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RESULTS OF ELECTRIC-VEHICLE PROPULSION SYSTEM PERFORMANCE ON THREE LEAD-ACID BATTERY SYSTEMS

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SUMMARY

Three types of nominal 6-V lead-acid batteries, one in current use and the other two proposed as near-term candidates for use by the electric vehicle industry, were tested at the Naval Weapons Support Center, Crane, Indiana, under laboratory conditions. The primary objective of this work was to determine the cycle life of lead-acid batteries as a function of electric vehicle propulsion system design. Included in this objective was a comparison of different battery types (EV106 baseline versus state-of-the art 3KQ-11 tubular and EV1000 thin plate batteries) as pertaining to cycle life, degradation rate, and respective failure modes. In addition, the secondary test objectives were to study the effects of testing in three versus six series strings in relation to overall performance.

The test profiles chosen are defined in the SAE J227a, schedule D specification for a hypothetical vehicle with the following characteristics: weight, 1701 kg (3750 lb); product of aerodynamic drag coefficient and projected frontal area C_DA, 0.84 M^2 (9 ft^2); and tire coefficient, $1.1x10^{-2}$. The electric vehicle battery pack is a 120-V system consisting of twenty 6-V lead-acid modules. The propulsion system was assumed to have 70 percent efficiency during acceleration and 50 percent efficiency during regenerative deceleration.

INTRODUCTION

Batteries in today's electric vehicles represent a small fraction of the initial cost of an electric vehicle. In the near term, as electric vehicle technology improves and markets develop and new types of batteries are made available, the batteries will constitute a higher, but still small, percentage of the initial cost. However, the driving costs (dollars/mi) are significantly impacted by the cycle life of the battery. Electric vehicle propulsion system designs, in the past, have concentrated on maximizing the capabilities of batteries on a per discharge basis but only minimal consideration was given to the design's impact on battery cycle life.

Buffered propulsion systems such as those with flywheels, offer increased acceleration and a possible increased range. Electrical regeneration propulsion systems may also offer extended range. The worthiness of these two systems will not only be based on their ability to extend the range of an electric vehicle, but also their effects on the cycle life costs of batteries (dollars/mi). The Government cannot afford to support and develop both system approaches. Therefore, we must narrow the alternatives by evaluating the effects these various systems have on the cycle life of batteries. Three generic types of propulsion systems have been chosen to evaluate their effect on battery cycle life and are as follows: (1) The baseline which has no buffer and no electrical regeneration, (2) The buffered system which tends to load level the battery and, (3) The electrically regenerative system.

Three types of lead-acid batteries were chosen for testing. One was a standard off-the-shelf golf car battery (EV106) used as a baseline. The remaining two batteries were improved types expected to be available in the near-term. One of the two was a tubular plate battery, model 3KQ-11, manufactured by Eagle-Picher, specifically designed for load leveled discharge. The other battery was a flat plate, Globe Union, model EV1000, designed for a nonleveled electrical regenerative system.

Thirty batteries were procured from each manufacturer. Each group of batteries underwent formation cycling at each manufacturer's recommended rates to verify battery capacity ratings. Once completed, 27 batteries were selected from each manufacturer for distribution on three constant power discharge profiles designed to simulate nonregenerative, electrical regenerative, and mechanical regenerative (load-leveled) propulsion systems. The nonregenerative discharge profile was considered to be the baseline system against which comparisons would be made to evaluate the performance of the regenerative and load-leveled propulsion systems. The following are some of the questions that are addressed and discussed in this paper: Are the benefits of electrical regeneration (increased vehicle range) offset by a decrease in cycle life? Is the increased complexity of a mechanical regenerative (load-leveled) system justified in terms of cycle life or range over an electrical regeneration systems? Which propulsion system optimizes battery cycle life and performance? And finally, will the state-of-the-art developments in lead-acid batteries significantly improve the performance of electric vehicles?

