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ENGINEERING EVALUATION TESTS OF 20-AMPERE AIRBORNE BATTERY CHAR--ETC(U)
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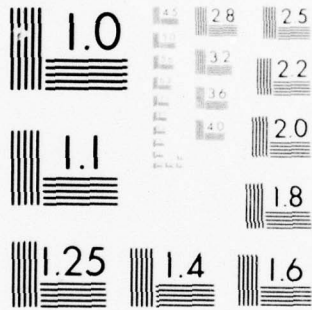
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DEPARTMENT OF THE NAVY
NAVAL WEAPONS SUPPORT CENTER
WEAPONS QUALITY ENGINEERING CENTER
CRANE, INDIANA 47522

6 ENGINEERING EVALUATION TESTS OF
20-AMPERE AIRBORNE BATTERY CHARGER (BREADBOARD)
MANUFACTURED BY
SUNDSTRAND CORPORATION

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REPORT BRIEF

ENGINEERING EVALUATION TESTS OF
20-AMPERE AIRBORNE BATTERY CHARGER (BREADBOARD)

MANUFACTURED BY
SUNDSTRAND CORPORATION

- Ref: (a) Proposed Military Specification for Airborne Chargers,
MIL-C-85050
(b) NAD-8P7-103 M/G3
(c) NWSC-4P7-117/24

I. INTRODUCTION

A. Secondary storage batteries are installed aboard aircraft to supply electrical power to essential equipment in the event of a primary power failure. The battery is also used for aircraft engine or APU starting when external power is unavailable.

B. The Navy is experiencing many battery problems related to inadequate ground maintenance, and improper airborne battery charging. Measures that have been taken to reduce battery failures are (1) introduction of improved field maintenance procedures and equipment; (2) development of new specifications; and (3) engineering evaluations of sophisticated on-board battery charging and fault warning systems.

II. PRESENT CHARGING SYSTEM

A. With few exceptions, the main aircraft battery is either of the lead-acid, or vented nickel-cadmium cell type; and typically, is connected directly across the aircraft's primary DC bus. Under heavy loads, the battery will aid the bus in supplying electrical power. Conversely, the battery will accept electrical charge when the DC bus is at a higher potential. In most cases, the bus voltage is unregulated, causing wide variations in charge voltage. (The nickel-cadmium battery is very sensitive to fluctuations in charge voltage due to its extremely low internal resistance.) Additionally, there is no provision for battery temperature sensing, which would provide the means for adjusting the charge voltage with respect to battery temperature.

III. NEW SYSTEMS

A. Engineering test programs were initiated by Naval Air Systems Command to evaluate new technological developments in aircraft battery charging systems.

B. A proposed military specification for aircraft Ni-Cd battery chargers, ~~reference (a), has been prepared by the Navy.~~

~~C. Cyclic testing, directed by reference (b),~~ was performed on a Vapor airborne battery charger manufactured for DC-9 aircraft, P/N 26340061-04 loaned to the Navy for evaluation. The results of this evaluation are reported herein.

~~D. Following the evaluation of the Vapor charger, a contract was awarded to Vapor Corporation to build one breadboard and three militarized 20-ampere airborne battery chargers.~~

~~E. Investigation of nickel-cadmium battery charge techniques with the use of the breadboard charger was conducted, in accordance with reference (c). The purpose of this investigation was to define a suitable charge technique for incorporation in three airborne battery chargers to be built to the requirements of reference (a) and delivered under contract. The results of this investigation are reported herein.~~

F. Prior to delivery of the breadboard charger to NAVWPNSUPPCEN Crane, Vapor Corporation was sold to Sundstrand Corporation.

IV. SUMMARY

A. Based upon the results of this evaluation, and other tests which were conducted during the preparation of reference (a), the chargers to be manufactured by Sundstrand Corporation shall:

1. Conform to MIL-C-85050 airborne charger specification.
2. Charge the battery at 1.0A until the battery reaches $16 \pm 1.0V$.
3. Pulse charge the battery (main mode) at an average current of 24 A within the average output power envelope shown in Figure 1, consisting of positive and negative pulses. The positive pulse shall have a duty cycle of 65% and a pulse amplitude necessary to comply with the power envelope of Figure 1, but not to exceed 65 A. The negative pulse amplitude shall be approximately 15 A with a duty cycle of 10%. Charge battery in main mode until temperature compensated voltage trip point is reached.
4. Pulse charge the battery (topping mode) at a constant average current of 5 A consisting of a positive and a negative pulse. The positive pulse shall have a duty cycle of 20% and an amplitude necessary to achieve 5 A average, but not to exceed 35 A. The negative pulse amplitude shall be approximately 15 A, and the duty cycle shall be 6%. Charge battery in the topping mode for 75% of time battery was in the main mode.

5. Trickle charge the battery at 0.050 A and allow the battery voltage to decay to 2.5V below trip voltage (main to topping), then charge in main mode to temperature compensated trip voltage, then charge in topping mode for 75% of main mode charge time, then at 0.050 A. This cycling mode is to be continued until the input power or the battery is removed from the charger.

V. RECOMMENDATIONS

A. It is recommended that the charge technique developed during this evaluation be incorporated into three qualification sample chargers to be manufactured by Sundstrand Corporation under contract N00164-75-C-0238.

B. It is recommended that upon successful completion of the charger evaluation, the developed charge technique be incorporated into the airborne battery charger specification, MIL-C-85050.

C. It is recommended that the Navy continue to pursue qualified airborne battery chargers for use aboard Navy aircraft.

RESULTS OF ENGINEERING EVALUATION TEST
OF
20-AMPERE AIRBORNE BATTERY CHARGER (BREADBOARD)

MANUFACTURED BY
SUNDSTRAND CORPORATION

I. TEST CONDITIONS

A. Each test was conducted at existing relative humidity, atmospheric pressure, and room ambient temperature ($21^{\circ} \pm 5^{\circ}\text{C}$) unless otherwise indicated.

II. DESCRIPTION OF CHARGERS

A. The Vapor battery charger, P/N 26340061-04, was designed to charge 22-cell, 40 ah (commercial rating) nickel-cadmium batteries within a maximum time of 45 minutes.

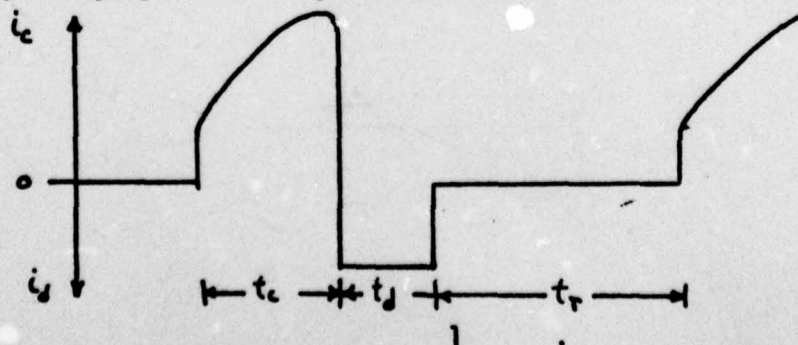
1. The battery charger converts 115V \emptyset 400 HZ input into a D.C. output for battery charging. The average output current is limited to 65A. During normal charging, the output current is between 40A and 60A until a sharp rise in battery voltage is detected at which time the charger provides high current pulses at an ever decreasing rate until the leakage and load current of the battery is supplied.

2. The charger utilizes a wire-wound resistor, having a resistance of 200 ohms at 21°C to sense battery temperature and control the charge voltage accordingly. The sensor is designed to be attached to the bottom of the battery container when installed in the DC-9 aircraft.

3. The battery charger's dimensions in millimeters are approximately 119 H X 197 W X 272 D, and weighs 8.4 kilograms. The Vapor charger is shown in photograph 1.

B. The Sundstrand battery charger (breadboard), P/N 27541526, was designed as a research tool to define a suitable charge technique for charging nickel-cadmium batteries in aircraft.

1. The charger converts 115V \emptyset 400 HZ input into a DC output for battery charging. The charger output waveform is shown below.



a. The positive charge current amplitude, i_c , is variable from 0 to 80A maximum.

b. The discharge current amplitude, i_d , is variable from 1.26 to 20A maximum (with battery voltage of 25.0V).

c. The duty cycle of the positive pulse width, t_c , is variable from 0 to 85 percent.

d. The duty cycle of the negative pulse width, t_d , is variable from 6 to 70 percent.

e. The battery charger has four modes of operation:

(1) Trickle charge until battery reaches 20.0V. Charge current is identical to topping charge.

(2) Main charge until battery reaches preset voltage compensated by temperature.

(3) Topping charge until battery reaches preset voltage compensated by temperature.

(4) Trickle charge until battery reaches preset voltage compensated by temperature.

f. The following parameters can be adjusted with 10-turn precision potentiometers:

(1) Main charge current pulse amplitude.

(2) Main charge current pulse width.

(3) Topping charge current pulse amplitude.

(4) Topping charge current pulse width.

(5) Main to topping mode voltage trip point.

(6) Topping to trickle mode voltage trip point.

(7) Main mode hysteresis voltage (voltage difference between turn off and turn on).

(8) Topping mode hysteresis voltage (voltage difference between turn off and turn on).

(9) Discharge current pulse width.

(10) Slope of voltage-temperature curve.

g. The discharge current amplitude can be varied by selecting resistance values of 19.7, 5.16, 4, 1.8 or 1.25 ohms.

h. The charger, when initially delivered to Crane, did not feature individual adjustments of parameters listed in items (3), (4), (7), (8) and (10). These controls were incorporated into the charger during the evaluation period.

i. The charger utilizes a wire-wound resistor having a resistance of 3000 ohms at 25°C to sense battery temperature and control the charge voltage accordingly. The charger also monitors thermal switches located inside the battery and charger, and battery cell imbalance.

j. The charger's dimensions in millimeters are approximately 318 H X 585 W X 458 D. The Sundstrand breadboard charger, as initially delivered to Crane, is shown in photographs 2 and 3.

III. TEST PROCEDURES AND RESULTS (VAPOR CHARGER P/N 26340061-04):

A. Room temperature performance:

1. A battery comprised of 22 cells was assembled with existing MS90321-75 cells having a rated capacity of 27 ah. The 200-ohm temperature sensor was located at the bottom of the battery, making physical contact with the bottom of a cell located in the center of the battery.

2. The battery was reconditioned, given a 5.4A constant-current charge until the voltage stabilized for one hour, and then discharged at the 1C-rate (27A) to a terminal potential of 20.9V, yielding 37.8 ah.

3. The battery was recharged with the Vapor charger for 80 minutes. The charger turned off after 13 minutes of charge at a battery voltage of 32.76V. During charge, the current ranged between 42.9A and 39.2A. During the last 67 minutes of charge, the battery voltage decayed from 32.76V to 30.28V.

a. The battery was discharged at the 1C-rate (27A) to a terminal potential of 20.9V, and yielded 22.5 ah.

