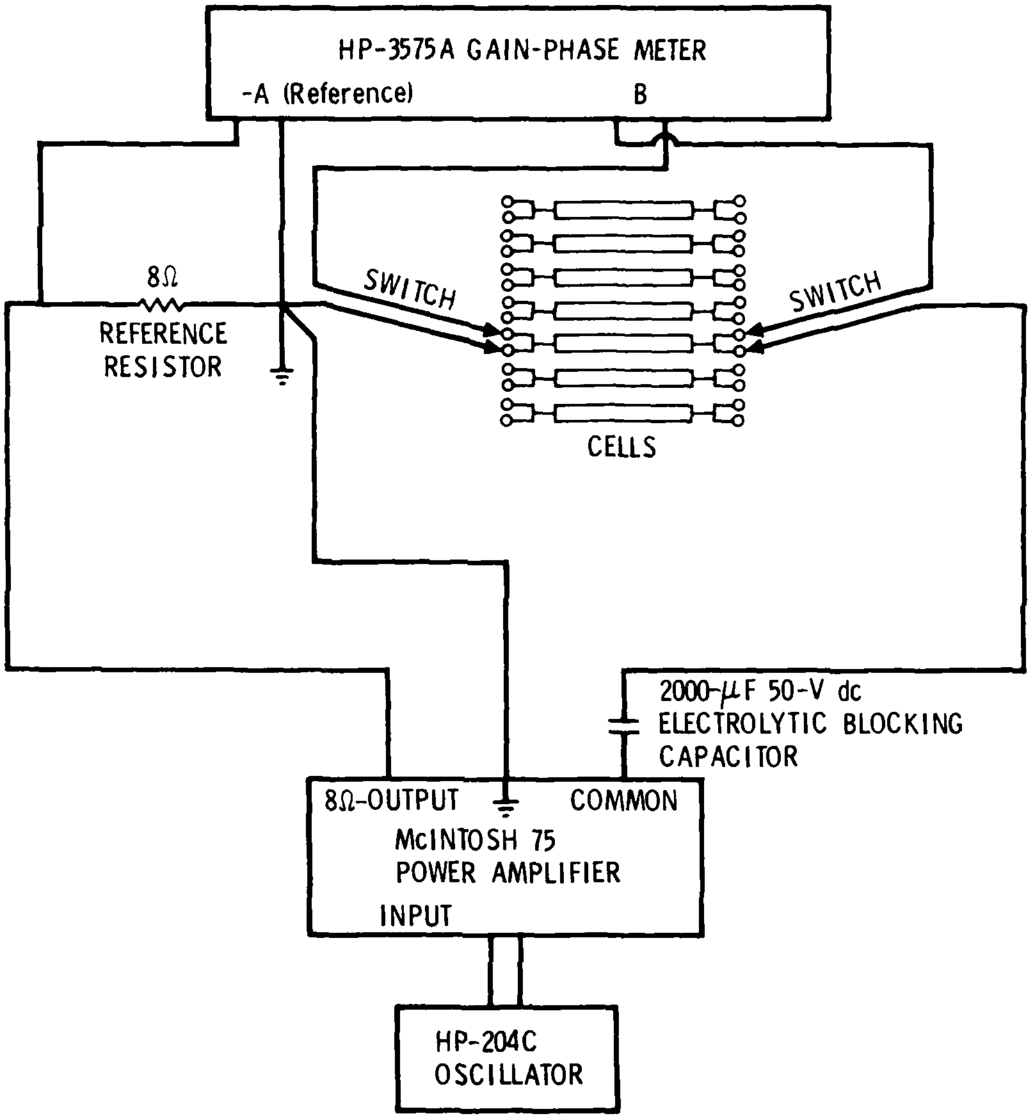


Figure 3. Phase-Angle Measurement Circuit

To determine the correlation between phase angle (θ) and state-of-charge (S), several measurements of θ at different S's were made on the various individual cells and the 19-cell battery. The battery was charged at the 11 ampere rate, and the charging times were intentionally varied from 15 min to 2.5 hr to obtain an experimental range for the state of charge. Because the phase-angle readings were found to be unstable immediately after charging (probably because of thermal and concentration gradient changes arising from electrode polarization effects[5]), the charging was generally begun automatically during the night by using a clock-timer switch. The phase-angle measurements were begun 3 hr after the charging had stopped. The state of charge for each cell was then determined by measuring the time required for discharging each cell to 0.1 V (1.9 V for the 19-cell battery) at 11 amperes.

III. RESULTS AND DISCUSSION

Two experiments were performed to measure the correlation of θ to S. In the first experiment, 18 measurements of θ and S were made on seven individual cells and on the 19-cell battery at frequencies of 35, 100, and 350 Hz. Because the phase angle is frequency dependent (see Eq. 2), one of the objectives of this initial experiment was to determine if higher or lower frequencies are better for the correlation between θ and S.

The data collected for each cell were subjected to a curve fitting program using least-squares analysis computed on the basis of the second-order power series:

$$S = a + b\theta + C\theta^2 \tag{2}$$

Along with fitting curves to the data, least-squares analysis allows the experimenter to compute the standard deviation of the data points from their corresponding curves, as well as the probable error of the fit. (Statistically, one is equally likely to find a measurement within the probable error as without.) These measurements provide a measure of the quality of the curve fitting and a means by which to judge the quality of the measured correlation between θ and S. The second-order power series gave the best and least ambiguous results. The results from first-order fits showed poorer correlations of θ to S, whereas fitting the data to third- and fourth-order power series did not significantly improve the measured probable errors.

A summary of the probable errors obtained from second-order least-squares analysis of the θ and S correlations measured in this first experiment is presented in Table 1. For the most part the measured correlations are quite poor. The 19-cell battery at 35 Hz gave the best probable error, 9.3 percent. The experiment shows that generally better results are obtained

Table 1. Probable Errors Obtained from Second-Order Least-Squares Analysis of θ versus S Data at 35, 100, and 150 Hz

Cell	Maximum Capacity, A-hr	35 Hz		100 Hz		350 Hz	
		Probable, A-hr	Error Percent of Capacity[a]	Probable, A-hr	Error Percent of Capacity[a]	Probable, A-hr	Error Percent of Capacity[a]
4	24.29	3.16	<u>13.0</u>	4.29	17.7	4.19	17.3
6	22.61	3.39	15.0	3.33	14.7	3.07	<u>13.6</u>
7	20.37	2.01	9.9	3.37	16.5	3.41	16.7
8	16.68	1.83	<u>11.0</u>	2.32	13.9	2.02	12.1
9	21.51	3.54	16.5	2.78	<u>12.9</u>	2.90	13.5
10	20.77	2.80	<u>13.5</u>	3.49	16.8	3.79	18.2
11	23.39	4.20	18.0	2.81	12.0	3.45	14.7
19-Cell Battery	20.78	1.93	<u>9.3</u>	2.42	11.6	3.12	15.0
Average Probable Error for 7 Cells			13.8		14.9		15.2

[a]The best correlation for each cell studied is underlined.

at lower frequencies; five of the eight correlations measured had lowest probable errors at 35 Hz.

The second experiment, designed to determine if better correlations could be found at still lower frequencies, was performed at 35, 17.5, and 11 Hz (10 Hz is the lowest frequency the McIntosh amplifier can deliver). Fourteen θ and S measurements were taken. The three cells that had shown the poorest correlations at 35 Hz, cells 6, 9, and 11, were removed from the monitoring circuit, and cells 15, 17 and 18 were added. The results of this experiment are summarized in Table 2.

The probable errors of the curve fits to the data from the second experiment are generally better than those of the first experiment, both for the individual cells and the 19-cell battery. The average of all the probable errors for all correlations of the individual cells measured in the first (higher frequency) experiment was 14.6 percent; in the second experiment it was 10.4 percent. The averages for the 19-cell battery fell from 12.0 percent in the first experiment to 5.0 percent in the second.