DETERMINATION OF TESTING PARAMETERS

Power-Time Profiles

The three power-time profiles designed to simulate nonregenerative, electrical regenerative, and mechanical regenerative (load-leveled) propulsion systems were derived from the SAE J227a Schedule D driving cycle (1). Each profile was 122 seconds in duration, with power levels based on either three-battery or six-battery series strings. Table I contains the power levels corresponding to time for each propulsion system. The power-time profiles are shown graphically in Fig. 1.

Cycle Definition

A discharge cycle was defined as a continuous repetition of discharge profiles (as defined above) to a predetermined depth of discharge or to a cut off voltage. On the regenerative profile, amp-hrs returned during the charge portion of the profile were subtracted from amp-hrs removed during discharge to determine the net amp-hr output. This net value was used to determine depth of discharge. A charge cycle was defined as the charge recommended by the manufacturer which brought the battery to the 100 percent state of charge. The combination of a discharge cycle and a charge cycle constituted one complete cycle.

Normalized Capacity Determination

As part of the test design, discharge cycles were to be conducted to a depth of discharge of 80 percent of rated capacity. Because the capacity of lead-acid batteries varies with changes in the discharge rate, the amp-hr ratings of these batteries (as determined by their respective manufacturers) were not applicable to the power profile discharges designed for this test.

A procedure for determining an appropriate capacity rating for each battery was agreed upon by the three battery manufacturers. This procedure uses the baseline (nonregenerative) discharge profile to establish capacity and in effect normalize test results between battery design and actual performance. The "normalized capacity procedure" is as follows:

Following formation, three batteries were selected from each manufacturer that were representative of the group as a whole in amp-hr output. Each battery was discharged three times at the manufacturer's discharge rate to 5.25 volts per battery. The average capacity of the three batteries was called the "prevailing capacity" of the battery. Each battery was then discharged three times on the SAEJ227a Schedule D driving cycle (nonregenerative) to 3.9 volts per battery. The averaged results of these discharges was called the "average observed capacity." From this data, the normalized capacity rating of each battery type was determined from the following formula.

$$\text{Normalized Capacity} = \frac{\text{Manufacturer Rated Capacity}}{\text{Prevailing Capacity}} \times \text{Average observed capacity}$$

LIFE CYCLE TESTS

Twenty-seven batteries from each manufacturer were selected for life cycle tests based on uniformity in amp-hr output during formation cycling. These batteries were randomly distributed on the three propulsion system tests as follows:

Nonregenerative	Regenerative	Load-Leveled
One 3-battery string	One 3-battery string	One 3-battery string
One 6-battery string	One 6-battery string	One 6-battery string

Life cycle testing was conducted on each battery string according to the following procedure. Battery strings were discharged on the applicable power profile to a depth-of discharge of 80 percent of normalized capacity or to an average string voltage of 3.9 volts/battery, whichever occurred first.

Charging of each battery string was conducted according to the manufacturer's recommended charge procedure (this will be discussed later in this paper). This cycling sequence (charge/discharge) was repeated at the rate of one cycle per day until battery failure(s) occurred. Every 50th cycle a capacity check (on the applicable power profile) was made on each battery to an average battery cut off voltage of 3.9 volts. Failure of a battery was defined as two successive cycles where a battery in a string reached the cut off voltage of 3.9 volts before 80 percent of the normalized capacity was removed. The failed battery was removed from the respective string and cycling was continued on the remaining batteries. The last battery remaining in each string was cycled until battery capacity removed dropped to 40 percent of the normalized capacity.

Charge Procedures

The charge procedures used for each battery type were those recommended by the manufacturer. All charges were the constant potential type to a fixed percentage recharge. These procedures are outlined below for each battery type:

Exide EV106 baseline: Using a starting current of 30 amperes, each battery string was charged until the average battery voltage reached 7.80 volts per battery. This voltage was maintained until 120 percent of the amp-hrs removed on discharge were returned. Equalization Charge - Twice every month, the normal charge procedure identified above was extended to include a constant current charge at 6 amperes for 10 hours to equalize the batteries.