4. The battery was recharged with the Vapor charger for 2 hours. The charger turned off after 42 minutes of charge at a battery voltage of 33.52V. During charge, the current ranged between 47.2A and 35.2A with

an initial surge of 52A. During the last 78 minutes of charge, the battery voltage decayed from 33.52V to 30.37V.

a. The battery was discharged at the 1C-rate (27A) to a terminal potential of 20.9V, and yielded 26.5 ah.

5. The battery was recharged with the Vapor charger for 2 hours. The charger turned off after 55 minutes at a battery voltage of 33.2V. During charge, the current ranged between 42.6A and 27.0A. During the last 65 minutes of charge, the battery voltage decayed from 33.2V to 30.6V.

a. The battery was discharged at the 1C-rate (27A) to a terminal potential of 20.9V, and yielded 27 ah.

6. The battery was recharged with the Vapor charger for 73 minutes. The charger turned off after 63 minutes of charge at a battery voltage of 33.0V. The resistance of the temperature sensor was 210 ohms throughout charge. This resistance value corresponds to a voltage trip point of 33.2V. The 200-ohm wire-wound resistor was replaced by a decade resistance box. The resistance was initially set at 210 ohms and then decreased until the charger reinitiated charge. The charger turned on at 25.0A with an input resistance of 190 ohms. The resistance was then increased to 200 ohms. The charger shut off at a battery voltage of 33.8V. After the charger shut off, the battery voltage was monitored. The voltage decayed from 33.8V to 30.9V, and the charger did not reinitiate charge.

a. The battery was discharged at the 1C-rate (27A) to a terminal potential of 20.9V, and yielded 31.5 ah.

7. The resistance of R-2 (inside charger) was changed by turning the control 1/2 turn CCW, which lowered the turn-on and turn-off voltage levels of the charger. The battery was recharged with the Vapor charger for 90 minutes. The charger turned off after 66 minutes at a battery voltage of 32.5V. The resistance of the temperature sensor was 204-205 ohms throughout charge. The current during charge ranged between 23.0A and 28.7A. The decade resistance box was used to control the charge and was initially set at 200 ohms. When the charger shut off the resistance was decreased until the charger reinitiated charge which occurred at 187 ohms and at a battery voltage of 30.8V. The charger terminated charge at 32.5V with a resistance of 199 ohms.

8. The resistance of R-2 was changed by turning the control CW, which raised the turn-on and turn-off voltage levels of the charger. The turn-off voltage levels vs input resistance of the temperature sensor are as follows:

<u>Resistance (ohms)</u>	<u>Battery Voltage (volts)</u>
200	34.1
202	34.0
205	33.9
210	33.5
215	33.1
220	33.0

a. The battery was discharged at the 1C-rate (27A) to 20.9V.

9. The resistance of R-2 was changed by turning the control one turn CW from its original position. The battery was recharged with the Vapor charger for 2 hours. The charger turned off after 76 minutes of charge at a battery voltage of 34.5V and a temperature sensor resistance of 206 ohms. The charge current ranged between 29.7A and 18.2A. The charger cycled on and off between battery voltages of 31.1V and 34.6V.

a. The battery was discharged at the 1C-rate (27A) to a terminal potential of 20.9V, and yielded 31.5 ah.

10. The battery and Vapor charger were cycled three more times. Following charge, the battery was discharged at 27A to 20.9V delivering 30.15 ah, 29.7 ah and 33.75 ah.

B. Cold Temperature Performance:

1. The battery was placed in a temperature chamber and stabilized at -40°C . The battery was charged for 20 minutes at which time a cell within the battery had exploded. The charge current ranged between 25A and 14.6A, and the battery reached a voltage of 40.8V. The cell exploded because of the high charge rate, the low charge efficiency of Ni-Cd's at -40°C and sluggish operation of vent caps at -40°C .

2. The battery was repaired and then stabilized at -29°C and charged for 3.25 hours. During charge the resistance of R-2 was decreased to lower the trip point voltages in the charger. The charger cycled on-off between 36.0V and 38.9V.

a. The battery was discharged, while remaining inside the -29°C temperature chamber at 18A to 20.9V, and delivered 16.8 ah.

3. The battery was stabilized at -18°C and charged for 4 hours. The battery charged for 30 minutes at 40.0A to 19.5A until its terminal potential reached 38.2V. The charger then cycled on-off between 35.5V and 38.6V. The total ah accumulated during charge was 30.36 ah.

a. The battery was discharged at 20.0A to 20.9V, while remaining inside the temperature chamber, delivering 27.66 ah.

4. The battery was stabilized at -29°C and charged for 4 hours. The battery charged for 1 hour at 14A to 16.5A until its terminal potential reached 39.0V at a temperature of -18.9°C . The charger then cycled on-off between 36.0V and 39.0V. The total ah accumulated during charge was 31.18 ah.

a. The battery was discharged at 20.0A to 20.9V, while remaining inside the temperature chamber, delivering 21.6 ah.

5. The battery was stabilized at -40°C and charged for 4 hours. The battery charged for 1 hour at 6.8A to 5.0A until its terminal potential reached 38.0V at a temperature of -34.4°C . The charger then cycled between 36.2V and 39.4V. The total ah accumulated during charge was 18.23 ah.

a. The battery was discharged at 20.0A to 20.9V while remaining in the -40°C temperature chamber, and delivered 8.3 ah.

6. The battery was constant-potential charged at 33.0V at 25°C for 5 hours. The battery was discharged at 20.0A to 20.9V, and delivered 24 ah. The battery was maintained in a shorted condition for 24 hours and then recharged with the Vapor charger for 2 hours. The battery charged for 48 minutes at 37.5 to 48.0A until its terminal potential reached 33.5V. The total ah accumulated during charge was 34.85 ah. The battery was discharged at 20.0A to 20.9V and delivered 28 ah.

C. Duty Cycling:

1. Following a 7.6A constant-current charge until the voltage stabilized, the battery and charger were subjected to a duty cycle test at room temperature as follows:

a. Discharge -- 27.0A (1C-rate) for 1 hour or to 20.9V cutoff.

b. Rest -- 1 hour

c. Charge -- 2 hours.

d. Rest -- 2 hours

2. The system only completed 6 cycles of discharge and charge, failing to meet the 1-hour discharge requirement during cycle 7 with a terminal potential of 20.9V occurring in less than 1-hour period.

a. The highest and lowest end-of-discharge voltages were 25.91V and 20.90V occurring during cycles 1 and 7 respectively.

b. The test results of the 7 cycles are shown below:

<u>Cycle No.</u>	<u>ah Out</u>	<u>ah In</u>	<u>% Charge</u>	<u>E-O-C Volts</u>	<u>E-O-D Volts</u>	<u>Disch time (Minutes)</u>	<u>Chg Curr (Amps)</u>
1	26.7	27.8	104	31.28	25.91	60	51.0
2	26.8	28.3	106	31.27	25.60	60	52.8
3	26.8	28.3	106	31.02	25.38	60	53.5
4	26.9	28.4	106	31.70	24.70	60	53.6
5	26.9	28.2	105	31.05	23.74	60	53.1
6	26.8	29.7	111	31.07	21.23	60	52.9
7	26.0	-	-	-	20.9	58.3	-

3. The battery was constant potential charged at 33.0V for 2.5 hours. The battery was then discharged at 27.0A to 20.9V, and delivered 27.0 ah. Three cells reversed polarity at the end of the 1-hour discharge. The battery was reconditioned, and cells 9, 14 and 18 were replaced. The battery was constant-current charged at 7.6A until its potential stabilized. The battery was then discharged at 27.0A to 20.9V, and delivered 41.4 ah.

4. The battery was recharged at 7.6A until its voltage stabilized and then subjected to the cycling test described in paragraph III.C.1.

a. The system completed 14 cycles of discharge and charge. The battery failed to meet the 1-hour discharge requirement during cycles 7 through 14 with terminal potentials of 20.9V occurring in less than the 1-hour period.

b. The test results of the 14 cycles are as shown below:

<u>Cycle No.</u>	<u>ah Out</u>	<u>ah In</u>	<u>% Charge</u>	<u>E-O-C Volts</u>	<u>E-O-D Volts</u>	<u>Bty Temp at bottom °C</u>	<u>Bty Temp Between Cells °C</u>	<u>Chg Curr (Amps)</u>
1	26.8	29.8	111	32.7	25.3			54.8
2	27.2	30.3	111	32.0	25.2	39.4		55.3
3	26.8	29.4	110	33.4	24.9	40.0		55.1
4	27.1	29.5	108	32.4	24.4	41.1		55.3
5	26.7	28.8	107	32.5	23.4	42.2		55.6
6	26.7	28.5	106	31.9	21.4	43.3		55.0
7	26.2	27.6	105	31.94	19.9	43.9		55.0
8	23.9	24.9	104	32.3	20.9	40.6		55.6
9	23.5	26.7	113	34.1	20.9	41.1	45.6	54.6
10	21.8	24.6	112	33.0	20.9	36.7	41.7	54.4
11	22.4	25.0	111	32.0	20.9	39.4	45.0	54.7
12	22.3	32.4	145	36.3	20.9	41.1	46.1	29.9
13	23.5	29.5	125	33.6	20.9	37.2	40.0	29.9
14	24.4	34.0	139	36.3	20.9	41.7	45.6	30.0

Note: (1) Cycle 9: Increased turn-off voltage to 36.0V at 34.5°C and made comparison of battery temperatures when measured between cells at center of battery, and at charger temperature sensor located at bottom of battery.

(2) Cycle 12: Reversed Phase A with Phase B input to charger.

5. The battery was reconditioned, constant-current charged at 7.6A until its voltage stabilized, and then discharged at 27.0A to 20.9V, and delivered 39.69 ah.

6. The battery was recharged at 7.6A until its voltage stabilized, and was then subjected to the cycling test of paragraph III.C.1.

a. The test was terminated after completion of only 3 cycles. During the charge portion of each cycle, the battery temperature rose by as much as 8.9°C as a result of the high percentage overcharge. There was a substantial difference in temperatures recorded from #1 sensor located at the charger temperature sensor mounted on the bottom of the battery and #2 sensor located between two cells located near center of battery.

b. Test results of the 3 cycles are shown below:

Cycle No.	ah Out	ah In	% Charge	E-O-C Volts	E-O-D Volts	Bty Temp at bottom °C	Bty Temp between Cells °C	Chag. Curr (Amps)
1	27.0	38.5	142	36.0	24.1	100	108	30.26
2	27.0	40.4	149	35.1	24.2	120	130	31.41
3	26.9	43.1	160	34.7	21.0	126	140	31.09

c. The temperature sensor (200-ohm wire-wound) was relocated to the side of the battery. The battery was recharged at 7.6A until its voltage stabilized. Water was added to each cell to adjust the electrolyte to proper level. The battery was discharged at 27.0A and delivered 27 ah.

7. The battery was reconditioned, constant-current charged at 7.6A until its voltage stabilized, and then discharged at 27.0A to 20.9V, and delivered 37.26 ah.

