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CONS/1044-1
NASA TM-73834-REV
(Revised)

(NASA-TM-73834-Rev) RESPONSE OF LEAD-ACID BATTERIES TO CHOPPER-CONTROLLED DISCHARGE (NASA) 11 p HC A02/MF A01 CSCL 13F

N78-25010

Unclas
G3/85 16788

RESPONSE OF LEAD-ACID BATTERIES TO CHOPPER-CONTROLLED DISCHARGE

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Work performed for

U.S. DEPARTMENT OF ENERGY
Office of Conservation and Solar Applications
Division of Transportation Energy Conservation

TECHNICAL PAPER to be presented at the
Thirteenth Intersociety Energy
Conversion Engineering Conference
San Diego, California, August 20-25, 1978

JUN 1978
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NASA STI FACILITY

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-73834 (Revised)		

4. Title and Subtitle	5. Report Date
RESPONSE OF LEAD-ACID BATTERIES TO CHOPPER-CONTROLLED DISCHARGE	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Robert L. Cataldo	E-9421
9. Performing Organization Name and Address	10. Work Unit No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Energy Division of Transportation Energy Conservation Washington, D.C. 20545	Technical Memorandum
	14. Sponsoring Agency Code Report No. CONS/1044-1

15. Supplementary Notes

Prepared under Interagency Agreement EC-77-A-31-1044. To be presented at the Thirteenth Intersociety Energy Conversion Engineering Conference, San Diego, California, August 20-25, 1978.

16. Abstract

The preliminary results of simulated electric vehicle, chopper, speed controller discharge of a battery show energy output losses up to 25 percent compared to constant current discharges at the same average discharge current of 100 A. These energy losses are manifested as temperature rises during discharge, amounting to a two-fold increase for a 400-A pulse compared to the constant current case. Because of the potentially large energy inefficiency, the results suggest that electric vehicle battery/speed controller interaction must be carefully considered in vehicle design.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Chopper controlled discharge/pulse discharge; Output energy losses; Pulse up to 25-percent loss over constant current; Temperature rise (up to 2 fold); Pulse discharge inefficient	Unclassified - unlimited STAR Category 85 DOE Category UC-94C

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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ABSTRACT

The results of tests on an electric vehicle battery, using a simulated electric vehicle chopper-speed controller, show energy output losses up to 25 percent compared to constant current discharges at the same average current of 100 A. However, an energy output increase of 22 percent is noticed at the 200 A average level and 44 percent increase at the 300 A level using pulse discharging. Because of these complex results, electric vehicle battery/ speed controller interactions must be considered in vehicle design.

ONE WIDELY USED TECHNIQUE for motor speed control in electric vehicles is the chopper (pulse) control (1)**. Electric vehicle designers have comparatively little data available on battery response to the pulse discharges presented by these choppers in contrast with alternative direct current discharge. This investigation was conducted to obtain such data on a typical commercial lead-acid electric vehicle battery.

The available energy and capacity of a lead acid battery are dependent on many factors, the most significant one being the magnitude of the discharge current, with higher currents resulting in less delivered capacity. It has been suggested (2) that discharging in a pulse mode will yield a greater delivered capacity from a battery than direct current. The basis for this increase in capacity is that after the discharge pulse, the off-time period in each cycle will allow additional discharge due to various recovery phenomena. It is possible, however, that the actual power and energy output from the battery will decrease in a pulse discharge mode.

In view of the current efforts to develop efficient, cost effective electric vehicles, it is of great practical interest to quantify these effects. Experiments were therefore undertaken to determine delivered battery energy and power at various peak to average current levels. The parameters being investigated are representative of values encountered in electric vehicle operation. They are peak discharge currents of 200, 300 and 400 A and average values of 100, 200 and 300 A at frequencies of 50, 100 and 500 Hz, as displayed in table I.

EXPERIMENTAL PROCEDURE

The batteries used in these tests were Willard 132.5-A-hr, 6-V, lead acid electric vehicle batteries. These separate batteries were studied at each test condition to check reproducibility of the data.