Globe Union EV1000 thin flat plate positive: The starting current for each charge cycle was again 30 amperes. Each battery string was charged until the average battery voltage reached a temperature corrected voltage determined by the equation $1/B = 8.96 - 0.012T$ (where T = battery electrolyte temperature in degrees F). This voltage was maintained until the charge current dropped to 5.5 amperes. At this time the charge was returned to the constant current mode and the battery string was charged at 5.5 amperes until 120 percent of the amp-hrs removed on discharge were returned. Equalization Charge - Every seven cycles, the constant current portion of the above procedure (at 5.5 amperes) was extended until 140 percent of the amp-hrs removed on discharge were returned.

Eagle-Picher 3KQ-11 tubular positive: The starting current for each charge cycle on the 3KQ-11 batteries was 25 amperes. Each battery string was charged until the average battery voltage reached 7.50 volts. This value was maintained until 115 percent of the amp-hrs removed on discharge were returned. Equalization Charge - Once every month, following the completion of the normal charge procedure identified above, each battery string was charged at 5 amperes constant current for 12 hours to equalize the batteries.

Maintenance Schedule

One each week, at the end of a charge cycle, each battery string was visually checked for loss of water and additions were made if necessary. Distilled water was used to service the batteries, and the amount used for each cell was recorded.

Environmental Controls

The test laboratory for this program was temperature controlled at 24° C (75° F) year-round. Charge and discharge cycles were not started unless the electrolyte temperature of each battery in a string was within 5° C (9° F) of room temperature.

DESCRIPTION OF FACILITY

The propulsion cycling facility at the Naval Weapons Support Center, Crane, Indiana, was designed to discharge battery strings up to 50 volts under any power-time profile. The test facility utilized a Hewlett-Packard Model HP-35 desktop computer with data acquisition and control expansion units to monitor and control 18 test stations, one for each battery string tested. Because of system demands during a discharge cycle, only one battery string could be discharged at any one time. To control the power-time profiles during discharge, the computer was programmed to read battery string voltage once each second and adjust the current level to maintain the constant power requirement. Three electronic loads were used for current control during discharge. Two 150 amp dc power supplies connected in parallel were used for the regeneration period of the profile. Eighteen dc power supplies were used for charging, one for each battery string.

Data Acquisition

The data acquisition for the Crane facility was fully automated with the exception of specific gravity and electrolyte temperature measurements, which were done manually. Important end point measurements of the acceleration, cruise, coast, and deceleration (regenerative) were taken and stored on magnetic tape for future analysis of the data. Also stored on magnetic tape was the accumulated amp-hrs and watt-hours for each profile and string.

TEST RESULTS AND DISCUSSION

Effects of Profile

The effects of the three profiles (non-regenerative, regenerative, and load-leveled) on capacity and cycle life of the three battery types were determined by observing the capacity loss and failure rates during the life cycle testing.

It should be noted that the differences in power levels between profiles would account for the variations in battery capacity. Using data from actual cycles performed on the batteries, the average current of the nonregenerative and regenerative profiles was approximately 110 amps. Whereas for the load-leveled profile, the average current was approximately 65 amps. The well-known relationship between amp-hr capacity and discharge rate of a lead-acid battery explains why such differences could be expected (2).

Figures 2 and 3 show the results of life cycling on three and six battery strings for the baseline EV106 battery (normalized capacity 112 amp-hrs). Capacity in amp-hrs is plotted against discharge cycles for each of the three profiles, which individual battery cycle failures are identified. From the data presented in Figs. 2 and 3, it is apparent that significant differences in capacity exist between the load-leveled and the nonregenerative and regenerative cases. Variations in capacity between the nonregenerative and regenerative cases are of relatively small magnitude, which indicates the cycle life does not appear to be significantly affected by the type of profile used, although failures of the load-leveled case did lag (slightly) those of the nonregenerative and regenerative cases. Table II summarizes the average cycle life of the baseline batteries for each profile both for three and six battery strings.