An interesting aspect of the results of the second experiment is the apparent improvement of the 35 Hz correlations over those measured in the first experiment. Cells 4, 7, 8, 10, and especially the 19-cell battery, showed marked decreases in probable errors at 35 Hz in the second experiment. Additional conditioning of the battery during the first experiment apparently caused this improvement. A similar improvement was observed[8] during a similar experiment performed by the authors on satellite NiCd cells.

The individual cells generally gave the best correlations of θ to S at 17.5 Hz. At 11 Hz the phase-angle readings for the individual cells became quite unstable. Low-frequency measurements of phase relationships between small signals are easily affected by slight noise on the signals being measured. Consequently, the 19-cell battery, which has a much greater

Table 2. Probable Errors Obtained from Second-Order Least-Squares Analysis of θ versus S Data at 35, 17.5, and 11 Hz

Cell	Maximum Capacity, A-hr	35 Hz		17.5 Hz		11 Hz	
		Probable, A-hr	Error Percent of Capacity[a]	Probable, A-hr	Error Percent of Capacity[a]	Probable, A-hr	Error Percent of Capacity[a]
4	23.89	1.87	7.8	0.78	3.3[b]	3.42	14.3
7	22.39	1.72	7.7	1.47	6.6[b]	2.65	11.8
8	9.31	0.96	10.3	0.94	10.1[b]	0.83	8.9[b]
10	21.40	2.54	11.9	2.04	9.5[b]	3.59	16.8
15	18.61	2.47	13.3	2.41	13.0[b]	2.64	14.2
17	18.19	2.06	11.3	1.33	7.3[b]	2.20	12.1
18	21.82	0.95	4.4[b]	2.71	12.4[b]	2.49	11.4
19-Cell Battery	18.68	1.07	5.7[b]	1.02	5.5[b]	0.71	3.8[b]

[a]The best correlation for each cell studied is underlined.

[b]Plots of these correlations, with the second-order least-squares curve fit, can be found in the appendix.

impedance than the individual cells, develops a larger signal for a given applied ac current and gives stable readings at 11 Hz.

Inasmuch as the capacitance of NiCd cells can be affected by temperature changes,[6] it was anticipated that the measured phase-angle shifts would be dependent on battery temperature. The previous determinations of θ for the 19-cell battery had been made in an air-conditioned laboratory at $23 \pm 0.6°C$. In order to examine the effect of temperature on θ, the fully charged battery was placed in an environmental test chamber, and the temperature was varied from 0 to 38° C. The phase angle was monitored as the battery came to thermal equilibrium at 0, 23, and 38° C. It was observed that θ increased by 0.11 ± 0.01 deg for each degree C rise in temperature at an ac signal input frequency of 35 Hz. The value of θ increased by 0.13 ± 0.02 deg per each degree C increase in temperature at the 17.5 Hz frequency of input signal. The relationship of θ to temperature was essentially linear over the temperature range studied for both monitoring frequencies. These results demonstrated that it is necessary to know the battery temperature to correlate θ with S, because changes in θ are less than 1 deg for changes in S from full charge to 30 percent charged.

IV. CONCLUSIONS

Although in two cases (cell 4 at 17.5 Hz and cell 18 at 35 Hz) the phase-angle method produced a correlation of θ to S with probable errors smaller than the stated goal of 5 percent, it does not hold much promise as a reliable source of state-of-charge indication for individual aircraft NiCd cells. The average of the best correlation of θ to S obtained for all 10 of the individual cells studied in this report was 9.2 ± 3.7 percent. At low frequencies the method does seem to hold promise for multicelled batteries, however. The 11-Hz probable error for the correlation of θ to S for the 19-cell battery was 3.8 percent.

Unfortunately, several findings in this study indicated that any application of the phase-angle method should be qualified. First, some aspects of the measurement technique reported here impose limitations on its practicality. The 3-hr delay before stable readings can be made is a problem if immediate or continuous monitoring of state of charge is desired. Continuous, closed circuit measurements were not attempted in this study. The 1.5 to 2 amperes ac measurement signal used in this report might involve too severe a power commitment for some uses; however, improvements in sensing circuit design would eliminate this problem. A more serious problem is that these studies indicate the relationship of θ to S is a function of the history of the cell. The difference between the results at 35 Hz in the first and second experiments indicates a cell-history dependence. The effect of long term cycling is unknown. A study[8] of satellite NiCd batteries strongly suggests that long term cycling could have a significant effect. The relationship between θ and S would, therefore, require re-evaluation periodically for the method to be applicable throughout battery life. Finally, this study showed that there is a definite temperature effect on the measured phase angle of a NiCd battery.

PRECEDING PAGE BLANK-NOT FILMED

An ideal state-of-charge indicator would be a measurable parameter that varies with state of charge and is independent of everything else (i.e., temperature, cell history, charging rates, and pressure). It is clear, from the results of this study, that the phase angle of a NiCd battery is not such a parameter. However, in the experiments reported here, even though no special care was taken to return the battery to a reproducible state, the phase angle at 11 Hz was found to be a state-of-charge indicator for a 19-cell 22 A-hr battery with a probable error of under 4 percent. Although no specific recommendations can be made on the basis of the results of this study, under certain special circumstances the phase-angle method of state-of-charge determination for aircraft NiCd batteries could be of use.

V. REFERENCES

1. S. Lerner, H. Lennon, and H. N. Seiger, Power Source, Vol. 3, D. H. Collins (Ed.), Oriel Press, Newcastle upon Tyne, England (1971) p. 135-148.

2. M. Lurie, H. N. Seiger, and R. C. Shair, State of Charge Indicators for Nickel Cadmium Batteries, Technical Documentary Report ASD-TDR-63-191, Gulton Industries, Metuchen, New Jersey (1963).

3. E. J. Dowgiallo and R. B. Anderson, Electrical Phase Measurements and State of Charge Indication, presented Fall 1974 Meeting of Electrochemical Society, New York, New York (1974).

4. E. J. Dowgiallo, Battery Workshop 1974, Report X-711-74-348, Goddard Space Flight Center, Greenbelt, Maryland (1974), p. 32-42.

5. N. Latner, Determining the State of Charge of Ni-Cd Batteries by Farad Capacitance Measurements, Report HASL-198, Atomic Energy Commission, Washington, D.C. (August 1968).

6. N. Latner, "State of Charge Measurement of Nickel-Cadmium Batteries" Rev. Sci. Instr. 40, 364 (1969).

7. Technical Manual — Operation, Service, and Repair — Aircraft Nickel Cadmium Storage Batteries, T.O. SD2-3-1, U.S. Air Force, Washington, D.C. (10 April 1970).

8. M. R. Martinelli, S. W. Mayer, and C. C. Badcock, Phase Meter Measurements of State-of-Charge for Satellite Ni-Cd Cells: A Preliminary Study, TR-0079(4970-10)-3 The Aerospace Corporation, El Segundo, California (30 August 1979).

APPENDIX

Plots of θ (degrees) versus capacity remaining S (ampere-hours) for the cells measured during the second (low frequency) experiment with second-order least-squares fit are shown in the following pages.