Ampere hours were not measured during battery recharge because it was not an experimental requirement. Recharging to the same state of charge every charge is a highly uncontrollable process. The charger was set to 2.40 V/cell and the current was allowed to vary. The initial current was 23 A tapering to 3 A as the cell voltage approached 2.40 V. Ambient and electrolyte temperatures and specific gravities were recorded before and after each discharge. A 75-A constant current discharge drain was carried out 1 hour after each discharge experiment to remove the remaining capacity of the battery. The pulse and direct-current discharges were terminated when the average battery voltage reached 5.10 V. A direct-current discharge at 100 A equal to the average value of the pulse discharge rate was performed before and after each group of tests for the baseline comparison.

The apparatus used was a chopper simulator shown in block diagram form in figure 1. It consists of transistors in the Darlington configuration as the switching device driven at appropriate variable pulse width and frequency (pulses per second). The discharge energy was dissipated noninductive in the transistor module itself, mounted on a water-cooled heat sink. The pulse peak was set on the oscilloscope and the average current was adjusted by the duty cycle to obtain the desired value. These values were monitored and held constant throughout the test.

The battery voltage and current pulses (via a noninductive shunt) were monitored on a calibrated dual-beam oscilloscope and traces photographed at the beginning and end of each chopper discharge test on each of three replicate batteries. V_s, the steady battery voltage during the pulse current draw was measured to ± 3 percent. The pulse current magnitude, I_p, could be set within ± 3 percent. $\bar{V}$, the average battery voltage, was monitored by an integrating digital voltmeter (IDVM) placed directly across the battery terminals with an accuracy of ± 0.1 percent. The average current $\bar{I}$, was read across the shunt with an IDVM capable of averaging the signals faithfully over the range of frequencies involved with an accuracy of ± 0.1 percent.

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*Revised version of CONS/1044-1, NASA TM-73834, entitled Response of Lead-Acid Batteries to Chopper-Controlled Discharge: Preliminary Results, by Robert L. Cataldo, published in February 1978.
**Numbers in parentheses designate references at end of paper.

Figure 2 shows a typical oscilloscope trace of the chopper simulator discharge. The trace for each test condition was used to set I_p at the desired value and to measure V_s and T, the period between pulses. All the other quantities were taken from the IVDMs.

The initial power output, P_i, obtained at the fully charged state and the final power output P_f, obtained at the end of the discharge time t(hr) to the 5.10-V cutoff, were calculated from eq. (1) using the appropriate measured quantitites.

$$P = \bar{I} V_s \tag{1}$$

The average power output during the discharge, $\bar{P}$, was obtained from eq. (2).

$$\bar{P} = \frac{P_i + P_f}{2} \tag{2}$$

The average energy delivered, $\bar{E}$, from eq. (3)

$$\bar{E} = \bar{P} t \tag{3}$$

and the average capacity $\bar{C}$ from eq. (4)

$$C = \bar{I} t \tag{4}$$

Energy and capacity were also measured by an integrating W-hr and A-hr meter. The values obtained were approximately equal to those obtained by equaeqs. 3 and 4.

RESULTS

Tables II, III and IV summarize the numerical results of the experiments for the various parameters and compares them to the constant current discharge (dc) at the same average current. For 100 A average current (table I) significant differences in energy and power output can be seen with varying peak to average current ratio as shown in figures 3(a) and (b). The energy output at a 400 A peak pulse is approximately 25 percent less than at constant current. The 300 and 200 A peak pulse result is a 22 and 18 percent loss in energy output, respectively. Similar decreases in power output are observed. Since the energy curve follows the power curve, one can conclude that pulsing the battery did not increase the available battery capacity to offset the loss in power attributed to the high peak pulses. This does not hold true, however, for higher average current levels.

Tables III and IV summarize the results for average values of 200 and 300 A, respectively. It should be noted that pulse discharging at these average current levels can offer greater energy output over the nonpulsed case, but with some loss in power output attributed to pulsing. This is illustrated in figures 4(a) and 5(a) where the increase in energy output is shown. The additional energy obtained by pulsing at the 400/200 A peak to average ratio at 500 Hz amounted to 22 percent and the 400/300 A peak to average ratio at 100 Hz yielded 44 percent increase over the direct or nonpulsed case. This reversal of energy versus power at the higher current levels results from greater capacity being obtained by pulse discharging in these cases. This contrasts with the 100 A average case where less capacity was obtained by pulse discharging (3).