Figures 4 and 5 shows the amp-hr capacity versus cycle life for the EV1000 batteries and Table IV is the summary of the average cycle life for the EV1000 batteries. The conclusions arrived are the same as those with the baseline EV106 batteries. Differences in capacity and cycle life for the nonregenerative and regenerative cases, although significant for the three battery string, cannot be explained for the six battery strings.

Life cycling results of the tubular positive 3KQ-11 battery are shown in Figs. 6 and 7. Batteries for the load-leveled case completed an excess of 200 cycles with no failures. As noted in Fig. 6, all three batteries on the nonregenerative and regenerative cases failed early in the cycling tests and testing was discontinued at the point where capacity fell below 80 percent of normalized capacity. Although a cluster of battery failures occurred early for the nonregenerative and regenerative case (six battery string) a decision was made to continue cycling the remaining battery until failure at the 40 percent of normalized capacity. This battery maintained capacity in excess of 80 percent of normalized for over 200 cycles at which point testing was discontinued. Table IV shows the results of the average cycle life for each discharge profile. Clearly, for a load-leveled application the tubular positive designed battery is vastly superior.

Comparison of Battery Types on Each Discharge Profile

Nonregenerative Profile: The performance of the three battery types on the nonregenerative profile was poor. Within 150 cycles, 44 percent of the EV106 baseline batteries had failed, 88 percent of the 3KQ-11 tubular/plate batteries had failed, and 90 percent of the thin plate EV1000 had failed. The maximum number of cycles completed by any battery type was 254 cycles (although one tubular plate battery was stopped before failure at 229 cycles). Capacity loss in all cases was very rapid, especially for the thin plate and tubular plate batteries (refer to figs. 2 to 7).

Regenerative Profile: The performance of each battery type on the regenerative profile differed very little from the performance observed on the nonregenerative profile. As before, 44 percent of the baseline and 88 percent of the tubular plate batteries failed before completing 150 cycles. One-hundred percent of the thin plate batteries failed before cycle 150. Again capacity loss occurred very rapidly for the thin plate and tubular positive batteries but comparatively slower for the baseline batteries (refer to figs. 2 to 7).

Load-Leveled Profile: The load-leveled profile, the least demanding in terms of power derived from the batteries, yielded the best performance from all three battery types. However, only in the case of the tubular plate batteries was a significant increase in performance noted. For the nine tubular plate batteries cycled on the load-leveled profile there were no recorded failures and the capacity was still above 90 percent of original capacity after 231 cycles (Testing terminated). Only 11 percent of the baseline batteries failed within 150 cycles, but within 250 cycles, 89 percent of the baseline batteries had failed. For the thin plate batteries, 78 percent failed within 150 cycles, and no battery exceeded 200 cycles.

The differences in the amp-hr ratings (normalized capacity) between battery types resulted in a variable range (profiles completed per cycle). Table V compares discharge data from a typical cycle for each battery type, including number of profiles completed and discharge times to 80 percent depth-of-discharge, and specific gravities and temperatures observed at the beginning and end of a cycle.

Performance Comparison of Three-Battery Versus Six-Battery Strings

Comparisons of amp-hr output (at 50 cycle intervals) and average cycle life for three versus six battery strings of each type battery are shown in Table VI. Only insignificant differences in capacity existed on a given profile between three and six battery strings throughout the life test, except in instances where shorted cells may have limited the capacity of the string prematurely. In terms of cycle life, the baseline EV106 and thin plate EV1000 batteries equated very closely when comparing three and six battery strings. The results for the tubular positive 3KQ11 batteries were more diverse, with cycle life for the six string from 50 to 100 percent greater than the three battery string. Cycle life comparison for the 3KQ11 batteries could only be made for the nonregenerative and regenerative profiles, since no failures occurred for the load-leveled profiles.

Failure Modes During Life Cycle Tests

Failure during life cycle tests was attributed to a different cause for each battery type through autopsies. Separator failures, causing shorted cells and subsequent loss of capacity were identified as the failure mode in all of the EV106 baseline batteries. The EV1000 thin plate batteries failed due to loss of capacity caused by excessive grid corrosion. The 3KQ11 tubular plate batteries showed no sign of mechanical type failure. Failure was simply attributed to the design limitations of the battery (batteries not designed for high current discharges such as those demanded by the nonregenerative and regenerative profiles).