PRECEDING PAGE BLANK-NOT FILMED

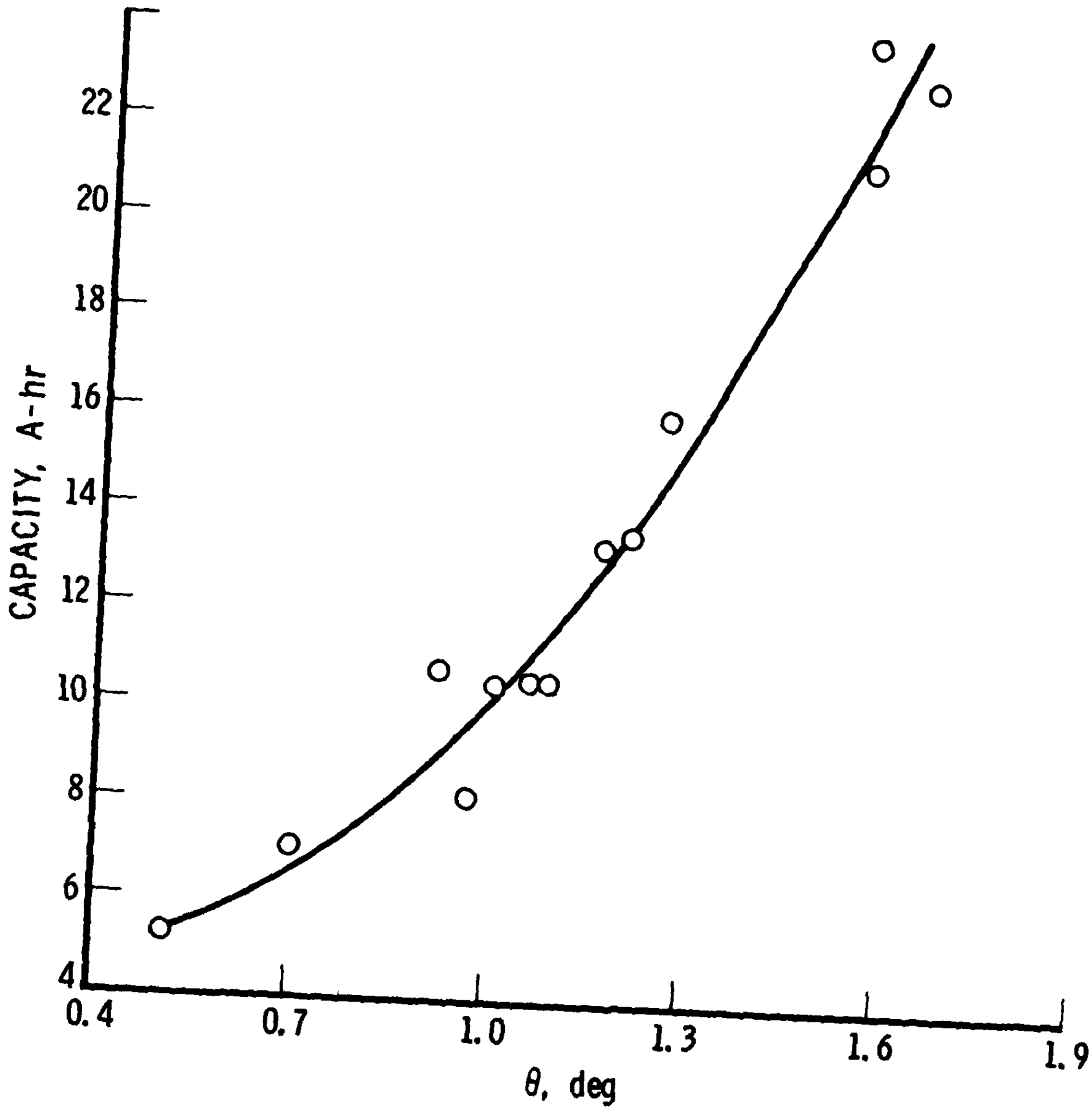


Figure A-1. Cell 4 at 17.5 Hz

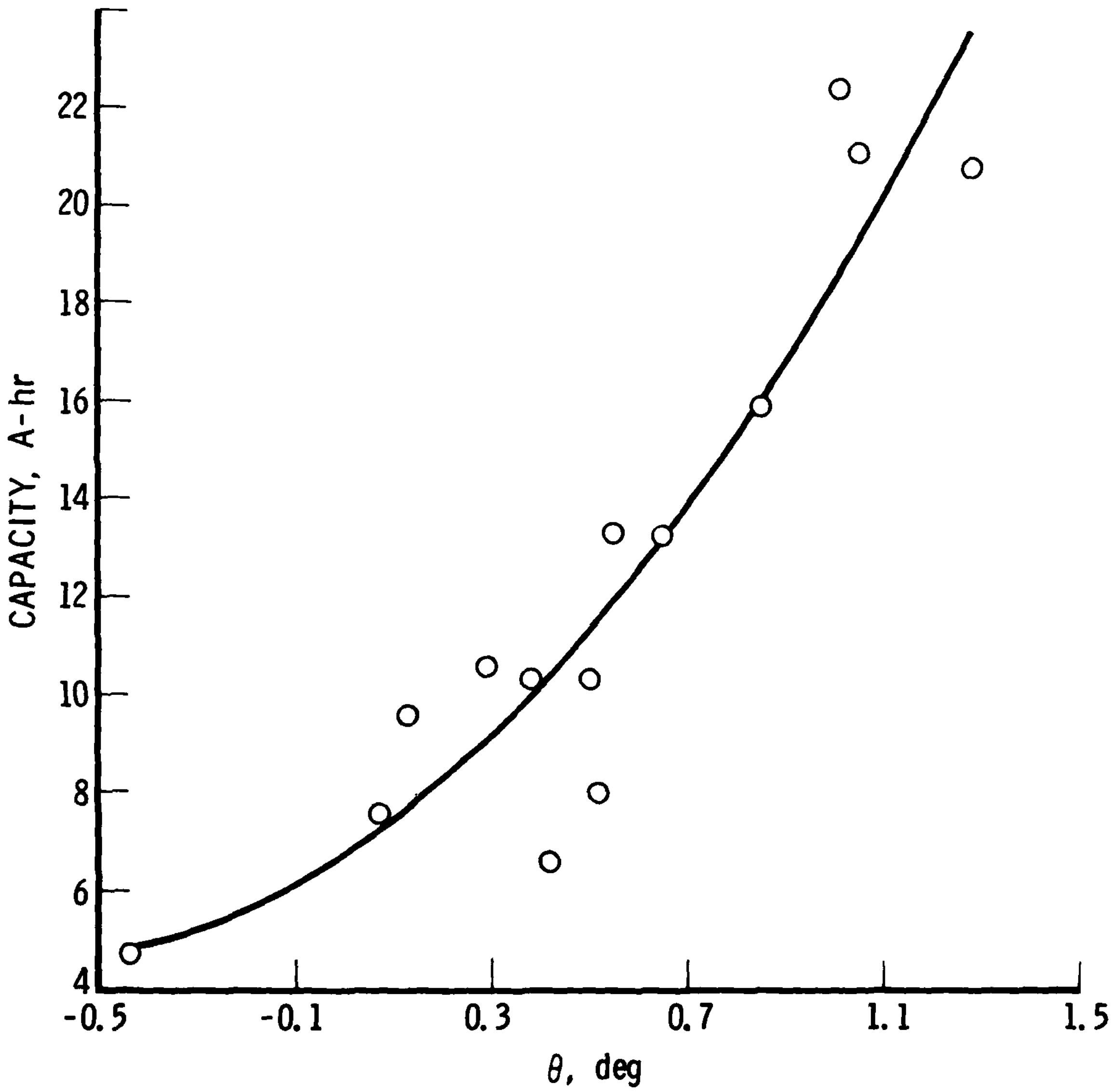


Figure A-2. Cell 7 at 17.5 Hz

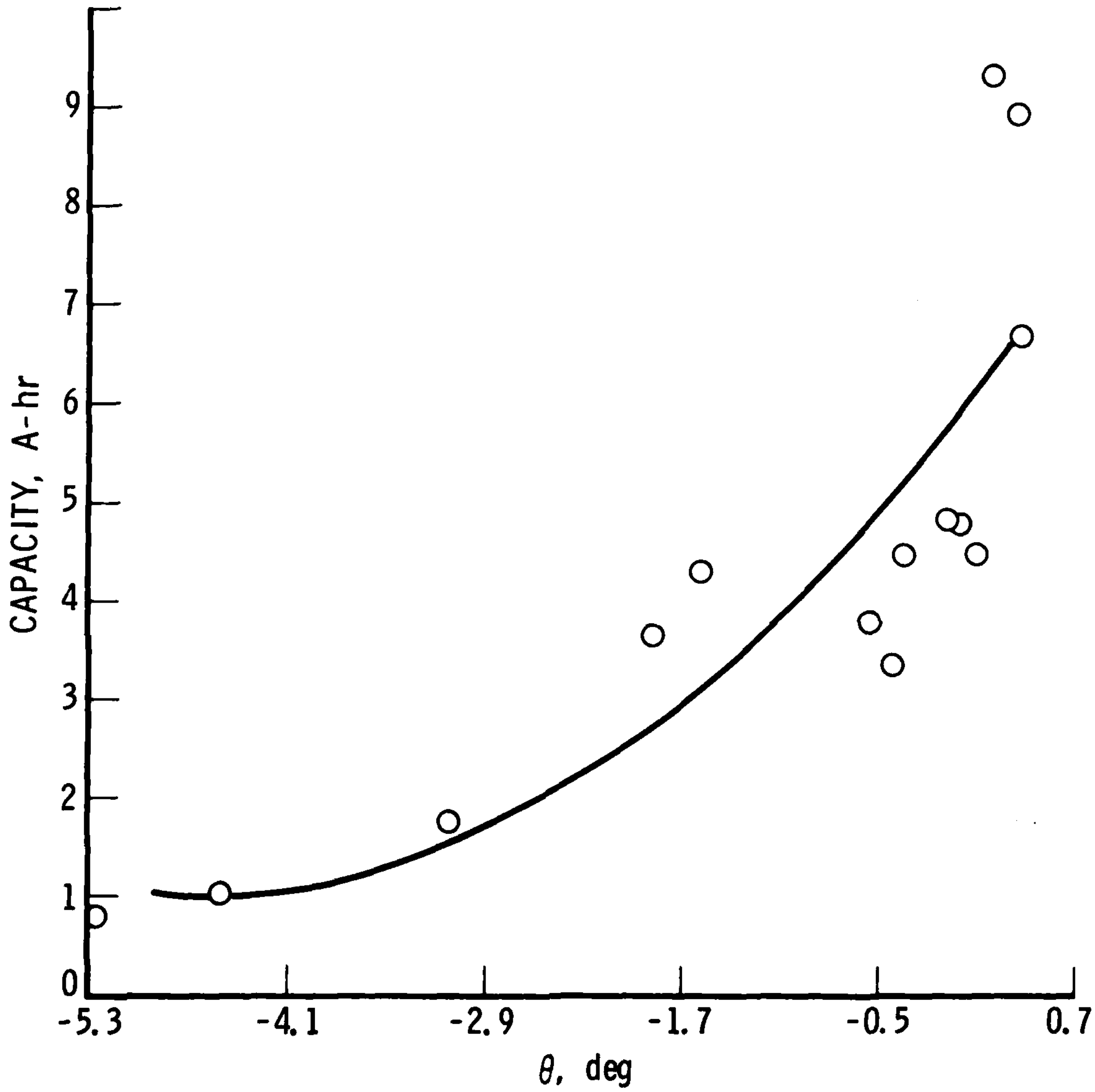


Figure A-3. Cell 8 at 17.5 Hz

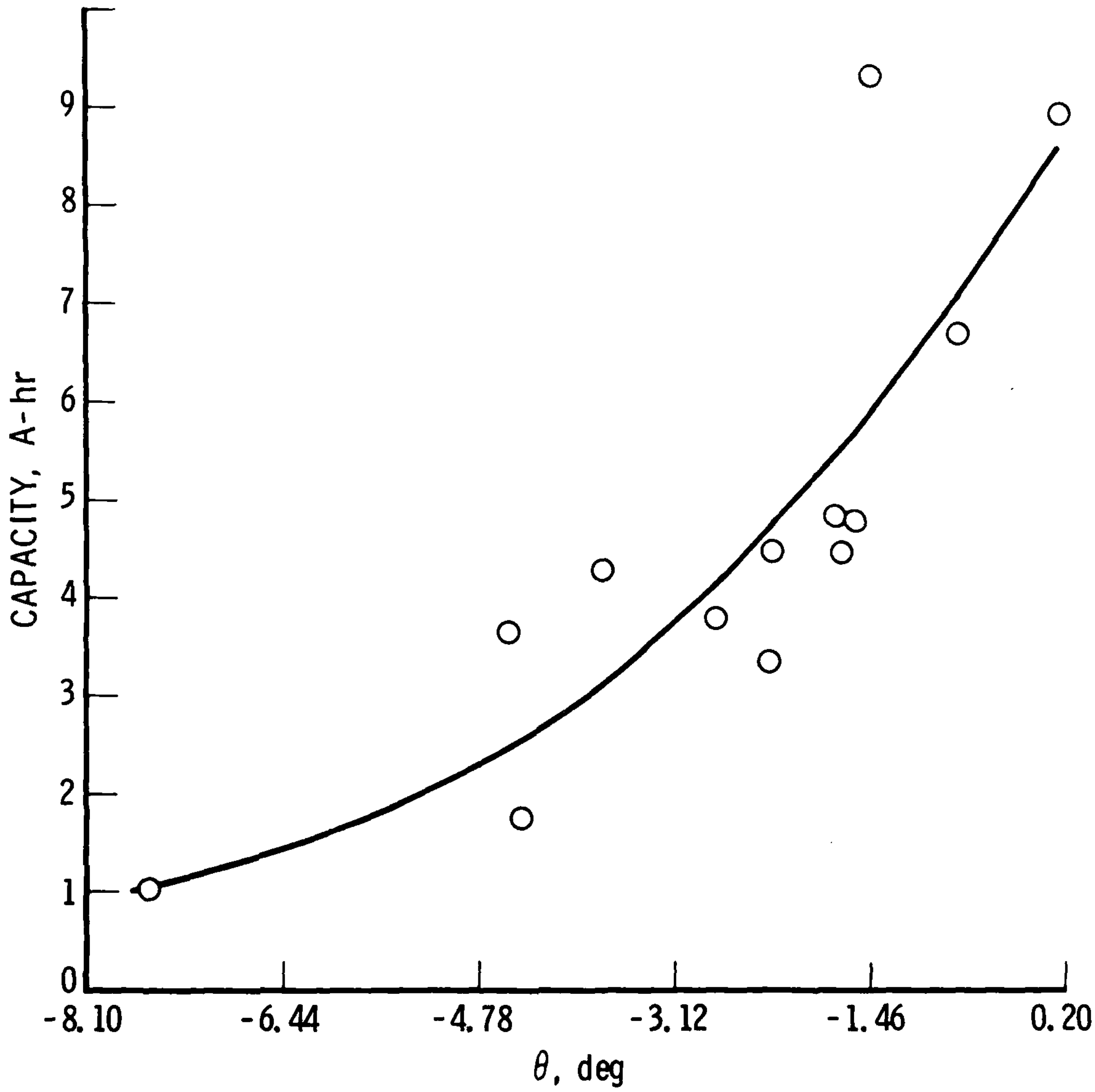


Figure A-4. Cell 8 at 11.0 Hz

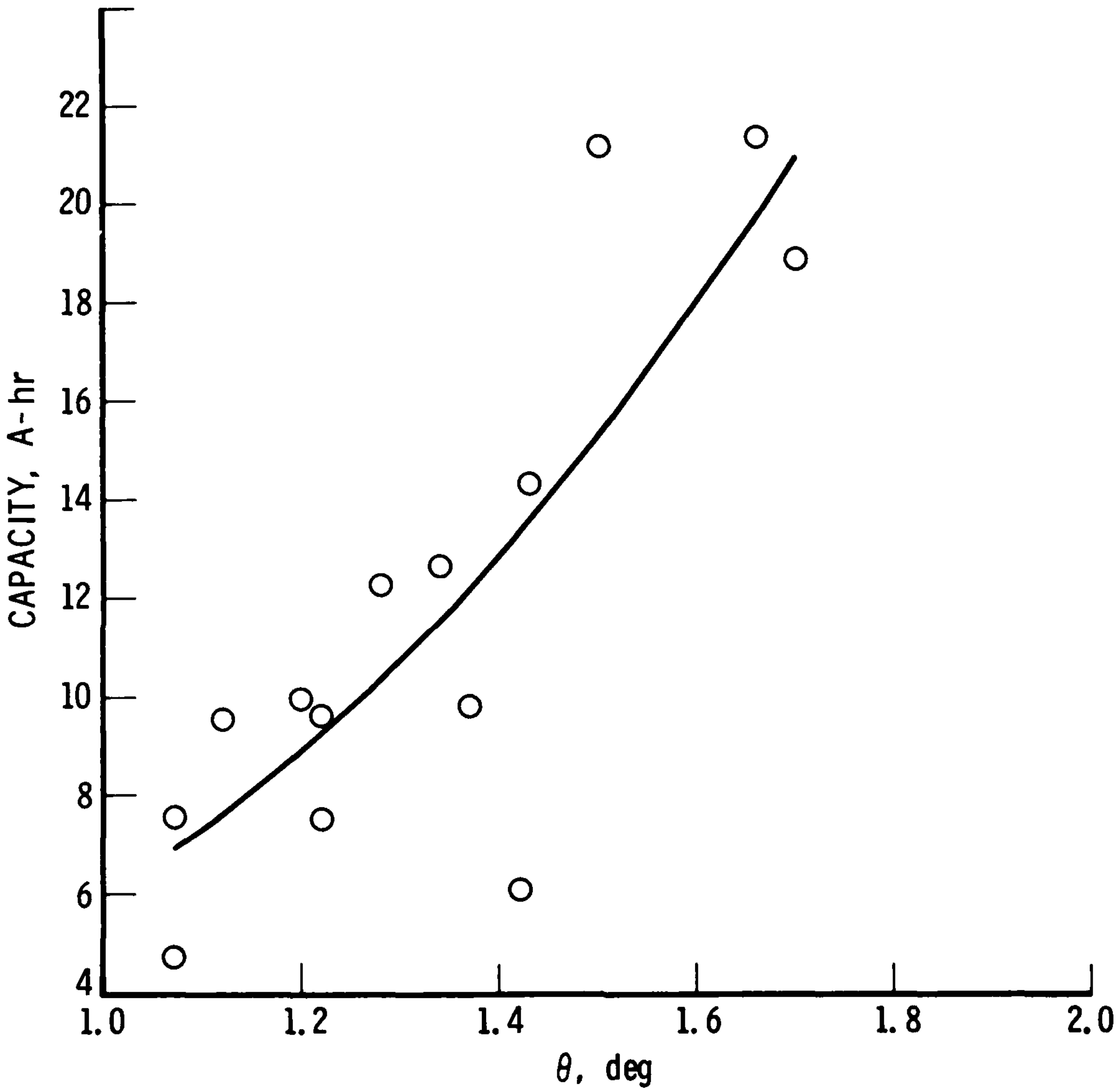


Figure A-5. Cell 10 at 17.5 Hz

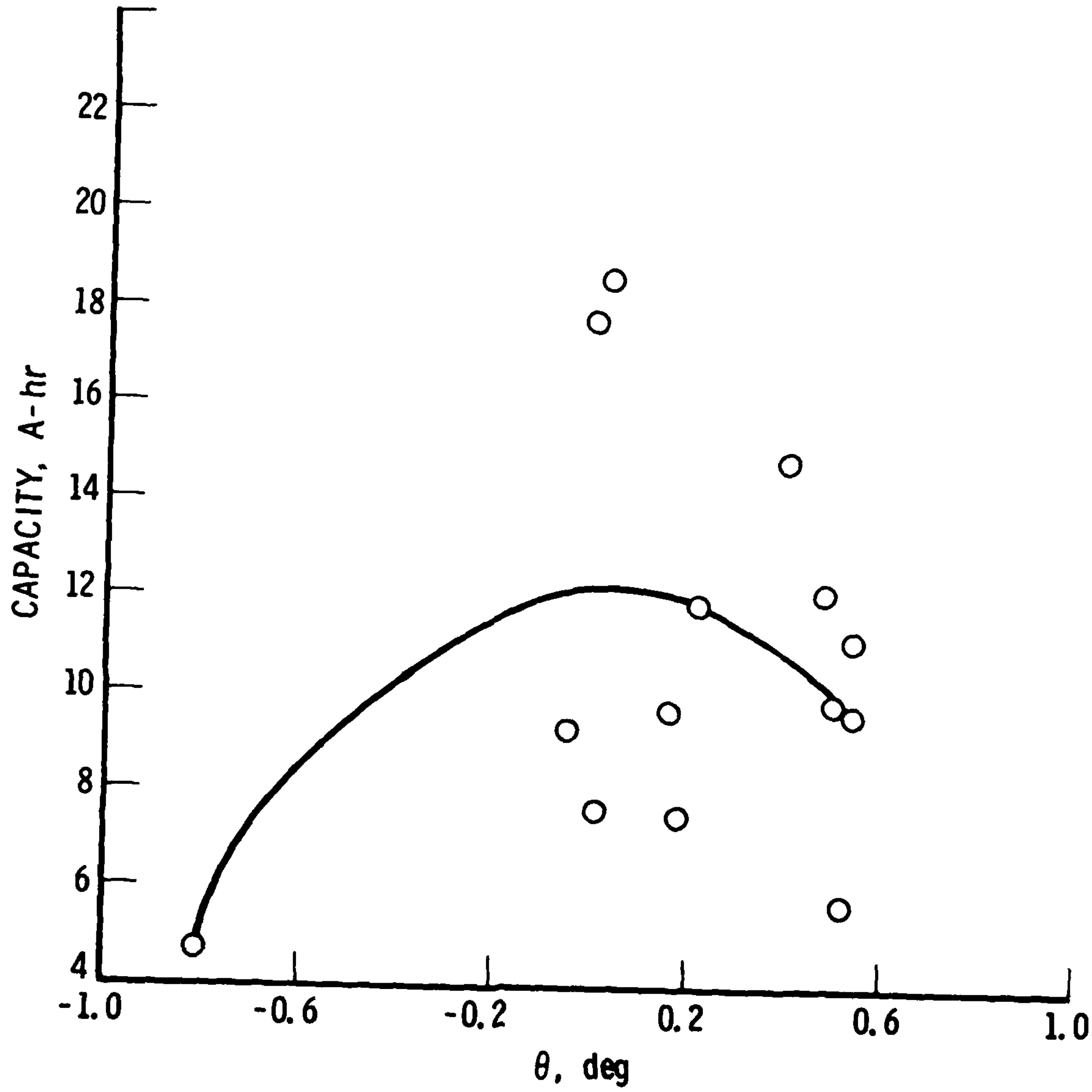