8. The battery was recharged at 7.6A until its potential stabilized, and then subjected to the cycling test of paragraph III.C.1.

a. The system completed 5 cycles of discharge and charge. The battery failed to meet the 1-hour discharge requirement during cycles 5 and 6 with terminal potentials of 20.9V occurring in less than 1-hour period.

b. The test results of the 6 cycles are shown below:

<u>Cycle No.</u>	<u>ah Out</u>	<u>ah In</u>	<u>% Charge</u>	<u>E-O-C Volts</u>	<u>E-O-D Volts</u>	<u>Bty Temp at Side °C</u>	<u>Bty Temp Between Cells °C</u>	<u>Chg Curr (Amps)</u>
1	27.0	31.8	117	33.7	25.75	92	99	30.0
2	27.0	32.8	121	36.3	25.33	99	110	30.78
3	27.0	30.4	112	33.16	24.73	99	112	30.83
4	27.0	29.9	110	33.25	22.81	102	113	30.17
5	26.2	29.3	111	34.3	20.9	101	112	30.05
6	25.0				20.9			

9. The battery was reconditioned, constant-current charged at 7.6A until its potential stabilized, and then discharged at 27.0A to 20.9V, and delivered 32.11 ah.

10. The battery was recharged at 7.6A until its potential stabilized, and then subjected to the cycling test of paragraph III.C.1.

a. The system completed 5 cycles of discharge and charge. The battery failed to meet the 1-hour discharge requirement during cycle 5 with a terminal potential of 20.9V in less than 1-hour period.

b. Phase A and Phase B charger inputs were reversed to original configuration.

c. Test results of the 5 cycles are shown below:

<u>Cycle No.</u>	<u>ah Out</u>	<u>ah In</u>	<u>% Charge</u>	<u>E-O-C Volts</u>	<u>E-O-D Volts</u>	<u>Bty Temp at Side °C</u>	<u>Bty Temp Between Cells °C</u>	<u>Chg Curr (Amps)</u>
1	27.0	29.9	109	33.7	25.2	91	93	55.2
2	26.5	30.8	115	33.1	25.0	99	110	56.0
3	27.0	30.4	112	33.5	24.4	101	117	55.8
4	26.6	29.3	110	34.1	23.5	100	115	55.4
5	26.9	29.3	109	33.3	20.9	101	115	54.8

11. The battery was reconditioned, constant-current charged at 7.6A until its voltage stabilized, and then discharged at 27.0A to 20.9V, and delivered 34.6 ah.

12. The charger was returned to Vapor to have the voltage trip points set in accordance with manufacturing specifications.

13. The battery was recharged at 7.6A until its potential stabilized, and then subjected to a cycling test with the charger after adjustments had been made at room temperature as follows:

- a. Discharge -- 510A (18.8 C-rate) for 30 seconds or to 11.0V cutoff. (Removes 4.25 ah to simulate APU start.)
- b. Charge -- 45 minutes.
- c. Rest -- 1 hour.

14. The system completed 200 cycles of discharge and charge, failing to meet the 30-second discharge requirement during cycle 200 with a terminal potential of 10.9V at the end of the 30-second discharge.

- a. The time required to recharge the battery following the 4.25 ah discharges was approximately 4.5 minutes.
- b. The battery was overcharged approximately 104 percent each cycle.
- c. The average battery temperature throughout cycling was 38°C.
- d. A total of 550 cc of water was required to adjust electrolyte to proper level.

15. The battery was reconditioned, constant-current charged at 7.6A until its voltage stabilized, and then discharged at 27.0A to 20.9V delivering 32.8ah.

16. The battery was recharged at 7.6A until its voltage stabilized, and then subjected to the cycling test described in paragraph III.C.13.

17. The system completed 523 cycles of discharge and charge, failing to meet the 30-second discharge requirement during cycles 520-523.

- a. The time required to recharge the battery following the 4.25 ah discharges was approximately 4.5 minutes.
- b. The battery was overcharged approximately 104 percent each cycle.
- d. The battery completed the 523 cycles without maintenance, or addition of water.

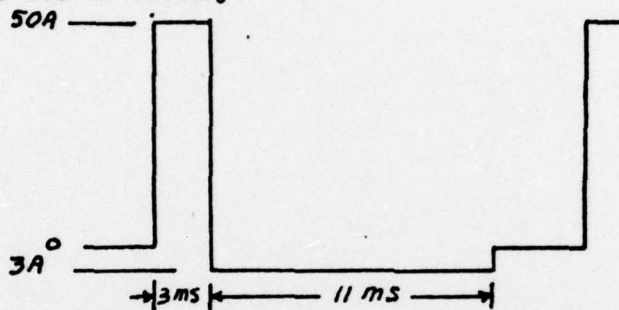
IV. TEST PROCEDURES AND RESULTS (Sundstrand charger (breadboard) P/N 27541526):

A. Analysis of Existing Pulse Charge Techniques:

1. Several pulse charge modes were investigated by the U.S. Army Electronics Technology and Devices Laboratory (ECOM), and reported in "Investigation of Charging Methods for Nickel-Cadmium Batteries," 26th Proceedings of the Power Sources Symposium, 1974.

2. The pulse charge techniques investigated included the Romanov and McCulloch modes. These modes are described below:

a. Romanov pulse. This pulse charge waveform was used to charge a 5.5 ah battery.



Positive pulse: $50A \times 3ms = 0.150 \text{ A-sec/cycle}$

Pulse rate = 60 cycles/sec

Positive pulse current = $0.150 \times 60 = 9.0A$

Negative pulse: $3A \times 11ms = 0.033 \text{ A-sec/cycle}$

Pulse rate = 60 cycles/sec

Negative pulse current = $0.033 \times 60 = 1.98A$

Average current (+ and -) = $9.0 - 1.98 = 7.02 \text{ A}$

Negative pulse current = 22 percent positive pulse current

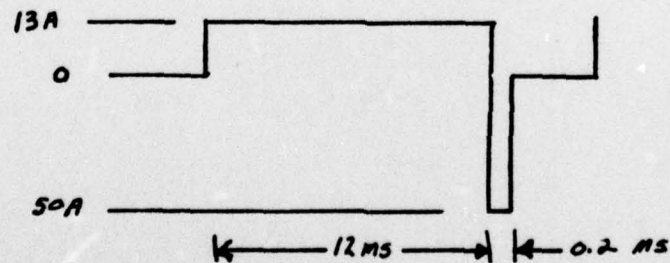
Duty cycle: + Pulse .003 sec = 18.08%

- Pulse .011 sec = 66.26%

Rest .0026 sec = 15.66%

100%

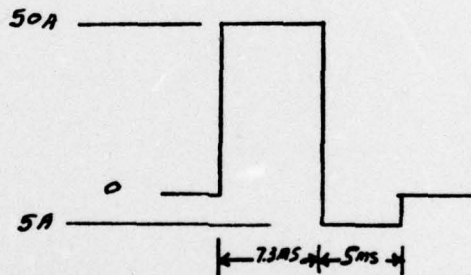
b. McCulloch pulse. This pulse charge waveform was used to charge a 5.5 ah battery.



Positive pulse: $13A \times 0.012 \text{ sec} = 0.156A\text{-sec/cycle}$
 Pulse rate = 60 cycles/sec
 Positive pulse current = $0.156 \times 60 = 9.36A$
 Negative pulse: $50A \times 0.0002 \text{ sec} = 0.01A\text{-sec/cycle}$
 Pulse rate = 60 cycles/sec
 Negative pulse current = $0.01 \times 60 = 0.6A$
 Average current (+ and -) = $9.36 - 0.6 = 8.76A$
 Negative pulse current = 6.4% positive pulse current

Duty cycle: + Pulse .012 sec = 72.3%
 - Pulse .0002 sec = 1.2%
 Rest .0044 sec = $\frac{26.5\%}{100\%}$

- c. ECOM reconditioning pulse: This pulse charge waveform
 (Romanov pulse) was used to recondition an
 11 ah battery which had been
 subjected to a fadeout
 cycling regime.



Positive pulse: $50A \times .0073 \text{ sec} = 0.365A\text{-sec/cycle}$
 Pulse rate = 60 cycle/second
 Positive pulse current = $0.365 \times 60 = 21.9A$
 Negative pulse: $5A \times .005 \text{ sec} = 0.025A\text{-sec/cycle}$
 Pulse rate = 60 cycles/sec
 Negative pulse current = $0.025 \times 60 = 1.5A$
 Average current (+ and -) = $21.9 - 1.5 = 20.4A$
 Negative pulse current = 6.8% positive pulse current

Duty cycle: + pulse .0073 sec = 43.98%
 - pulse .005 sec = 30.12%
 Rest .0043 sec = $\frac{25.90\%}{100\%}$

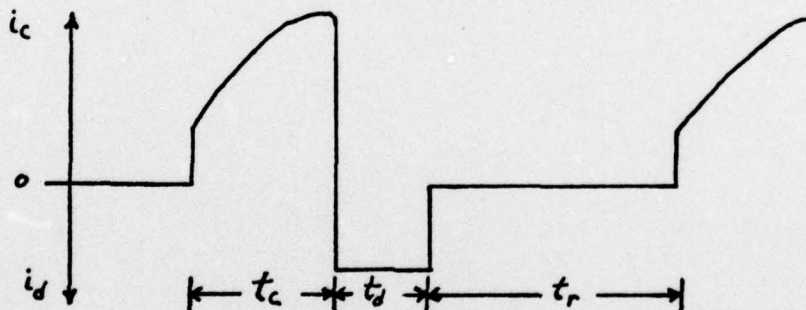
d. It was noted in the ECOM report that although the waveforms of the Romanov and McCulloch modes are radically different, there is little difference in their effect on the charge acceptance of nickel-cadmium batteries. A comparison of these waveform parameters is shown below.

<u>Waveform Parameter</u>	<u>Romanov</u>	<u>McCulloch</u>
Peak Positive Pulse Current	50A	13A
Average Positive Pulse Current	9.0A	9.36A
Peak Negative Pulse Current	3.0A	50.0A
Average Negative Pulse Current	1.98A	0.6A
Average Current (+ and -)	7.02A	8.76A
Average Charge Rate	1.27C	1.59C
- Pulse Current = X% of + Pulse Current	X = 22%	X = 6.4%
Magnitude $\frac{\text{Peak Pos. Current}}{\text{Avg Pos. Current}}$	5.5	1.38
Magnitude $\frac{\text{Peak Neg. Current}}{\text{Avg. Neg. Current}}$	1.5	83.3

B. First Charge Technique (Sundstrand Charger):

1. The charge technique described below was designed to charge a 19-cell 20 ah nickel-cadmium battery instrumented with a wire-wound resistor having a resistance of 3000 ohms at 25°C and a TC of 4100 + 30 PPM/°C above 25°C, and a TC of 3900 + 30 PPM/°C below 25°C. The resistor is used for charge control. The battery also contained an N.O. thermal switch for high temperature charge termination and a center tap wire for cell imbalance detection.

a. Set up for average charge current of 25A (1.25C)



in main mode and 4A (C/5) in topping mode.

Main Mode

Negative pulse = 1.388A: based upon $\frac{25V}{1.8 \text{ ohms}} = 13.88A$ at a 10 percent duty cycle.