CONCLUSIONS

The performance of all three battery types for the nonregenerative and regenerative cases does not raise expectations that an economically feasible battery system currently exists for these propulsion systems. Each pair of battery strings for all three batteries followed virtually the same failure pattern during life cycle testing. It is perhaps significant that the modes of failure for each battery type were different, suggesting that these profiles cause degradation not in any one design area but in all areas. Only for the tubular plate batteries on the load-leveled profile were the cycle life results encouraging. Finally, it does not appear that state-of-the-art developments in lead-acid batteries have significantly improved performance over the baseline batteries. A possible exception is the tubular plate battery for a load-leveled application.

In terms of profiles completed during a discharge cycle, both electrical regeneration and mechanical regeneration (load-leveled) significantly increased the range of the vehicle driving cycle. Using average figures for the three battery types, electrical regeneration increased the range by 29 percent over the driving profile with no regeneration. For the load-leveled profile, this increase was 42.5 percent.

REFERENCES

1. "Electric Vehicle Test Procedure," SAE Recommended Practice J227a, SAE Handbook, Society of Automotive Engineers, Inc., Warrendale, PA, 1979, pp. 27.07-27.12.
2. J. G. Ewashinka, and J. M. Bozek, "Characterization, Performance, and Prediction of a Lead-Acid Battery Under Simulated Electric Vehicle Driving Requirements," DOE/NASA/51044-19, NASA TM-81771, 1981, p. 10.

TABLE I. - POWER-TIME PROFILES

Propulsion System	Time, sec	Three-battery series string, kW	Six-battery series string, kW
Baseline	0 to 6	0 to 3.48 discharge[a]	0 to 6.96 discharge[a]
	6 to 28	3.48 discharge	6.96 discharge
	28 to 78	1.23 discharge	2.46 discharge
	78 to 122	0	0
Electrical regenerative	0 to 6	0 to 3.48 discharge[a]	0 to 6.96 discharge[a]
	6 to 28	3.48 discharge	6.96 discharge
	28 to 78	1.23 discharge	2.46 discharge
	78 to 88	1.905 charge	3.81 charge
	88 to 97	4.125 to 0 charge[a]	8.25 to 0 charge[a]
Load-leveled	0 to 28	0.051 to 1.485 discharge[a]	0.102 to 2.97 discharge[a]
	28 to 78	1.485 discharge	2.97 discharge
	78 to 97	1.485 to 0.051 discharge[a]	2.97 to 0.102 discharge[a]
	97 to 122	0.051 discharge	0.102 discharge

[a]Linear change in power with time.

TABLE II. - SUMMARY OF AVERAGE CYCLE LIFE LIFE FOR EV106 BATTERIES FROM LIFE CYCLING TEST

Profile type	Average cycles completed	
	Three-battery strings	Six-battery strings
Nonregenerative	159	169
Regenerative	157	160
Load-leveled	209	[a]212

[a]One battery still cycling at the time testing was discontinued.

TABLE III. - SUMMARY OF AVERAGE CYCLE LIFE LIFE FOR EV1000 BATTERIES FROM LIFE CYCLING TEST

Profile type	Average Cycles Completed	
	Three-battery strings	Six-battery strings
Nonregenerative	[a]86	101
Regenerative	84	95
Load-leveled	132	132

[a]Does not include one battery damaged during testing and discontinued at 39 cycles.

TABLE IV. - SUMMARY OF AVERAGE CYCLE LIFE LIFE FOR 3KQ-11

BATTERIES FROM LIFE CYCLING TEST

Profile type	Average cycles completed	
	Three-battery strings	Six-battery strings
Nonregenerative	[a]61	[b]131
Regenerative	[a]64	[b]94
Load-leveled	[c]233	[c]231

[a]All batteries discontinued at this point.
[b]One battery remaining at the time testing was discontinued.
[c]No failures at the time testing was discontinued.