Figure 6 shows the percent increase or decrease in capacity obtained at the various peak to average current ratios against frequency. Pulsing at a 400/200 peak to average current ratio increased the battery's capacity 28 percent and the 400/300 case increased capacity 40 percent. This increase in capacity obtained by pulsing overcomes the expected decrease in energy output associated with pulse discharging.

Figure 7 shows the optimum operating conditions for maximum battery energy output. This was obtained by picking the greatest energy output at each point for both the pulse mode and direct mode and plotting as a function of average current. The pulse curve crosses the direct current curve at 160 A average current. THis means that for optimum range in a vehicle from the viewpoint of optimizing the battery the chopper controller should be operating when average currents higher than 160 A are needed. This would be during acceleration and high speeds. However, at current drains below 160 A, typically cruise, the controller should be bypassed and direct current discharge used. It is evident from the plot of energy output against frequency at various peak to average currents (fig. 8) that the frequency of the controller at 300 A average current should be about 100 Hz, while at 200 A average current 500 Hz or perhaps even higher should be used. Pulsing at a frequency of 50 Hz at any current level provided less energy output and controllers should not be used in this range.

Figure 9 shows the thermal behavior of the battery during tests. As expected, the electrolyte temperature rise is greater with increasing peak currents. In the 100 A average case the 400 A peak pulse resulted in a temperature rise of 130 percent over direct discharge, and in the 200 A average case the 400 A peak pulse resulted in a 140 percent rise and a 40 percent rise was noted at the 300 A average level. These temperature increases are consistent with the losses associated with the higher peak currents.

Two batteries failed during the testing at 100 A average current and were replaced. Another battery failed at the start of the 200 A tests. From this experience one can conclude that pulse discharging may have a detrimental effect on the cycle life of the battery. This effect will be studied in greater detail in the near future.

CONCLUSIONS

Pulsing is not an efficient means of discharging at 100 A average current as stated in the preliminary results (3). However, the results at higher average currents prove that pulsing can be an efficient method of discharging. Despite the greater loss in power output because of the I^2R heating losses for higher peak pulses, (figs. 3(b), 4(b) and 5(b)), pulse discharging in these limited tests yielded greater capacity under certain conditions:

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1. 400/200 peak to average current ratio at 500 Hz or above, and

2. 400/300 peak to average current ratio at 100 Hz.

The complication of these results for electric vehicle chopper-controller design is that it may be desirable in order to maximize batter energy efficiency to vary frequency with average current level. As an example, 400/300 and 400/200 current ratios may be used at 100 and 500 Hz or greater, respectively, during acceleration and higher current demands, while direct current used for moderate demands during cruise.

REFERENCES

1. Morrison, John J.: Electronic Control of Battery Electric Vehicles. Radio Electron. Eng., vol. 42, no. 2, Feb. 1972, pp. 91-100.

2. Jayne, Marcel G.: The Behavior of Lead-Acid Batteries Under Pulsed Discharge conditions. Presented at the 10th International Power Sources Symposium, (Brighton, England), Sep. 13-16, 1976, pp. 1-12.

3. Cataldo, Robert L.: Response of Lead-Acid Batteries to Chopper-Controlled Discharge: Preliminary Results. NASA TM-73834, DOE CONS/1044-1, Feb. 1978, pp. 1-8.

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TABLE I. - PULSE DISCHARGE TEST PARAMETERS

Group	Peak Current (amperes)			Average Current (amperes)	Frequency (Hz)
1	400	300	200	100	50
	400	300	200	100	100
	400	300	200	100	500
2	400	300		200	50
	400	300		200	100
	400	300		200	500
3	400			300	50
	400			300	100
	400			300	500