Positive pulse = 25A + 1.388A = 26.388A

Pulse width = 0.141 ms = 56.4% duty cycle

Peak current = $\frac{26.388}{.56 \times .8} = 58.9A$

Peak $i_c = 58.9A$ Avg $i_c = 26.388A$
 Peak $i_d = 13.88A$ Avg $i_d = 1.388A$
 Avg charge current (+ and -) = 25.0A
 Negative pulse current = 5.25% positive pulse current

Duty cycle: $t_c = .141 \text{ ms} = 56.4\%$
 (0.25 ms/cycle) $t_d = .025 \text{ ms} = 10\%$
 $t_r = .084 \text{ ms} = 33.6\%$
 100%

Battery voltage trip point (main to topping mode) = 29.0V at 21°C.
 Slope control = 4.6 MV/°C per cell. (This control was installed soon after the charger was received at Crane.)

Topping Mode

Negative pulse: 6 percent duty cycle = 0.015 ms

$$i_d = \frac{25V}{1.8 \text{ ohms}} = 13.88A$$

$$\text{Avg } i_d = 13.88 \times .015 \times 4000 = 0.83A$$

Positive pulse = 4A + 0.83 = 4.83A
 15.5% duty cycle = .038 ms

$$\text{Peak current} = \frac{4.83}{.155 \times .8} = 38.95A$$

Peak $i_c = 38.95A$ Avg $i_c = 4.83A$
 Peak $i_d = 13.88A$ Avg $i_d = 0.83A$
 Avg charge current (+ and -) = 4.0A
 Neg pulse current = 17.18% positive pulse current

Duty cycle: $t_c = .038 \text{ ms} = 15.5\%$
 (0.25 ms/cycle) $t_d = .015 \text{ ms} = 6\%$
 $t_r = .197 \text{ ms} = 78.5\%$
 100%

Battery voltage trip point (topping to trickle mode) = 29.0V at 21°C

Continuous trickle charge current = 0A

2. In setting up the charger with the above described charge parameters, the power output of the charger was disabled, and a DC power supply was connected to the output terminals of the charger. The trip point voltages were set with the use of this supply. Also, waveforms were reviewed and adjusted with the use of an oscilloscope and 10-turn precision potentiometers. The controls used to adjust the current amplitude and pulse width in the main charge mode were also used to adjust these parameters in the topping charge mode.

3. Familiarization with the charger was gained after several hours of charging batteries and adjusting the charge parameters. It became apparent that the following modifications to the charger would be necessary to successfully complete the evaluation of charge techniques.

a. Provide additional hysteresis in main mode (voltage range between turn off and turn on.)

b. Provide additional and adjustable hysteresis in topping mode (voltage range between turn off and turn on.)

c. Provide separate controls for pulse amplitude and pulse width in both main and topping charge modes.

4. These modifications were incorporated in the charger by Crane personnel and the operation of the unit was verified by Sundstrand. The number of cells in the battery was reduced from 19 to 17 in order to maintain a nearly constant current during charge.

5. As a result of the modifications to the charger and battery the parameters of the charge technique described in paragraph IV.B.1.a were modified as follows:

Main Mode:

Peak i_c = 58.57A	Avg i_c = 26.24A
Peak i_d = 12.42A	Avg i_d = 1.24A
Avg charge current (+ and -) = 25.0A	
Negative pulse current = 4.7% positive pulse current	
Duty cycle	t_c = .140 ms = 56%
(0.25 ms/cycle)	t_d = .025 ms = 10%
	t_e = .085 ms = 34%
	100%

Topping Mode:

Peak i_c = 38.95A	Avg i_c = 4.75A
Peak i_d = 12.42A	Avg i_d = 0.75A
Avg charge current (+ and -) = 4.0A	
Negative pulse current = 15.7% positive pulse current	
Duty cycle:	t_c = .038 ms = 15.2%
(0.25 ms/cycle)	t_d = .015 ms = 6.0%
	t_r = .197 ms = 78.8%
	100%

Continuous trickle 6 charge current = 0A

AT 21°C:

Battery voltage trip point (main to topping mode) = 25.94V
 Battery voltage trip point (topping to trickle 6 mode) = 26.84V
 Topping mode hysteresis = 26.84V - 23.88V = 3V
 Main mode hysteresis = 25.94V - 22.42V = 3.52V
 Slope control = 4.6mv/°C per cell.

6. Duty Cycle Test:

a. The battery was constant-current charged at 4.5A until its voltage stabilized, and then discharged at 20.0A (1C-rate) until its voltage reached 16.1V, delivering 26 ah.

b. The battery was subjected to a duty cycle test of 8 cycles/day consisting of:

(1) 2-hour charge with the Sundstrand charger connected to 115V 3Ø 400Hz.

(2) 3-minute discharge into a fixed resistance load of 0.11 ohm.

(3) 57-minute rest.

(4) The voltage cut-off = 13.0V.

(5) The high temperature cut-off = 60°C.

c. The battery completed 64 cycles of charge and discharge prior to reconditioning. Minor adjustments to the charge parameters were made during the course of cycling.

(1) During cycle 1 the battery was charged for 2 hours with the Sundstrand charger at 25A to 25.9V, 4A to 26.9V, and then cycled on and off at 4A between 23.9V and 26.9V. The voltage at the end of discharge was 18.3V during which the battery delivered 8.3 ah.

(2) During the charge portion of cycle 10, the topping mode hysteresis was changed from 3V to 1.5V resulting in a slightly increased percent overcharge.

(3) During the 2-hour charge of cycle 13 the battery was charged at 26.7A-24A for 12 minutes at which time the battery reached 23.8V at 42.2°C. The battery was then charged at 4A for 49 minutes at which time the battery reached 25.9V at 39.9°C. The charger cycled on and off between battery voltages of 24.35V and 25.9V. The battery received 5 ah during main mode, 3.27 ah during topping charge and 0.37 ah during trickle charge totaling 8.64 ah, which is 103.1 percent of previous discharge. The voltage at the end of discharge was 17.8V during which the battery delivered 8.33 ah.

(4) During the 2-hour charge of cycle 14, the battery was charged at 27 - 22A for 20 minutes. The trip voltage from main to topping modes was changed from 23.8V to 24.6V (at 41.1°C). The battery was then charged at 4.5A for 5.5 minutes at which time the battery reached 25.8V at 41.1°C. The charger cycled on and off between battery voltages of 24.2V and 25.8V. The battery received 7.9 ah during main mode, 0.33 ah during topping mode, and 0.62 ah during trickle mode totaling 8.85 ah, which is 106.2% of previous discharge. The voltage at the end of discharge was 17.8V during which the battery delivered 8.46 ah.

(5) During the 2-hour charge of cycle 22, the battery was charged at 26 - 22A for 20.5 minutes at which time the battery reached 24.6V at 42.2°C. The battery was then charged at 4.5A for 5.5 minutes at which time the battery reached 25.6V at 42.2°C. The charger cycled on and off between battery voltages of 24.0V and 25.7V. The battery received 7.85 ah during main mode, 0.39 ah during topping mode, and 0.50 ah during trickle mode totaling 8.74 ah, which is 105.1% of previous discharge. The voltage at the end of discharge was 17.4V during which the battery delivered 8.31 ah.

(6) The voltage at the end of discharge during cycle 28 was 16.0V, 1.0V less than the end of discharge voltage during cycle 27, resulting from one cell's terminal potential being reduced to zero during the discharge.

(7) The voltage at the end of cycle 40 dropped to 12.0V, 1 volt less than the specified minimum of 13.0V.

(8) During the 2-hour charge of cycle 44, the battery was charged at 27.5 - 22.3A for 20 minutes at which time the battery reached 24.3V at 43.9°C. The battery was then charged at 4.5A for 8 minutes at which time the battery reached 25.6V at 43.3°C. The charger cycled on and off between battery voltages of 24.0 and 25.6V. The battery received 7.5 ah during main mode, 0.63 ah during topping mode, and 0.75 ah during trickle mode, totaling 8.88 ah, which is 112% of the previous discharge. Upon completion of charge the charger was adjusted for minimum reflex: Pulse width of 0.15 ms and i peak of 1.26A at 25V.

(9) During cycle 44, the battery was discharged for 1.0 minute instead of 3 minutes to assess the charger's capability of returning the proper amount of charge back into the battery when discharged to different depths of discharge. The end of discharge voltage was 18.8V.

(10) During the 2-hour charge of cycle 45, the battery was charged at 25A for 6.5 minutes at which time the battery reached 24.6V at 42.2°C. The battery was then charged at 4.5A for 2.5 minutes at which time the battery reached 25.6V at 42.2°C. The charger cycled on and off between battery voltages of 24.7 and 25.8V. The battery received 2.68 ah during main mode, 0.13 ah during topping mode, and 0.17 ah during trickle mode, totaling 2.98 ah, which is 104% of the previous discharge.

(11) The battery was again discharged for 1.0 minute instead of 3. The end-of-discharge voltage was 18.6V.

(12) After the battery was recharged during cycle 46, the battery electrolyte levels were adjusted for the first time. The total water added was 66 ml or an average of 3.88 ml/cell (only 20% of reservoir.)

(13) The discharge portion of cycle 46 consisted of a 20.0A discharge to 16.1V (capacity test) yielding a low 9.66 ah.

(14) The battery was recharged 146% to help restore capacity, and then was subjected to normal cycling. During the next discharge (cycle 47) the battery had an end-of-discharge voltage of 16.2V.

(15) During the 2-hour charge of cycle 53, the battery was charged at 25-23A for 17 minutes at which time the battery reached 24.25V at 47.2°C. The battery was then charged at 4.5-4.0A for 15 minutes at which time the battery reached 26.9V at 46.7°C. The battery received 6.8 ah during main mode, 1.37 ah during topping mode and 2.06 ah during trickle mode, totaling 10.23 ah, which is 126.6% of the previous discharge. The charger cycled on and off at battery voltages of 25.4V and 26.9V. These voltages were readjusted to 24V and 27V.

(16) During cycles 54 through 64 the battery recharge varied from 124% to 160%. During each recharge the battery temperature increased to preclude desirability of overcharging by this amount on aircraft. (Overcharge percentages are inconsistent due to hysteresis circuit not remaining constant.)

(17) The battery was removed from cycling following completion of cycle 64 and reconditioned. The end-of-discharge voltage for this cycle was 14.4V.

(a) The battery was constant-current recharged at 4.5A until its potential leveled or decreased within a 1-hour period.

(b) The battery was constant-current discharged at 20.0A to 16.1V yielding 11 ah.

(c) The battery was placed in a shorted condition for 24 hours and then constant-current charged at 4.5A until the voltage leveled or decreased within a 1-hour period.

(d) The battery was again discharged at 20.0A rate to 16.1V yielding 20.6 ah. Two cells reversed polarity after 30 minutes of discharge and were replaced after the battery had again been shorted.