TABLE V. - DISCHARGE CYCLE TEST RESULTS

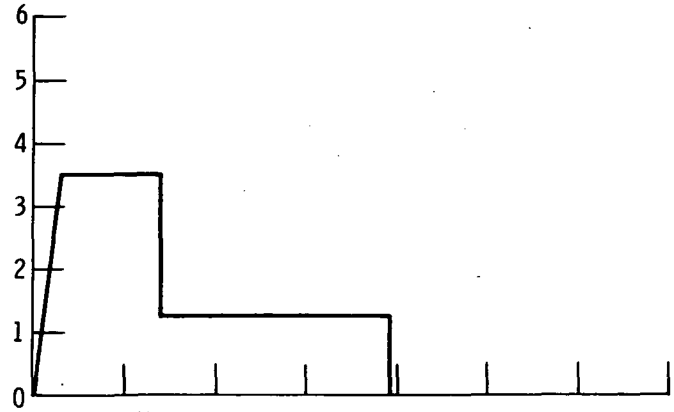
Manufacturer/ battery type	Discharge profile	Total discharge time, min	Temperature, °C		Ampere-hour capacity		Specific gravity[a]		Number of profiles per cycle
			Initial	Final	Removed	Regenerated	Initial	Final	
Exide/EV106	Nonregenerative	72	26	33	89.6	0	1.283	1.179	35
	Regenerative	94	26	37	114.7	25.1	1.288	1.190	46
	Load-leveled	103	25	28	89.6	0	1.282	1.209	50
Globe Union/ EV1000	Nonregenerative	98	26	33	117.6	0	1.291	1.178	48
	Regenerative	128	25	35	151.8	34.2	1.289	1.178	63
	Load-leveled	137	25	28	117.6	0	1.287	1.201	67
Eagle-Picher/ 3KQ-11	Nonregenerative	78	26	34	100.8	0	1.278	1.171	38
	Regenerative	100	25	38	127.0	26.2	1.281	1.180	49
	Load-leveled	112	25	30	100.8	0	1.278	1.180	55

[a]Temperature corrected.