TABLE II. - RESULTS OF TESTS AT 100A AVERAGE CURRENT, GROUP 1, AVERAGES WITH AVERAGE DEVIATIONS FOR THREE REPLICATES

Frequency (Hz)	Peak Current (Amperes)	Average Energy (Watt Hrs)	Average Power (watts)	Average Capacity (Amp Hrs)	Temperature Rise (°C)
500	400	525 ± 8	470 ± 7	112 ± 8	20
500	300	555 ± 15	505 ± 7	119 ± 8	15
500	200	576 ± 36	540 ± 3	107 ± 7	10
100	400	513 ± 6	460 ± 13	111 ± 3	22
100	300	515 ± 22	490 ± 7	104 ± 6	16
100	200	546 ± 5	520 ± 7	104 ± 3	11
50	400	495 ± 3	450 ± 26.7	110 ± 2	19
50	300	515 ± 6	490 ± 7	105 ± 3	15
50	200	565 ± 9	538 ± 10	105 ± 4	11
D.C.	100	712 ± 83	587 ± 3	129 ± 15	10

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TABLE III. - RESULTS OF TESTS AT 200A AVERAGE CURRENT, GROUP II, AVERAGES WITH AVERAGE DEVIATIONS FOR TWO REPLICATES

Frequency (Hz)	Peak Current (Amperes)	Average Energy (Watt-Hrs)	Average Power (Watts)	Average Capacity (Amp-Hrs)	Temperature Rise (°C)
500	400	520 ± 19	1010 ± 10	102 ± 4	20
500	300	470 ± 30	1000	89 ± 4	12
100	400	506 ± 6	1000	101 ± 1	19
100	300	424 ± 1	1002 ± 2	65	15
50	400	406 ± 10	980	73 ± 13	17
50	300	418 ± 18	1000 ± 10	84 ± 3	14
DC (before)	-	426 ± 1	1065 ± 5	81 ± 1	8
DC (after)	-	425 ± 25	1070	80 ± 4	8

TABLE IV. - RESULTS OF TESTS AT 300A AVERAGE CURRENT, GROUP III, AVERAGES WITH AVERAGE DEVIATIONS FOR TWO REPLICATES

Frequency (Hz)	Peak Current (Amperes)	Average Energy (Watt-Hrs)	Average Power (Watts)	Average Capacity (Amp-Hrs)	Temperature Rise (°C)
500	400	201 ± 1	1470	38	6
100	400	263 ± 20	1485	52 ± 4	10.5
50	400	183 ± 7	1470	37.5 ± 1.5	7
DC (before)	-	191 ± 23	1535 ± 10	37 ± 4	5
DC (after)	-	174 ± 31	1515 ± 45	38 ± 1	6