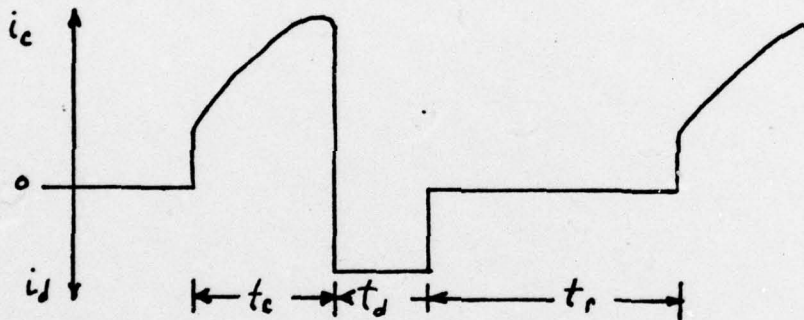
(e) The battery was constant-current charged at 4.5A until its potential leveled or decreased within a 1-hour period.

(f) The battery was discharged at a 20A rate until its potential reached 16.1V yielding 25.6 ah.

(g) The battery was recharged at the 4.5A rate until its voltage leveled or decreased within a 1-hour period.

C. Second Charge Technique (Sundstrand charger):

1. Set up for average charge current of 25A (1.25C) in main mode and 4.5A (C/5) in topping mode. Reduce reflex current to minimum. Maintain same trip voltages and hysteresis as in first charge technique.



MAIN MODE

Negative pulse = 0.075A: based upon $\frac{25V}{19.7 \text{ ohms}} = 1.26A$

at a 6 percent duty cycle.

Positive pulse = 25A + .075A = 25.075A

Pulse width = 83% (max) = .207 ms

Peak current = $\frac{25.075A}{.83 \times .8} = 37.76A$

Peak $i_c = 37.7A$

Avg $i_c = 25.075A$

Peak $i_d = 1.26A$

Avg $i_d = 0.075A$

Avg charge current (+ and -) = 25.0A

Negative pulse current = 0.29% positive pulse current

Duty cycle: $t_c = .207 \text{ ms} = 83\%$

(0.25 ms/cycle) $t_d = .015 \text{ ms} = 6\%$

$t_r = .027 \text{ ms} = 11\%$

100%

Topping Mode

Negative Pulse: 6 percent duty cycle = 0.015 ms

$$i_d = \frac{25V}{19.7 \text{ ohms}} = 1.26A$$

Avg $i_d = 1.26A \times .015 \text{ ms} \times 4000 = .075A$

Positive pulse = 4.5A + .075A = 4.575A

Pulse width = 60% = 0.15 ms

Peak current = $\frac{4.575A}{.6 \times .8} = 9.53A$ Peak $i_c = 9.53A$ Avg $i_c = 4.575 A$ Peak $i_d = 1.26A$ Avg $i_d = 0.075A$

Avg charge current (+ and -) = 4.5A

Negative pulse current = 1.63% positive pulse current

Duty Cycle: $t_c = .15 \text{ ms} = 60\%$ $t_d = .015 \text{ ms} = 6\%$ $t_r = .085 \text{ ms} = 34\%$

100%

Continuous trickle charge current = 0A

2. Duty Cycle Test:

a. The battery was subjected to the duty cycle test described in para. IV.B.6.b. Adjustments were made to the charge parameters during the course of cycling to improve charge efficiency and discharge performance.

(1) During cycle 1, the battery having already been fully charged, required very little charge from the Sundstrand unit. While the battery was cycling between the trickle and topping charge modes, the topping-trickle trip point voltage was lowered slightly. It was observed that trickle charge current was present, and was adjustable by varying the main mode pulse width control. The trickle charge current was adjusted to 0.225A, which substantially reduced the on-off cycling of the charger.

(2) The voltage at the end of discharge during the first cycle was 18.0V (17 cells).

(3) During cycle 2, the battery was charged for 2 hours with the Sundstrand unit. The main mode charge current was 25A for 20 minutes at which time the battery reached 25.2V at 36.7°C. The battery was then charged at 5.25-4.5A for 4 minutes. The topping to trickle hysteresis was readjusted for 2.2V. The trickle charge current was 0.25A. The battery received 7.87 ah during main mode, 0.27 ah in topping mode and 0.18 ah in trickle mode. The ah counter used during the test was insensitive to currents less than 0.5A.

(4) During the 2-hour charge of cycle 9 the battery was charged at 25.25 - 24.5A for 21 minutes at which time the battery reached 24.7V at 42.2°C. The battery was then charged at 5.25 - 4.5A for 10 minutes at which time the battery reached 26.7V at 42.2°C. The trickle charge current was 0.25A. The topping-trickle trip point was increased slightly, and the topping charge peak current was increased to 20A and the duty cycle was reduced to 20%.

(5) The voltage at the end of discharge during cycle 9 was 17.7V.

(6) During cycle 10, the battery was discharged at 20.0A to 16.1V and yielded 22.6 ah. The battery was then shorted.

(7) During cycle 11, the battery was recharged from a shorted condition. The battery was charged at 24A for 70 minutes to 25.9V at 26.7°C and then 4.5A for 65 minutes to 27.5V at 28.9°C. The battery received 25.25 ah during main mode and 4.63 ah during topping mode.

(8) The battery delivered 23.83 ah when discharged at 20.0A to 16.1V during cycle 11.

(9) During the 2-hour charge of cycle 12 the battery accepted 24.98 ah of charge. The temperature rise of the battery when 100% of the charge was returned to the battery was 0.6°C.

(10) The battery delivered 23.66 ah when discharged at 20.0A to 16.1V during cycle 12.

(11) During cycle 13 the battery was discharged for 3 minutes into a fixed-resistance load of 0.11 ohm. The end of discharge voltage was 18.6V.

(12) During the 2-hour charge of cycle 14 the battery was charged at 25A for 20 minutes to 24.85V at 42.8°C and then 4A for 10 minutes to 26.5V at 42.8°C and then at 0.5A trickle. The battery received 8.16 ah during main mode, 0.37 ah during topping mode and 0.83 ah during trickle mode.

(13) The battery was discharged for 3 minutes into a 0.11 ohm load and had an end of discharge voltage of 18.4V.

(14) The charge technique that was used during the last few cycles appeared to be good and it was decided that some temperature testing should be conducted at this time.

3. Cold Temperature (-29°C) Test:

a. The battery was discharged at 20.0A to 16.1V and then placed into a -29°C temperature chamber and allowed to stabilize at that temperature.

b. The charger was set up to charge at 25A in the main mode. When the battery was placed on charge, the charger tripped into the topping charge mode after only one minute after the start of charge due to the very high internal impedance of the battery at cold temperatures and the high charge current. The trip voltage was approximately 30V (1.76 volts per cell). The charger began charging at 2A in the topping mode. The charge current amplitude and pulse width was increased to achieve an 8A charge rate. The battery charger tripped into trickle charge mode at 30.6V and at a battery temperature of -16.7°C. The trickle charge current was adjusted for 60 ma, and the topping-trickle hysteresis was adjusted for 4.6V such that the battery was cycling between 26V and 30.6V. The battery was charged for 4 hours (in accordance with reference (a) and accepted 20.94 ah.

c. The battery while remaining in the -29°C chamber was rested one hour and then discharged at 20.0A to 16.1V and yielded 18.33 ah. Reference (a) required a minimum of 11.6 ah.

d. The charge technique described in the preceding paragraph worked satisfactorily, however, it was not consistent with the charge techniques evaluated at higher temperatures. One charge technique must be used within the entire temperature range to be encountered in service. The -29°C test was rerun with the charger set up as it had been during high temperature operation.

(1) As soon as charge was initiated, the charger tripped into the topping charge mode. The battery was then charged at 4.5-3.5A for 4 hours, during which time the battery reached 31.25V and accepted 16.76 ah (91% recharged). The battery temperature increased by 6.1°C during the charge period. The battery did not trip into tickle charge, but the trip point was determined to be 31.5V.

(2) The battery, while remaining in the -29°C temperature chamber, was rested for 2.5 hours and then discharged at 20.0A to 16.1V. The battery yielded 16.0 ah, exceeding the 11.6 ah requirement of reference (a).

4. Cold Temperature (-18°C) Test:

a. The battery was stabilized at -18°C and then charged for 4 hours. The battery charged at 25.5 to 22.0A for 33 minutes at which time the battery reached 28.9V at -16.1°C. The battery then charged at 4.5A-3.6A for 1.6 hours at which time the battery reached 30.55V at -13.3°C. The battery then trickle charged for 20 minutes at 60 ma and cycled between 25.9-30.55V. During the remaining 1.5 hours, the trickle charge was adjusted to 0.4A to maintain a C.P. of 26.0V instead of on/off cycling.

b. The battery, while remaining at -18°C , was discharged at 20.0 A to 16.1V and yielded 20.16 ah.

5. Duty Cycle Test (60 cycles):

a. The battery was reconditioned, and charged at 4.5A until its voltage leveled or decreased within a 1-hour period. The battery received 38.25 ah within an 8.5-hour period. The battery temperature increased 10°C as a result of this charge.

b. The battery and charger began a duty cycle test as described in paragraph IV.B.6.b, except that 6 cycles were conducted each day instead of 8, allowing for a 2-hour rest period between cycles, instead of 1 hour.

(1) The end of discharge voltage during cycle 1 was 18.6V.

(2) During the 2-hour charge of cycle 2, the battery charged at 27.5-25A to 25.6V at 35°C , and then charged at 4.5A to 26.8V at 36.1°C . The battery was then trickle charged at 0.15A. The battery received 8.15 ah during main mode, 1.30 ah during topping mode, resulting in a 110.9% charge.

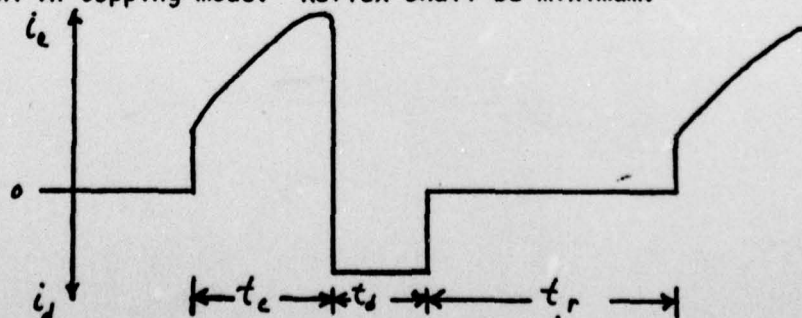
(3) During cycles 3-58, the battery was overcharged between 135% and 150%. The high overcharge was the result of the topping charge current being limited to 2.5A, and consequently the charger did not trip from topping mode to trickle mode. Water was added during cycle 40 totaling 625cc (37cc/cell) which is excessive.

(4) During cycle 59, the topping charge current was raised to 4.0A and the charger tripped into trickle charge normally.

(5) During cycle 60, the charger operated normally and put 109.2% back into the battery. However, the end of discharge voltage was 12.6V and cycling was terminated.

D. Third Charge Technique (Sundstrand Charger):

1. Set up for an average charge current of 24.5A in main mode and 5A in topping mode. Reflex shall be minimum.



Maintain same trip point voltage and slope control. Set up on-off cycling from main mode to trickle mode with hysteresis of 2.5V with respect to main mode trip point.