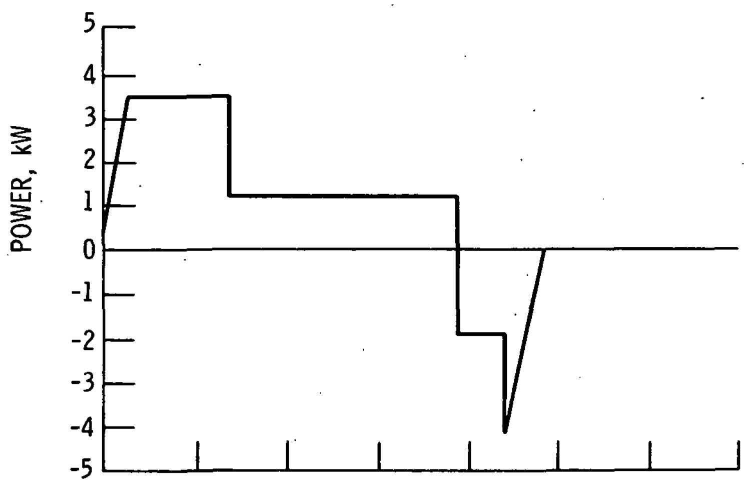
TABLE VI. - PERFORMANCE COMPARISON OF THREE VS. SIX-BATTERY STRINGS

Manufacturer/ battery type	Discharge profile	Cycle number	Ampere-hour output		Cycles completed prior to failure (average)	
			Three-battery strings	Six-battery strings	Three-battery	Six-battery
Exide/EV106	Nonregenerative	50	113	112		
		100	97	104		
		150	100	99	159	169
		200	91	83		
		250	N/A	55		
	Regenerative	50	123	120		
		100	113	113		
		150	107	101	157	160
		200	85	99		
		250	53	N/A		
	Load-leveled	50	140	137		
		100	138	138		
		150	132	117	209	[a]212
		200	108	106		
		250	94	90		
Globe Union/ EV1000	Nonregenerative	50	137	136		
		100	101	129		
		150	N/A	81	86	101
		200	N/A	N/A		
		250	N/A	N/A		
	Regenerative	50	137	135		
		100	106	111		
		150	N/A	N/A	84	95
		200	N/A	N/A		
		250	N/A	N/A		
	Load-leveled	50	159	161		
		100	135	129		
		150	93	100	132	132
		200	N/A	N/A		
		250	N/A	N/A		
Eagle-Picher 3KQ-11	Nonregenerative	50	102	107		
		100	N/A	104		
		150	N/A	114	[b]61	131
		200	N/A	112		
		250	N/A	N/A		
	Regenerative	50	105	107		
		100	N/A	120		
		150	N/A	111	[b]64	94
		200	N/A	110		
		250	N/A	N/A		
	Load-leveled	50	134	125		
		100	129	124		
		150	127	120	[c]233	[c]231
		200	124	118		
		250	N/A	N/A		

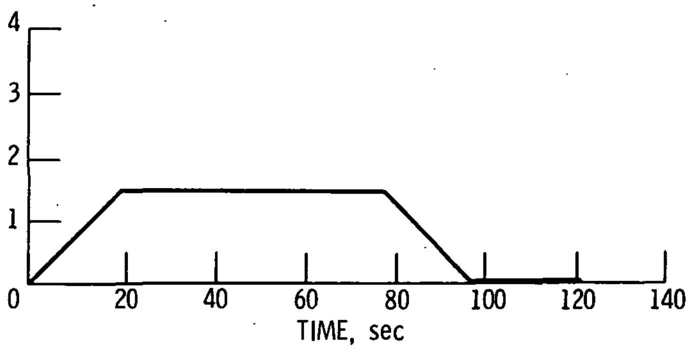
[a]One battery still cycling at the time testing was discontinued.
[b]All batteries discontinued at this point.
[c]No failures at the time testing was discontinued.



(a) Nonregenerative profile (122 sec duration).



(b) Regenerative profile (122 sec duration).



(c) Load-leveled profile (122 sec duration).

Figure 1. - Power time profiles. (3-Battery string) kW values double for 6- battery string.

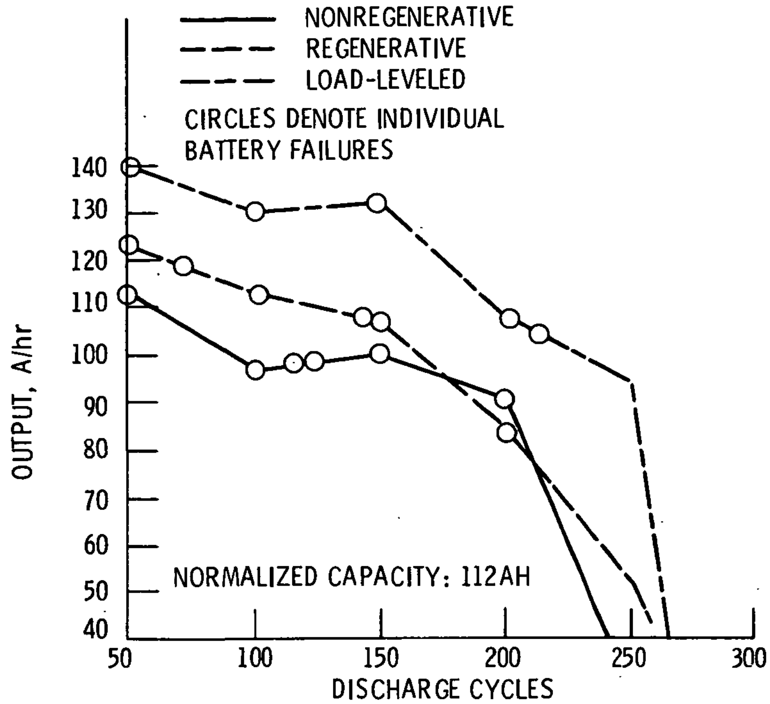


Figure 2. - EV106 three-battery test string, 50 cycle capacity to 3.9 V/battery.