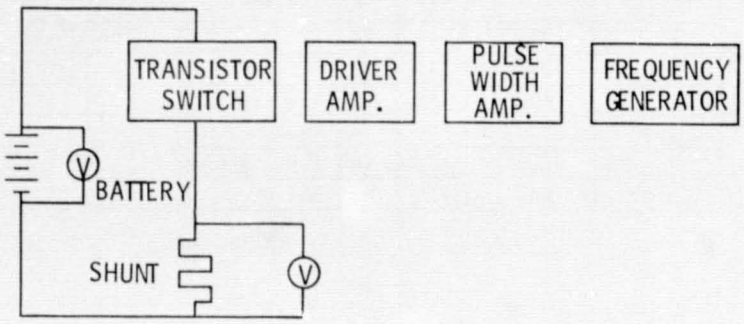


Figure 1. - Block diagram of chopper simulator

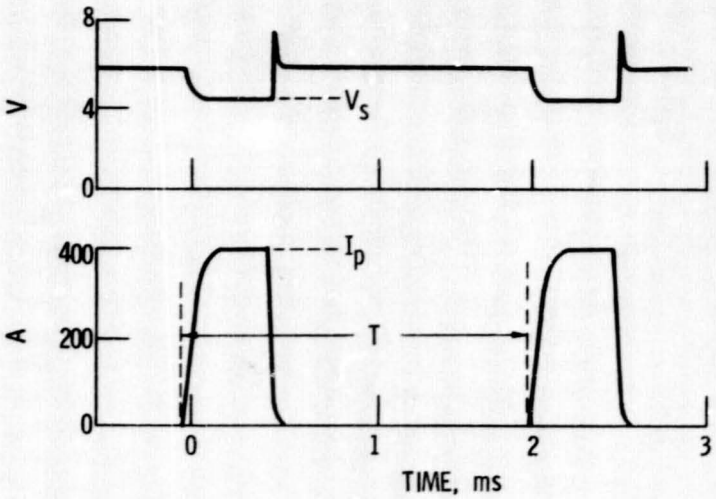
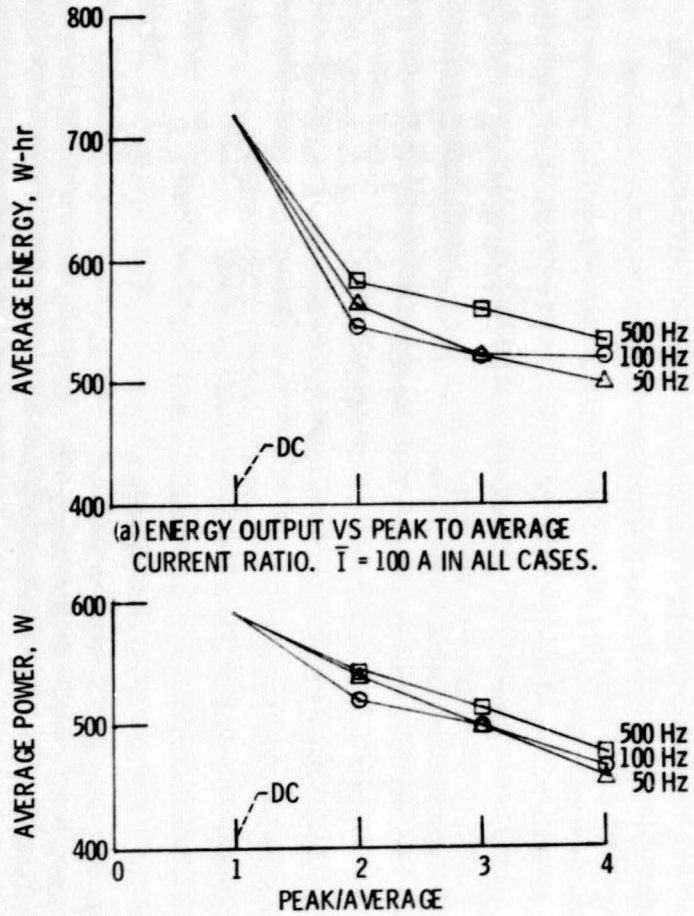


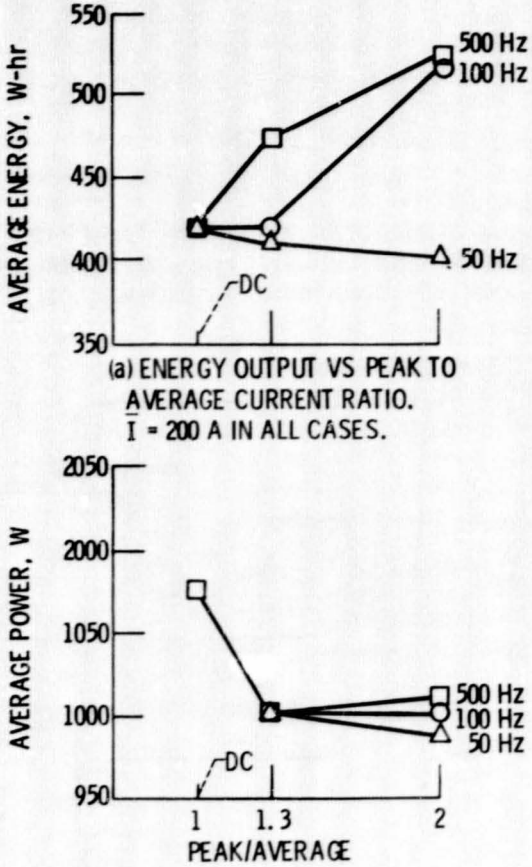
Figure 2. - Typical oscilloscope trace of the chopper simulator discharging a lead acid battery at a 400 A. Peak current with a 100 A. Average current at 500 Hz.



(a) ENERGY OUTPUT VS PEAK TO AVERAGE CURRENT RATIO. $\bar{I}$ = 100 A IN ALL CASES.