Figure A-6. Cell 15 at 17.5 Hz

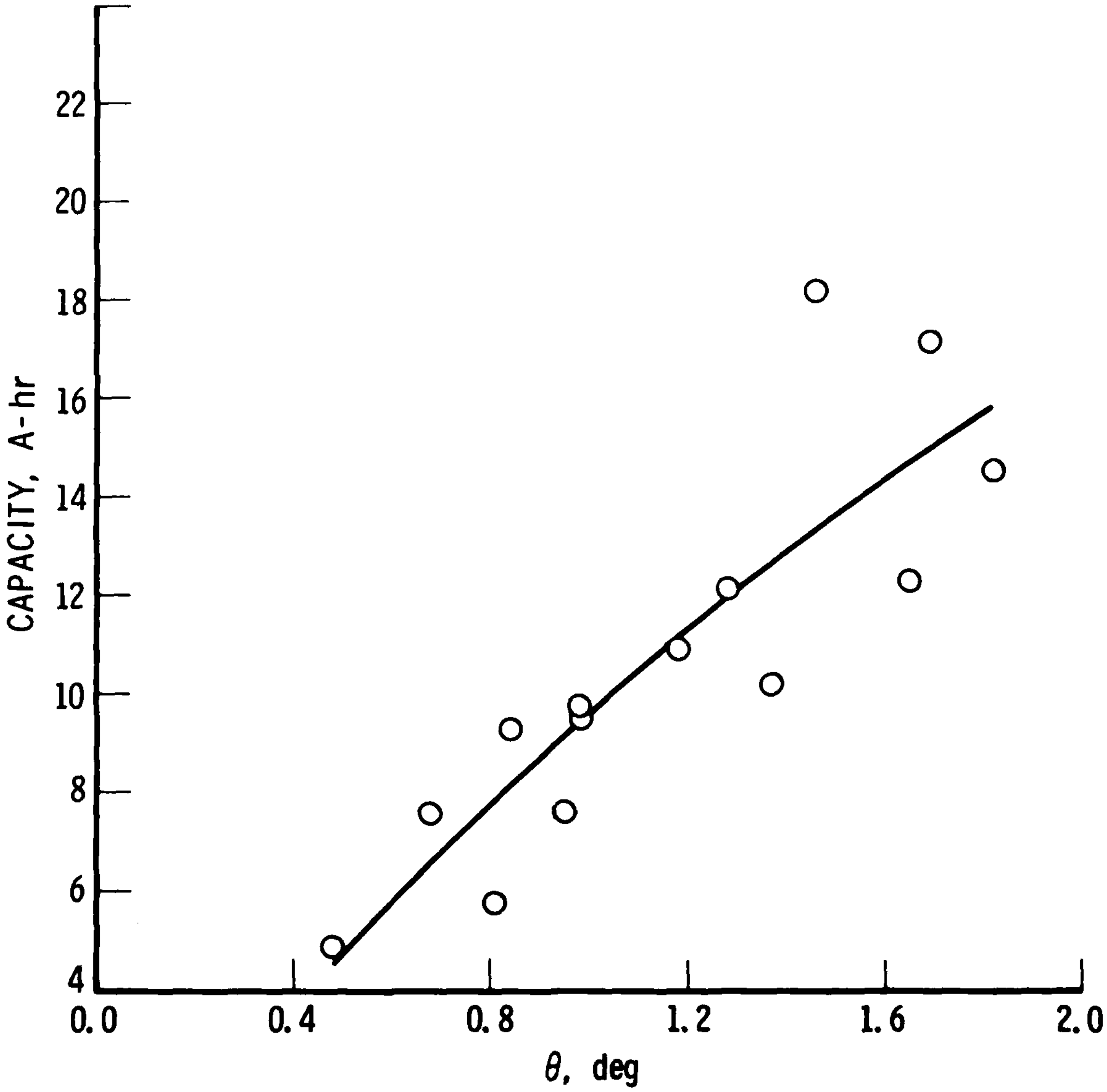


Figure A-7. Cell 17 at 17.5 Hz

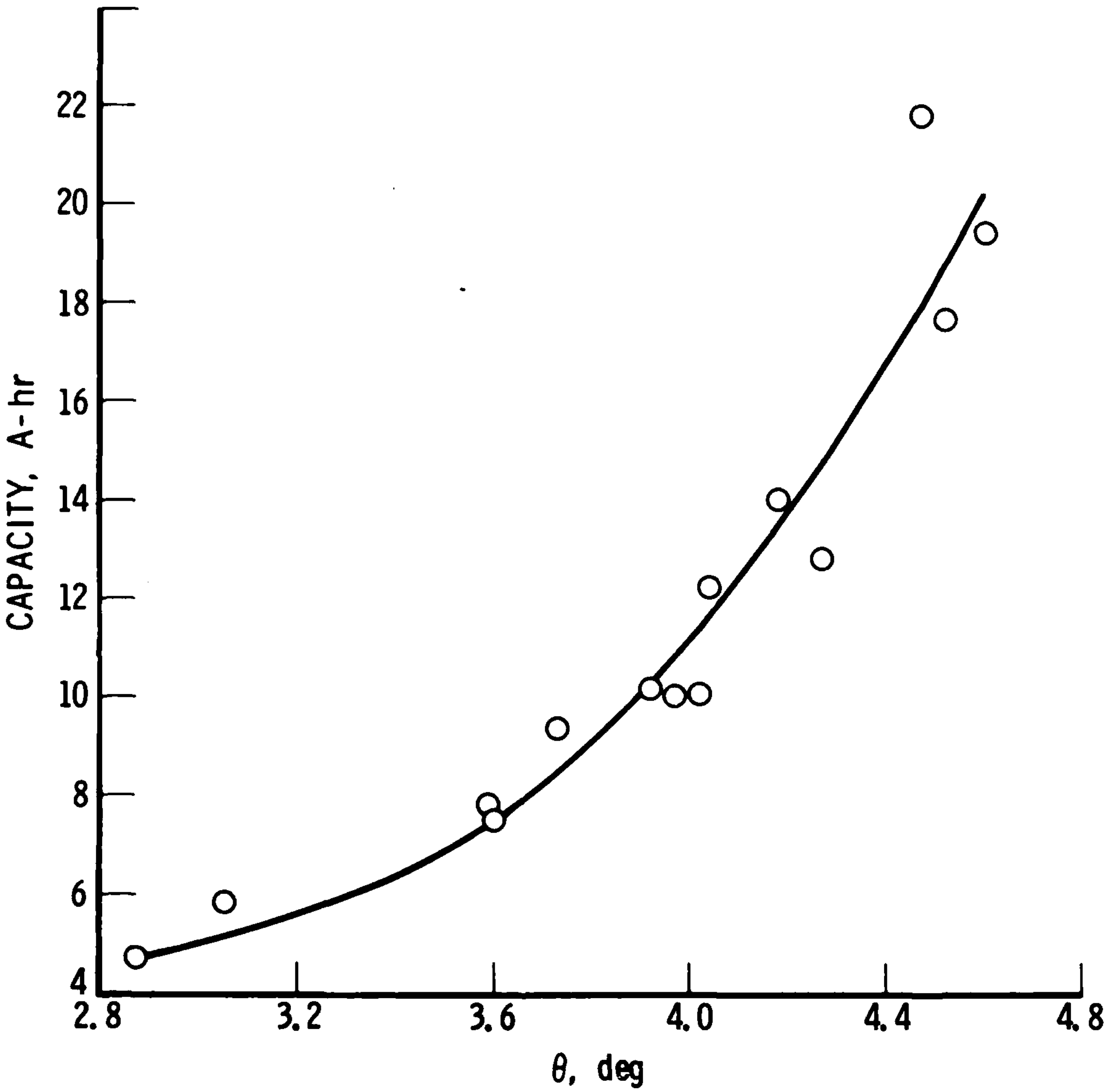


Figure A-8. Cell 18 at 35 Hz

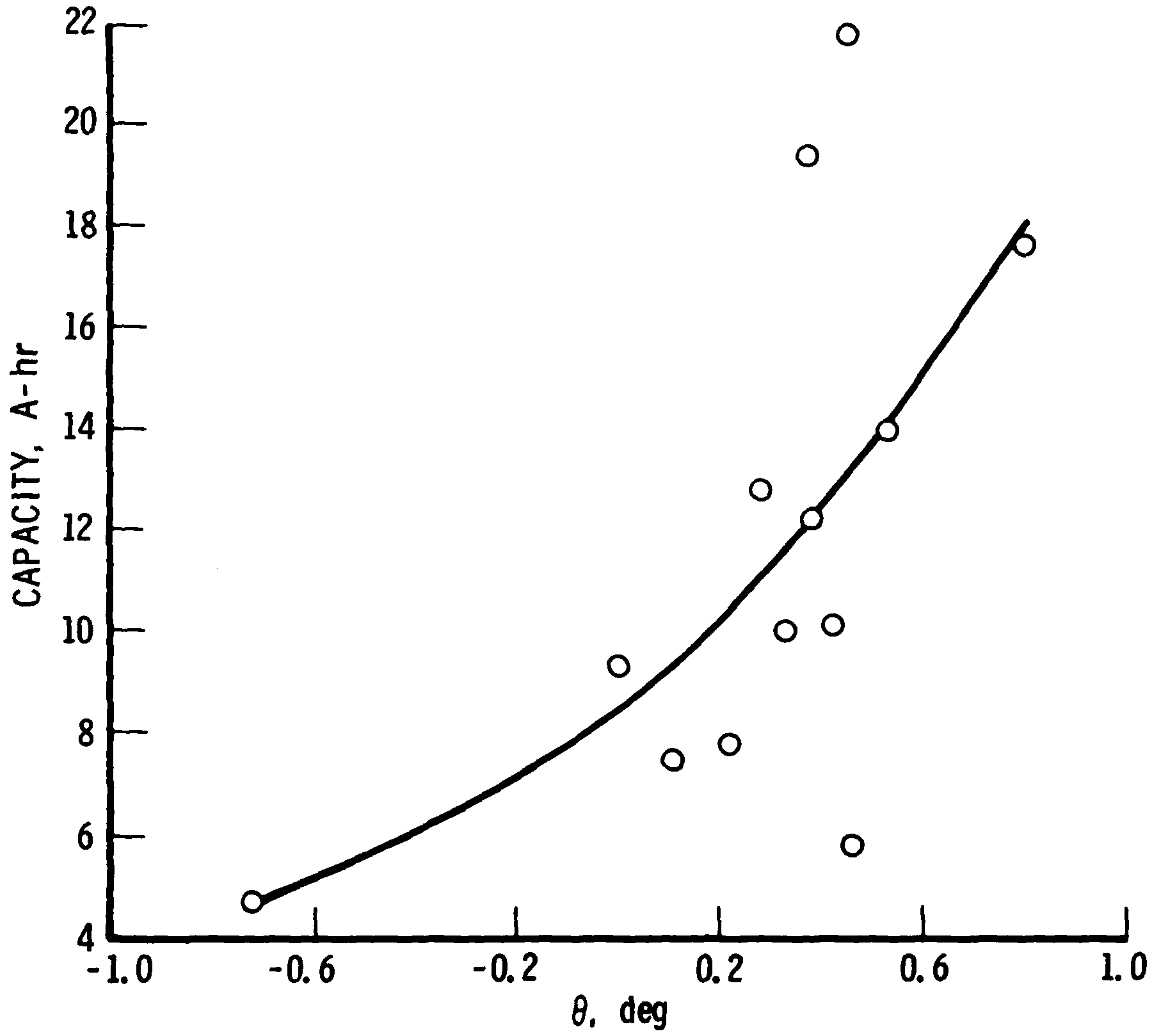


Figure A-9. Cell 18 at 17.5 Hz

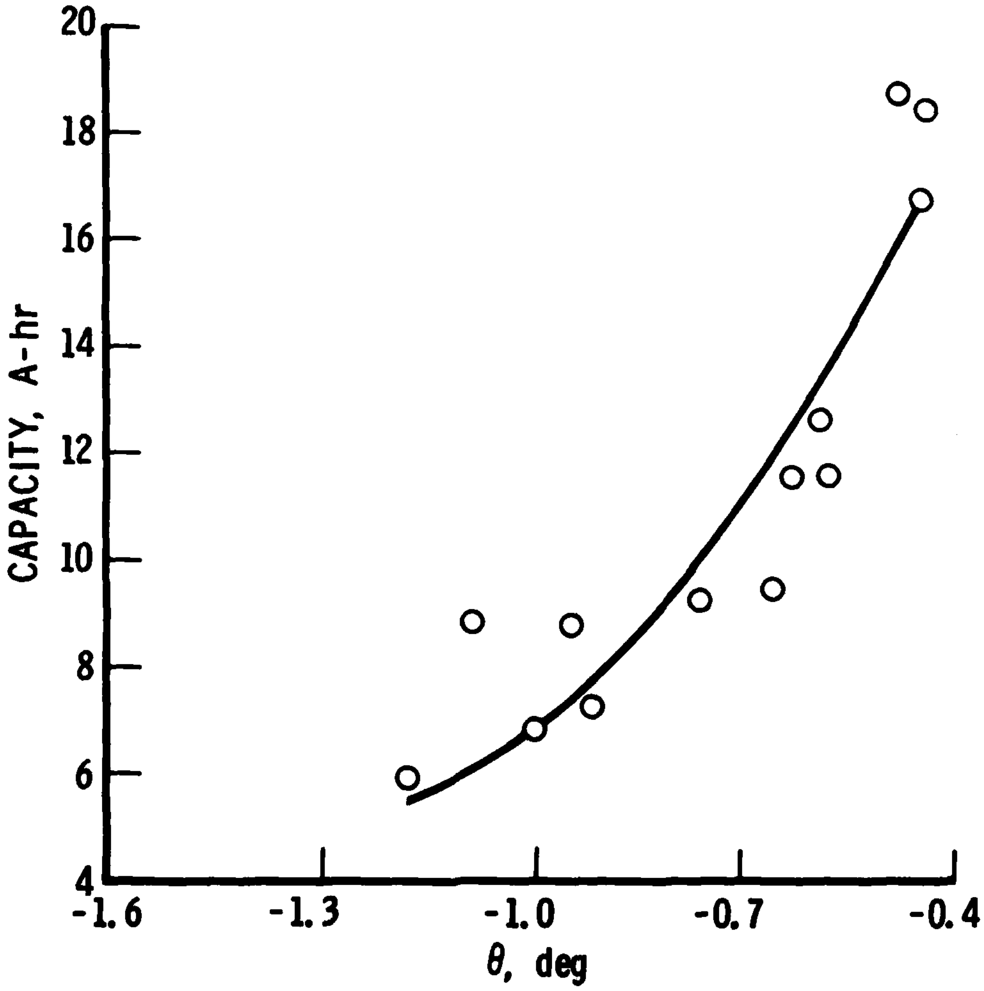


Figure A-10. 19-Cell Battery at 35 Hz

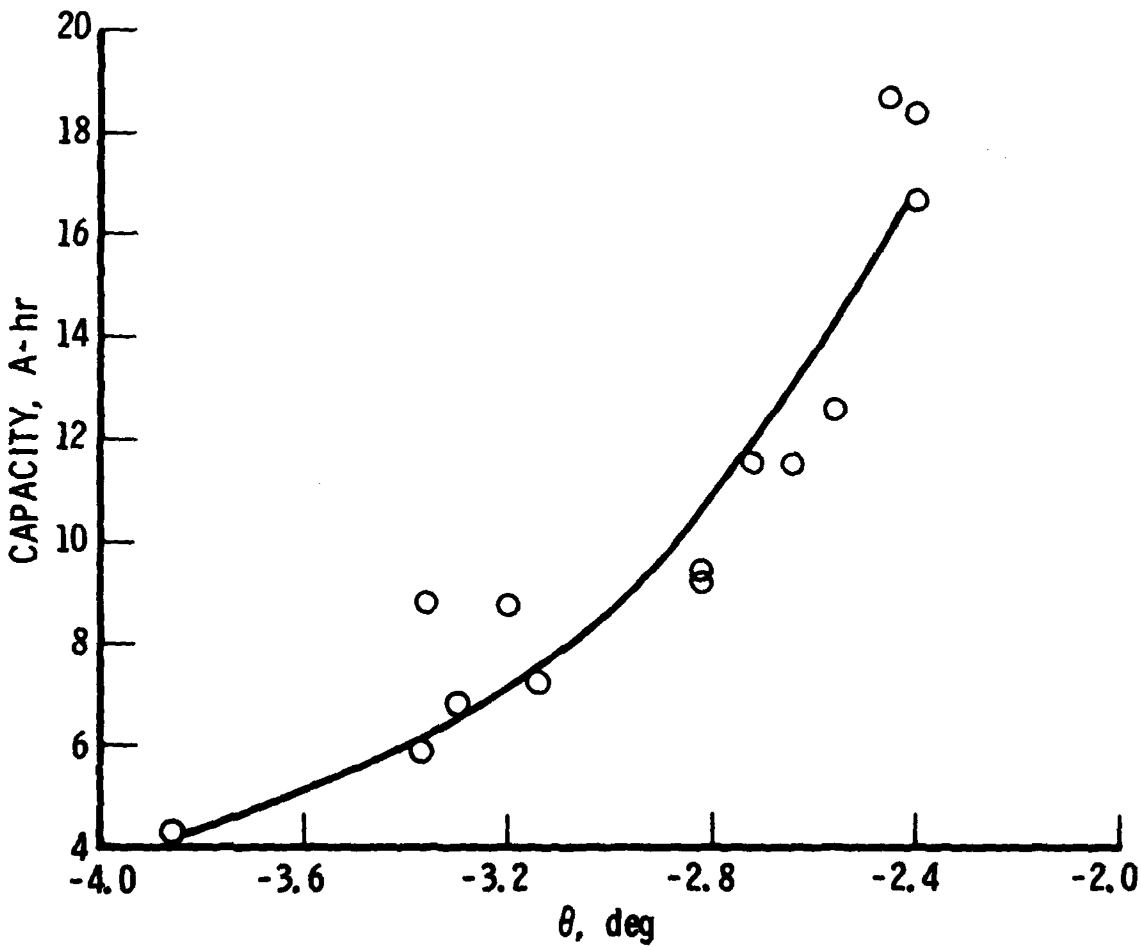


Figure A-11. 19-Cell Battery at 17.5 Hz