MAIN MODE

Negative pulse = 0.075A: based upon $\frac{25V}{19.7 \text{ ohms}} = 1.26A$ at 6% duty cycle

Positive pulse = $24.5A + .075A = 24.575A$
 Pulse width = 63% = 0.157 ms
 Peak current = $\frac{24.575}{.63 \times .8} = 48.75A$

Peak $i_c = 48.75A$ Avg $i_c = 24.575A$
 Peak $i_d = 1.26A$ Avg $i_d = 0.075A$

Avg. charge current (+ and -) = 24.5A
 Negative pulse current = 0.30% positive pulse current
 Duty cycle: $t_c = .157 \text{ ms} = 63\%$
 (.25 ms/cycle) $t_d = .015 \text{ ms} = 6\%$
 $t_r = .078 \text{ ms} = 31\%$
 100%

TOPPING MODE

Negative pulse = 0.075A based upon $\frac{25V}{19.7 \text{ ohms}} = 1.26A$ at 6% duty cycle

Positive pulse = $5.0A + .075A = 5.075A$
 Pulse width = 31.7% duty cycle = .079 ms
 Peak current = $\frac{5.075}{.317 \times .8} = 20A$

Peak $i_c = 20A$ Avg $i_c = 5.075A$
 Peak $i_d = 1.26A$ Avg $i_d = 0.075A$
 Avg. charge current (+ and -) = 5.0A
 Negative pulse current = 1.48% positive pulse current
 Duty cycle: $t_c = .079 \text{ ms} = 31.7\%$
 $t_d = .015 \text{ ms} = 6\%$
 $t_r = .155 \text{ ms} = 62.3\%$
 100%

Adjust trickle charge to 0.15A

2. Duty Cycle Test (91 cycles):

a. The battery was reconditioned (3 weak cells were replaced) and charged at 4.5A until the voltage leveled or decreased in a 1-hour period. The battery received 40.5 ah within a 9-hour period.

b. The battery and charger began a duty cycle test as described in paragraph IV.B.6.b, except that 6 cycles were conducted each day instead of 8, allowing for a 2-hour rest period between cycles, instead of 1 hour.

(1) The end of discharge voltage during cycle 1 was 18.05V.

(2) During the 2-hour charge of cycle 2, the battery charged at 25.5-25.0A for 20 minutes at which time the battery reached 25.9V at 36.7°C, and then charged at 5.0-4.7A for 25 minutes at which time the battery reached 27.3V at 36.7°C. The battery received 7.7 ah in the main mode, 1.95 ah in the topping mode, and 0.39 ah during trickle charge, totaling 10.04 ah (119.8% recharge). Attempt was made to return 8 ah in the main mode (charge for 20 minutes to return 95%), then 1.6 ah in topping mode (20 minutes), then pulse in main mode to topping mode to trickle mode with hysteresis of 2.5V with respect to main mode trip point. However, this on-off cycling cannot be performed in the manner described on the Sundstrand charger, so all on-off cycling was eliminated, and the battery simply trickle charged at 0.15A during the trickle mode. The end of discharge voltage of the battery during cycle 1 was 18.0V.

(3) During the 2-hour charge period of cycle 7, the charge current in the main mode was trimmed slightly to achieve 24.0A and the trickle charge current was trimmed to 100 ma. The battery charged at 24A for 21.5 minutes to 24.95V at 36.1°C, then at 5.0-4.75A for 19.5 minutes to 27.5V at 36.1°C, and then trickle charged at 0.1A. The battery received 8.05 ah during main mode and 1.55 ah during topping mode (115.1% total recharge). The end of discharge voltage of the battery during cycle 7 was 17.6V.

(4) During cycle 9, the topping charge current was 3.1A instead of 5A. Consequently, the battery did not reach the preset trip point and was charged at 3.1A for the duration of the charge period. The battery received 162% recharge.

(5) The reflex pulse was increased for the charge of cycle 13. The reflex pulse load was set to 1.8 ohms. The duty cycle of the reflex pulse was set to 10%.

MAIN MODE

$$i_{dAvg} = \frac{25V}{1.8 \text{ ohms}} = 13.8A \times .1 = 1.38A$$

Negative pulse current = 5.4% of positive pulse current.

Adjust main mode amplitude control to achieve 24.0A in main mode.

TOPPING MODE

$$i_{dAvg} = \frac{26.5V}{1.8 \text{ ohms}} = 14.7A \times .1 = 1.47A$$

Negative pulse current = 22.7% of positive pulse current.

Adjust topping mode amplitude control to achieve 5.0A in topping mode.

(a) The battery charged at 24.0-23.25A for 20 minutes to 25.0V at 38.3°C (8.10 ah), and then at 5.0A for 7 minutes to 27.2V at 37.8°C, (0.59 ah), and then trickle charged at 0.15A for 3 minutes. The charger was then reset to the topping charge mode to allow battery to reach 114% recharge. This required 10 minutes of additional charge in the topping mode. At the end of this 10-minute period, the battery voltage reached 27.7V and the temperature was 37.8°C. The end of discharge voltage during cycle 13 was 17.4V.

(6) The reflex pulse was increased for the charge of cycle 14. The reflex pulse load was set to 1.25 ohms. The duty cycle remained at 10%.

MAIN MODE

$$i_{dAvg} = \frac{25V}{1.25 \text{ ohms}} = 20A \times .1 = 2.0A$$

2.0A is 7.6% of 26A

Adjust main mode amplitude control to achieve 24A.

TOPPING MODE

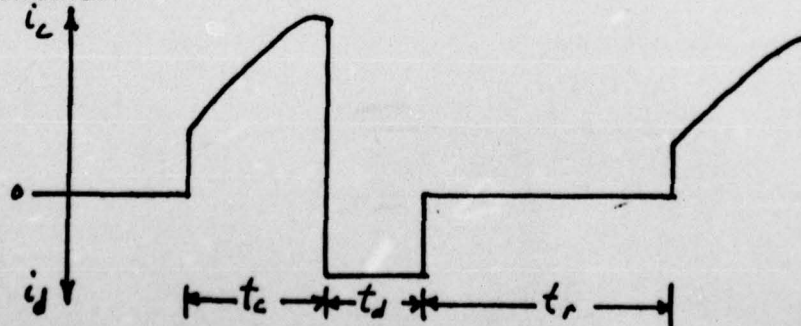
$$i_{dAvg} = \frac{26.5V}{1.25 \text{ ohms}} = 21.2A \times .1 = 2.12A$$

2.12A is 29.7% of 7.12A

Adjust topping mode amplitude control to achieve 5.0A.

(7) During the 2-hour charge of cycle 31, the battery charged at 24.25-23.25A for 21.5 minutes to 25.0V at 37.2°C (8.1 ah which is 97% recharge), and then 5.5-5.0A for 7.5 minutes to 27.8V at 36.7°C (8.77 ah total which is 105.4% recharge), and then trickle charged at 0.14 to 0.1A. The battery temperature decreased 4.5°C during charge. The end of discharge voltage of the battery during cycle 31 was 17.1V.

(8) After the battery was charged during cycle 42, 140cc of water was added, which averages to 8.23cc/cell. Based on this figure, a cell which has 20cc reserve electrolyte capacity, the battery could attain 102 cycles of charge and discharge before the electrolyte reserve is exhausted.



(9) Cycling was terminated after completion of 91 cycles without maintenance except for an addition of water during cycle 42. The battery end of discharge voltage was 15.7V. This cycling regime, which is illustrated below, provides excellent results in terms of both water consumption and capacity loss.

MAIN MODE

$t_c = 65\%$
 $t_d = 10\%$
 $t_r = 25\%$

$i_{cPeak} = 37A$
 $i_{dPeak} = 20A \text{ at } 25V$

$i_{cAvg} = 26A$
 $i_{dAvg} = 2.0A$

TOPPING MODE

$t_c = 35\%$
 $t_d = 10\%$

$i_{cPeak} = 20A$
 $i_{dPeak} = 21.2A \text{ at } 26.5V$

$i_{cAvg} = 7.12A$
 $i_{dAvg} = 2.12A$

3. Cold Temperature (-18°C) Test:

a. The battery was shorted for 21 hours, and then recharged for 8.5 hours at 4.5A. The battery was discharged at 20.0A to 16.1V and yielded 21 ah.

b. The battery was placed into a -18°C temperature chamber and allowed to stabilize at that temperature.

c. The battery was subjected to the charge profile described in preceding paragraph. The topping charge was manually turned off to simulate a time controlled topping charge based on main mode charge time.

(1) The battery was charged in the main mode at 18.6 - 11.9A for 69 minutes to 28.75V at -8.3°C, and then in the topping mode at 3.7 - 2.5A for 51 minutes to 28.2V at -8.8°C. The charger average output power in main mode ranged from 502W to 342W.

(2) The charger was manually shut off after 2 hours to represent main charge time +75% main charge time $(69 + .75(69)) = 120$ minutes. The charger did not have the necessary timing circuitry to accomplish this automatically. Normally the charger would then go into a trickle and on-off cycling mode.

(3) The battery, while maintained inside of -18°C chamber, was discharged at 20.0A to 16.1V and yielded 20.3 ah.

(4) The charger exceeded the minimum specified requirements of reference (a) in that it charged the battery for 2 hours instead of the 4 hours allowed, and that the battery yielded 20.3 ah, exceeding the 15 ah minimum.

4. Cold Temperature (-29°C) Test:

a. The battery was placed into a -29°C temperature chamber and allowed to stabilize at that temperature

b. The battery was charged without any adjustments made to the charger. The topping charge was manually turned off to simulate a time controlled topping charge based on main mode charge time, (main mode charge time +75% main mode charge time).

(1) The battery was charged in the main mode at 13.2 - 8.8A for 76.5 minutes to 29.75V at -19.5°C, and then in the topping mode at 3.2 - 1.7A for 58 minutes to 29.1V at 20.6°C. The charger average output power in main mode ranged from 369 to 261 watts.

(2) The battery, while maintained in the -29°C temperature chamber, was discharged at 20.0A to 16.1V and yielded 17.75 ah.

(3) The charger exceeded the minimum specified requirements of reference (a) in that it charged the battery for 2.25 hours instead of the 4 hours allowed, and that the battery yielded 17.75 ah, exceeding the 11.6 ah minimum.

5. Cold Temperature (-1°C) Test:

a. The battery was placed into a -1°C temperature chamber and allowed to stabilize at that temperature.

b. The battery was charged with the Sundstrand unit. The topping charge was manually turned off to simulate a time controlled topping charge based on main mode charge time. (Main mode charge time +75% main mode charge time).

(1) The battery was charged in the main mode at 27.1 - 16.0A for 47 minutes to 27.7V at 2.7°C, and then in the topping mode at 4.5 - 3.8A for 35 minutes to 27.0V at 2.7°C. The charger average output power in main mode ranged from 636 to 443 watts.

(2) The battery, while maintained in the -1°C temperature chamber, was discharged at 20.0A to 16.1V and yielded 21.3 ah.

(3) There are no specified requirements in reference (a) for a -1°C temperature test, however, the charger exceeded the requirements specified at 25°C.