(b) AVERAGE POWER DELIVERED VS PEAK TO AVERAGE CURRENT RATIO. $\bar{I}$ = 100 A IN ALL CASES.

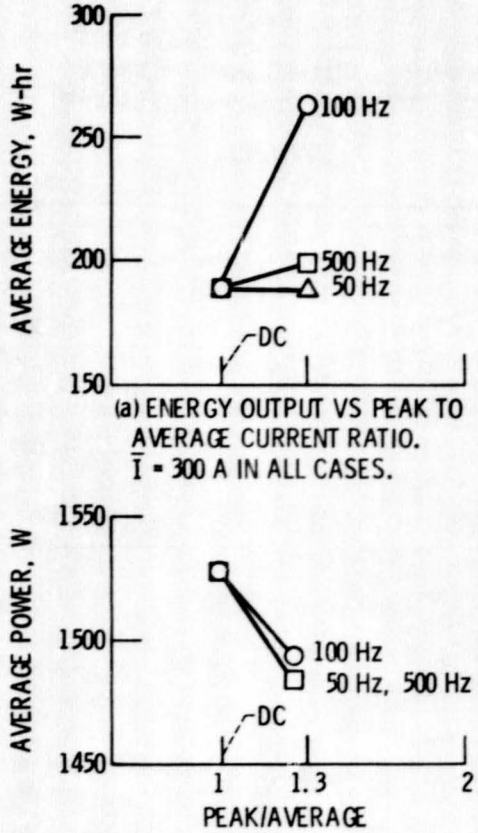
Figure 3.



(a) ENERGY OUTPUT VS PEAK TO AVERAGE CURRENT RATIO. $\bar{I}$ = 200 A IN ALL CASES.

(b) AVERAGE POWER DELIVERED VS PEAK TO AVERAGE CURRENT RATIO. $\bar{I}$ = 200 A IN ALL CASES.

Figure 4.



(a) ENERGY OUTPUT VS PEAK TO AVERAGE CURRENT RATIO. $\bar{I}$ = 300 A IN ALL CASES.

(b) AVERAGE POWER DELIVERED VS PEAK TO AVERAGE CURRENT. $\bar{I}$ = 300 A IN ALL CASES.

Figure 5.

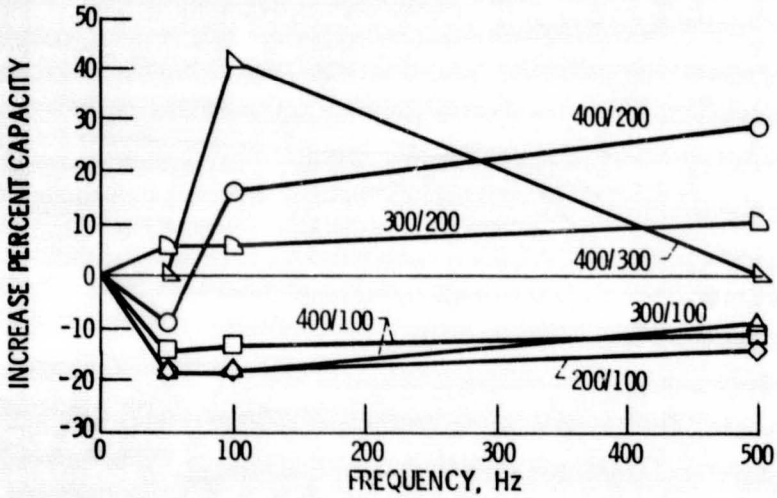


Figure 6. - Effects of frequency on capacity at various peak to average current ratios.