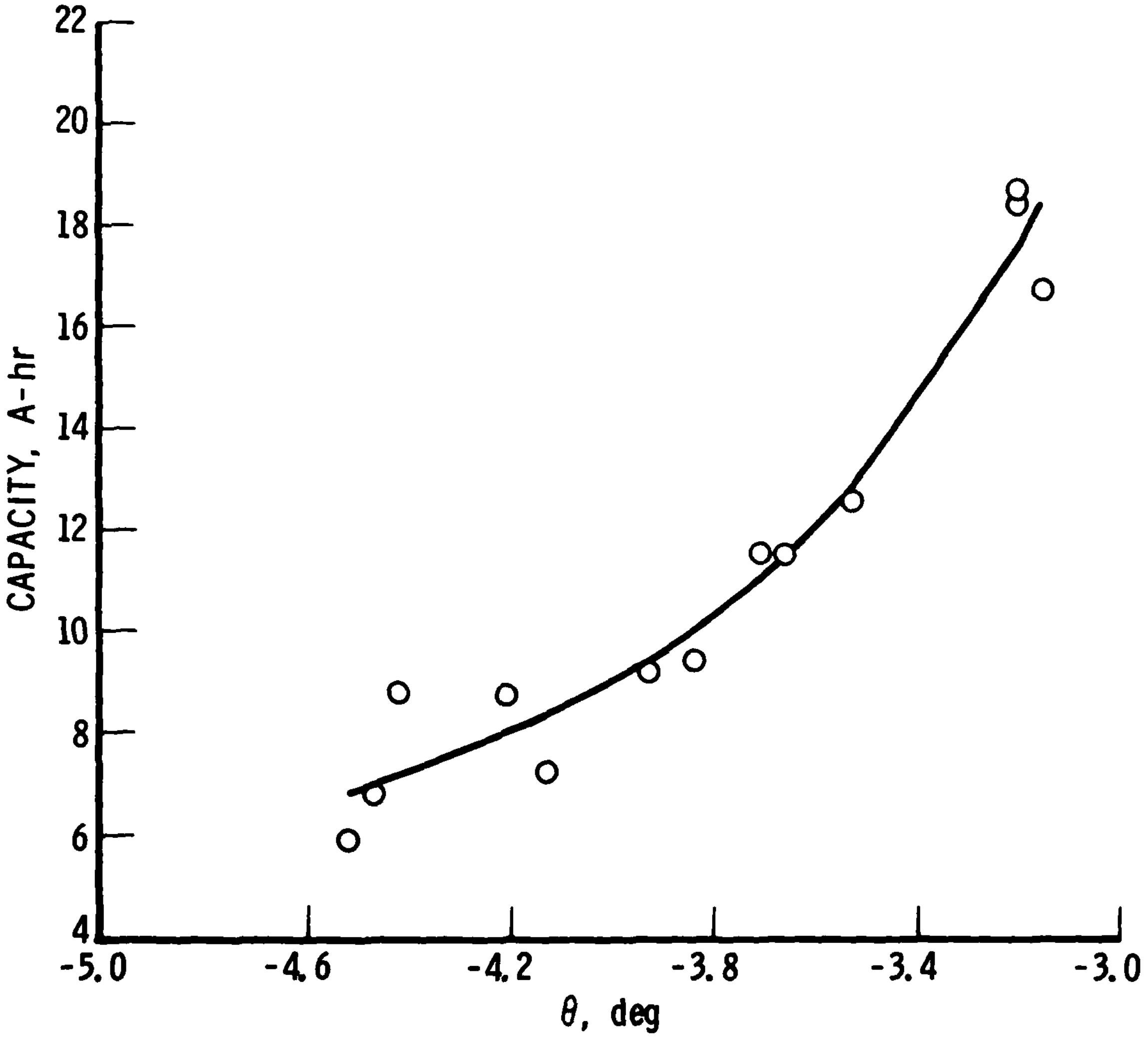


Figure A-12 19-Cell Battery at 11.0 Hz

LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space and missile systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Launch and reentry aerodynamics, heat transfer, reentry physics, chemical kinetics, structural mechanics, flight dynamics, atmospheric pollution, and high-power gas lasers.

Chemistry and Physics Laboratory: Atmospheric reactions and atmospheric optics, chemical reactions in polluted atmospheres, chemical reactions of excited species in rocket plumes, chemical thermodynamics, plasma and laser-induced reactions, laser chemistry, propulsion chemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, photosensitive materials and sensors, high precision laser ranging, and the application of physics and chemistry to problems of law enforcement and biomedicine.

Electronics Research Laboratory: Electromagnetic theory, devices, and propagation phenomena, including plasma electromagnetics; quantum electronics, lasers, and electro-optics; communication sciences, applied electronics, semiconducting, superconducting, and crystal device physics, optical and acoustical imaging; atmospheric pollution; millimeter wave and far-infrared technology.

Materials Sciences Laboratory: Development of new materials; metal matrix composites and new forms of carbon; test and evaluation of graphite and ceramics in reentry; spacecraft materials and electronic components in nuclear weapons environment; application of fracture mechanics to stress corrosion and fatigue-induced fractures in structural metals.

Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

THE AEROSPACE CORPORATION
El Segundo, California