6. High Temperature (49°C) Test:

a. The battery was placed into a 49°C temperature chamber and allowed to stabilize at that temperature.

b. The battery was charged with the Sundstrand unit, and then, while maintained in the 49°C temperature chamber, discharged at 20.0A to 16.1V. This test was conducted four times to optimize the main mode to topping mode trip point and verify the slope control setting.

(1) The final charge provided 23.50 ah to the battery within 1.3 hours. The trip point selected at this temperature was 1.43V/cell.

(2) The charger exceeded the minimum specified requirements of reference (a) in that it charged the battery for 1.3 hours instead of the 3 hours allowed, and that the battery yielded 20.3 ah, exceeding the 16.6 ah minimum.

6. Charge/Discharge Test at 21°C

a. The battery was placed into a 21°C temperature chamber and allowed to stabilize at that temperature.

b. The charger returned 94.4% recharge into the battery in the main mode and 15.6% recharge in the topping mode resulting in 110% recharge. The battery temperature increased 2.7°C during the charge. The main-topping trip point was 1.55V/cell at 21°C. The charger average output power ranged from 733 to 644 watts.

c. The battery, while maintained in the 21°C chamber, was discharged at 20.0A to 16.1V and yielded 21 ah.

d. The charger exceeded the minimum specified requirements of reference (a) in that it charged the battery for 1.2 hours instead of the 2 hours allowed, and that the battery yielded 21 ah, exceeding the 20 ah minimum.

7. Based upon the results of the tests described, and other tests which were conducted for the preparation of reference (a), the battery chargers to be manufactured by Sundstrand Corporation shall:

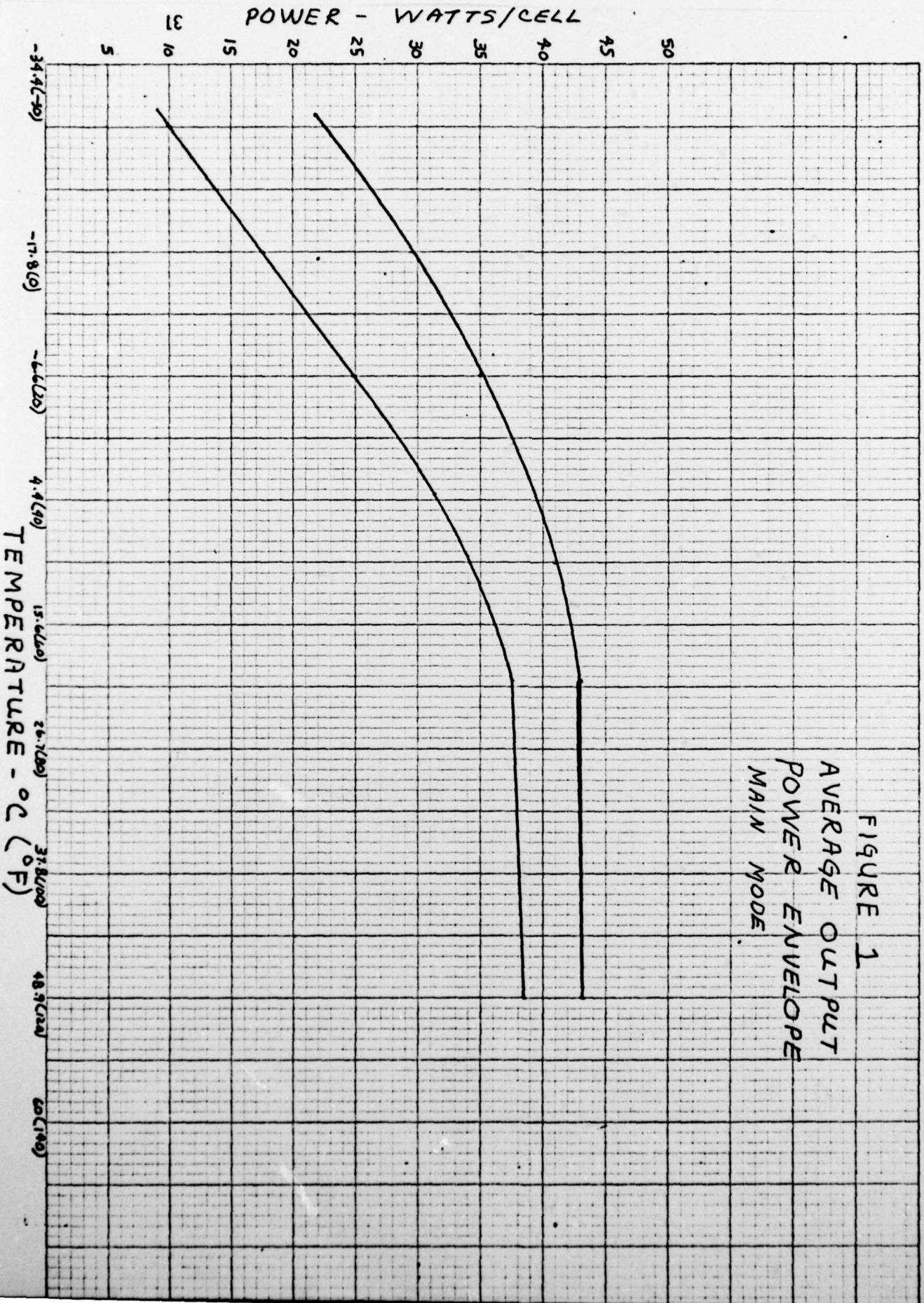
a. Conform to MIL-C-85050 airborne charger specification.

b. Charge the battery at 1.0A until the battery reaches $16 \pm 1.0V$.

c. Pulse charge the battery (main mode) at an average current of 24A within the average output power envelope shown in Figure 1, consisting of positive and negative pulses. The positive pulse shall have a duty cycle of 65% and a pulse amplitude necessary to comply with the power envelope of Figure 1 but not to exceed 65A. The negative pulse amplitude shall be approximately 15A with a duty cycle of 10%. Charge battery at this rate until temperature compensated voltage trip point is reached.

d. Pulse charge the battery (topping mode) at a constant average current of 5A consisting of a positive and a negative pulse. The positive pulse shall have a duty cycle of 20 percent and an amplitude necessary to achieve 5A average, but not to exceed 35A. The negative pulse amplitude shall be approximately 15A, and the duty cycle shall be 6%. Charge battery in topping mode for 75% of time battery was in the main mode.

e. Trickle charge the battery at 0.050A and allow battery voltage to decay to 2.5V below trip voltage (main to topping) then charge in main mode to temperature compensated trip voltage, then charge in topping mode for 75% of main mode charge time, then at 0.050A. This cycling mode is to be continued until the power or the battery is removed from the charger.



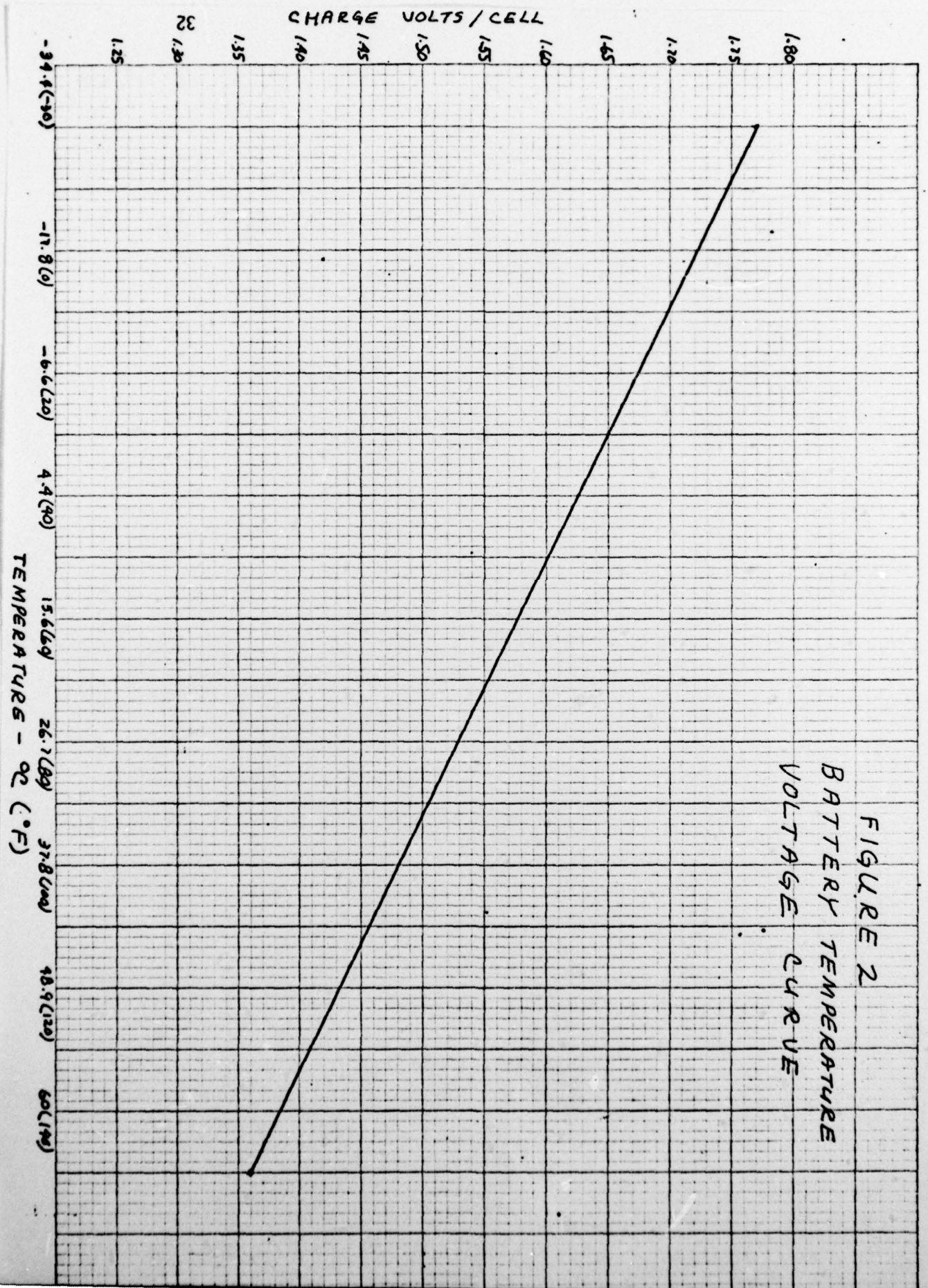
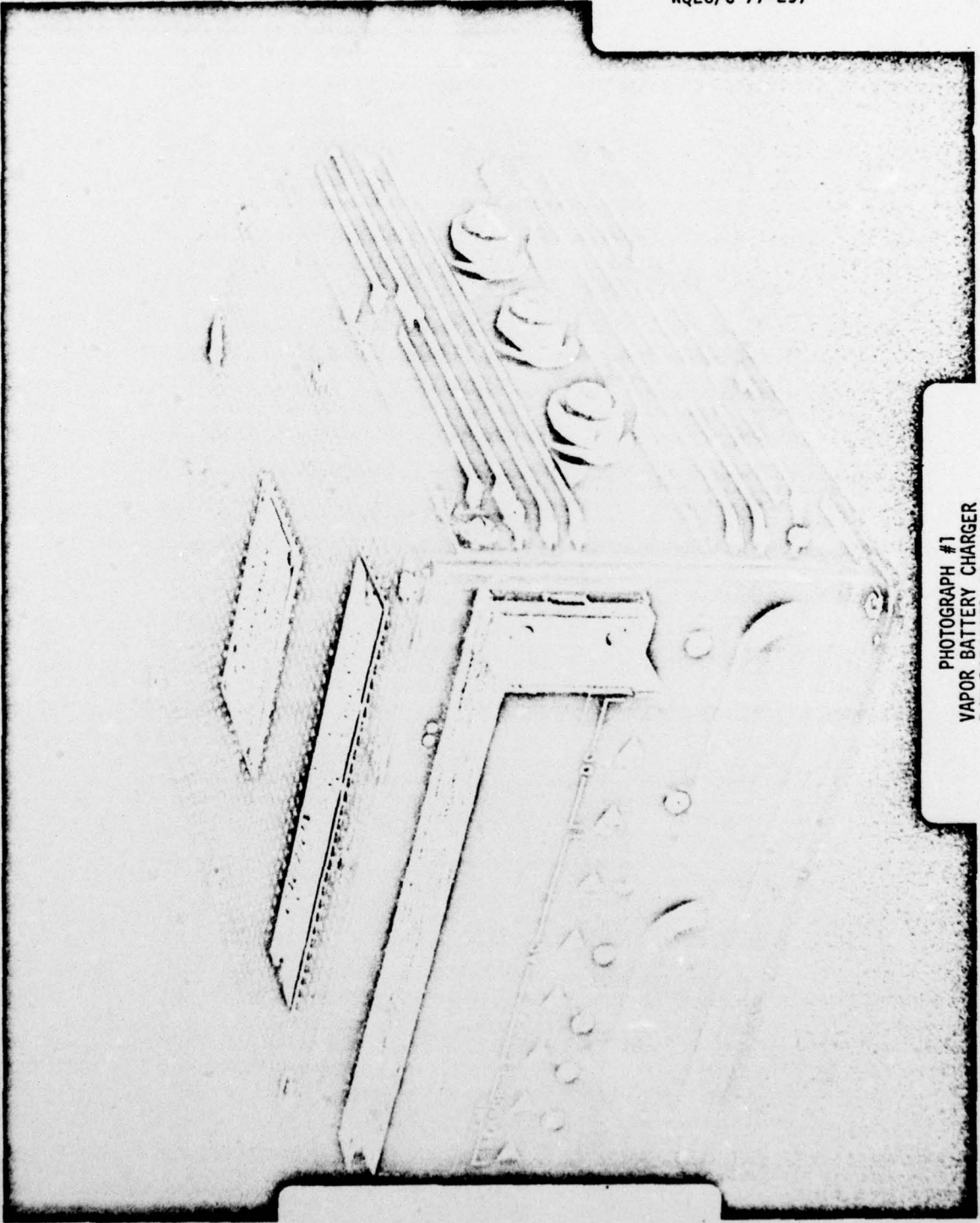