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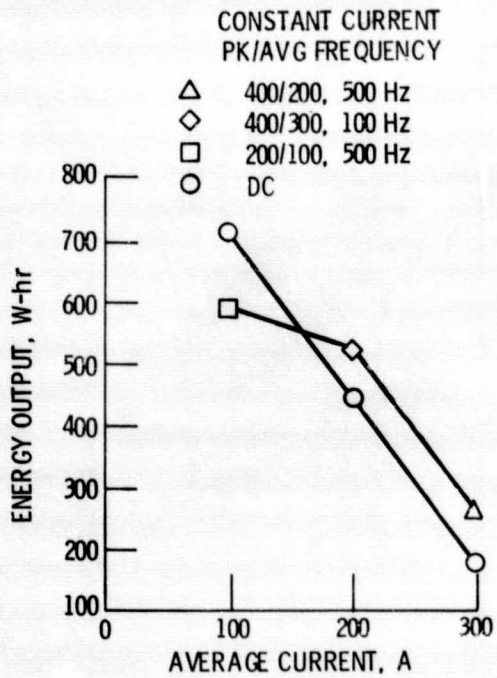

Figure 7. - Optimum operating condition for maximum battery energy output.

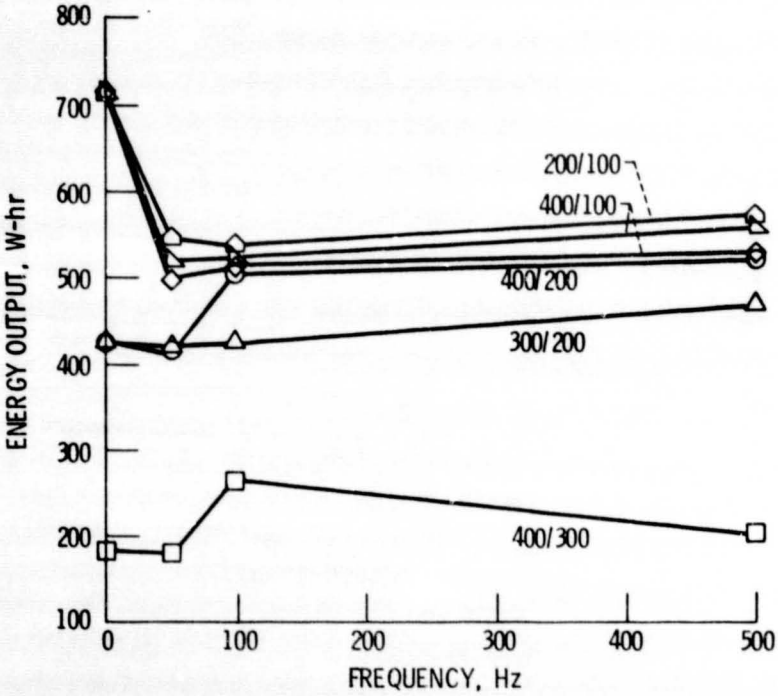

Figure 8. - Effect of peak to average current on energy output versus frequency.

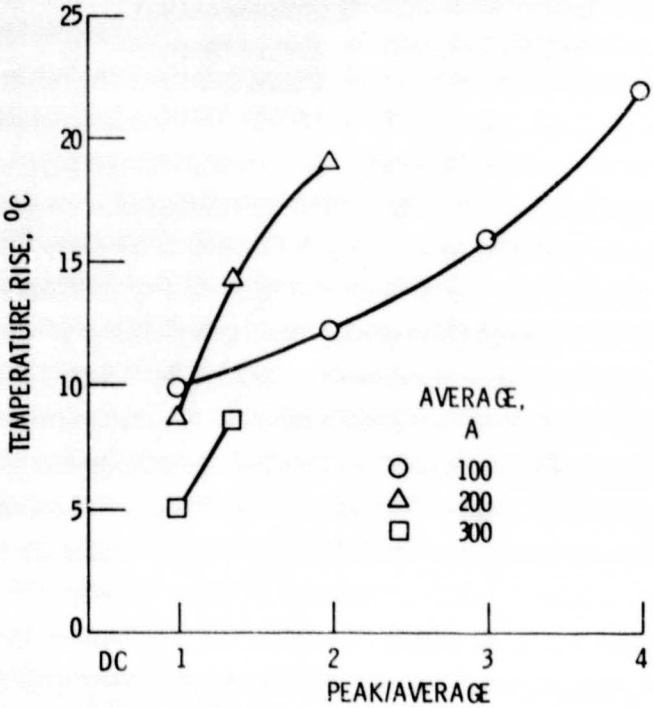

Figure 9. - Temperature rise versus peak to average current ratio.