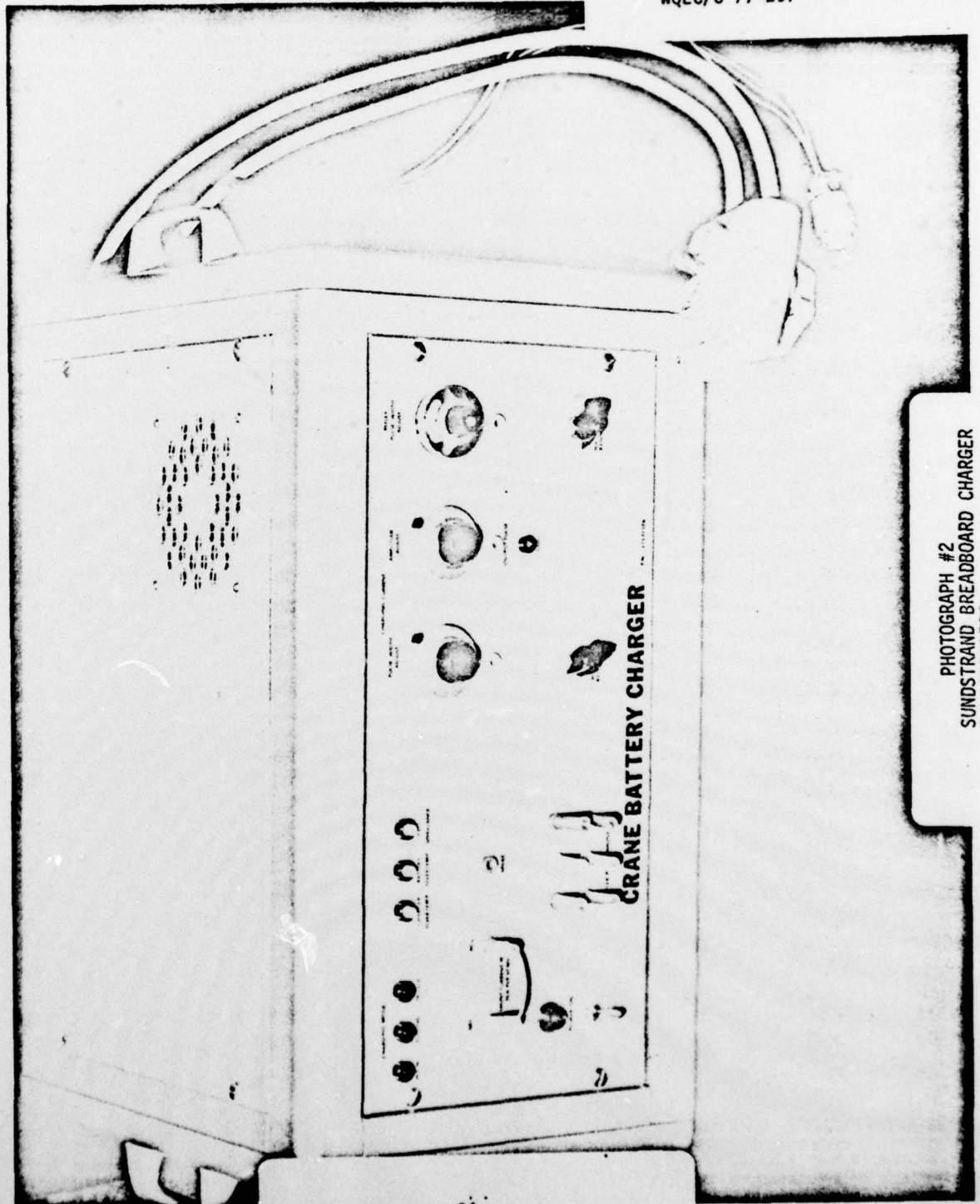
FIGURE 2
BATTERY TEMPERATURE
VOLTAGE CURVE

WQEC/C 77-297



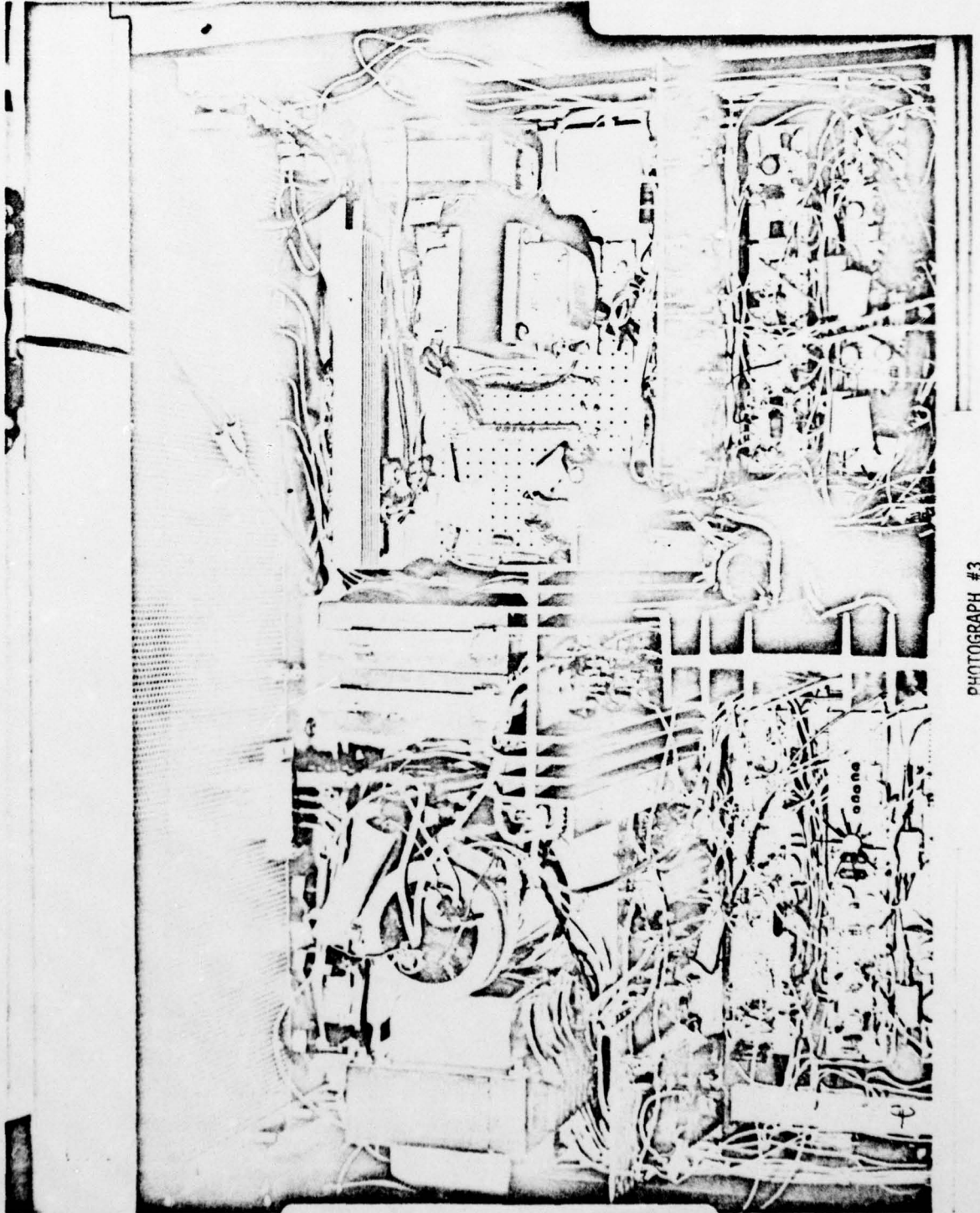
PHOTOGRAPH #1
VAPOR BATTERY CHARGER
P/N 26340061-04

WQEC/C 77-297



PHOTOGRAPH #2
SUNSTRAND BREADBOARD CHARGER
P/N 27541526

WQEC/C 77-297



PHOTOGRAPH #3
SUNDBERG READBOARD CHARGER

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