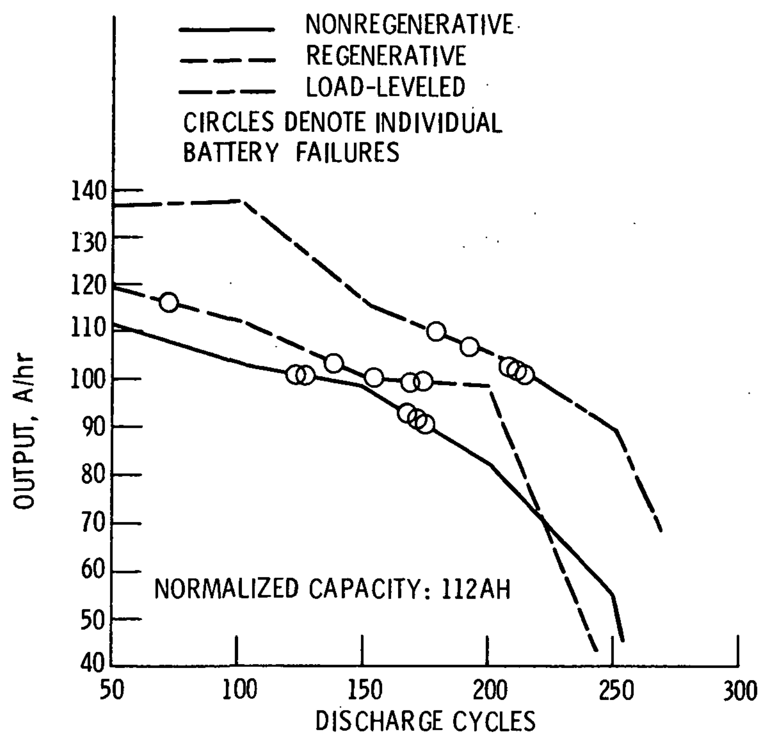


Figure 3. - EV106 six-battery test string, 50 cycle capacity to 3.9 V/battery.

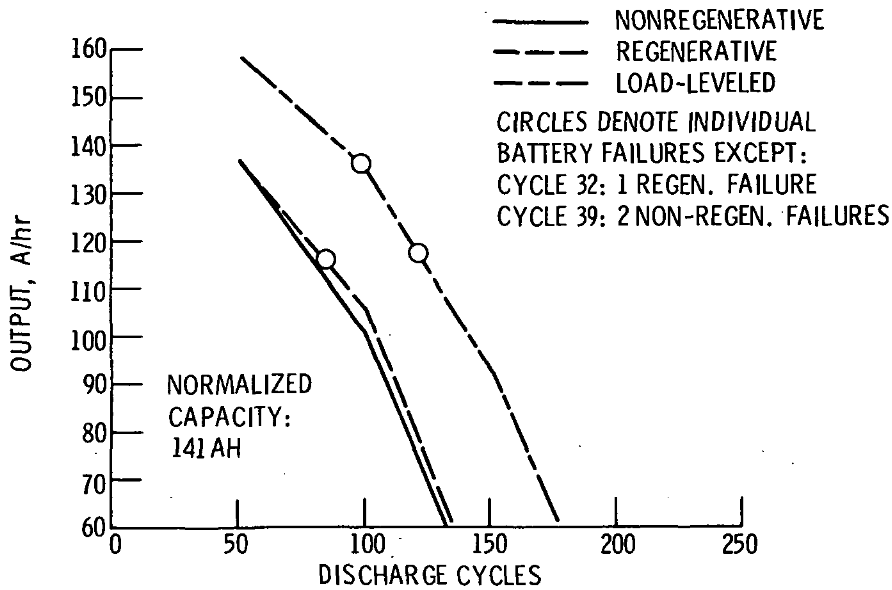


Figure 4. - EV 1000 three-battery test string, 50 cycle capacity to 3. 9 V/battery.

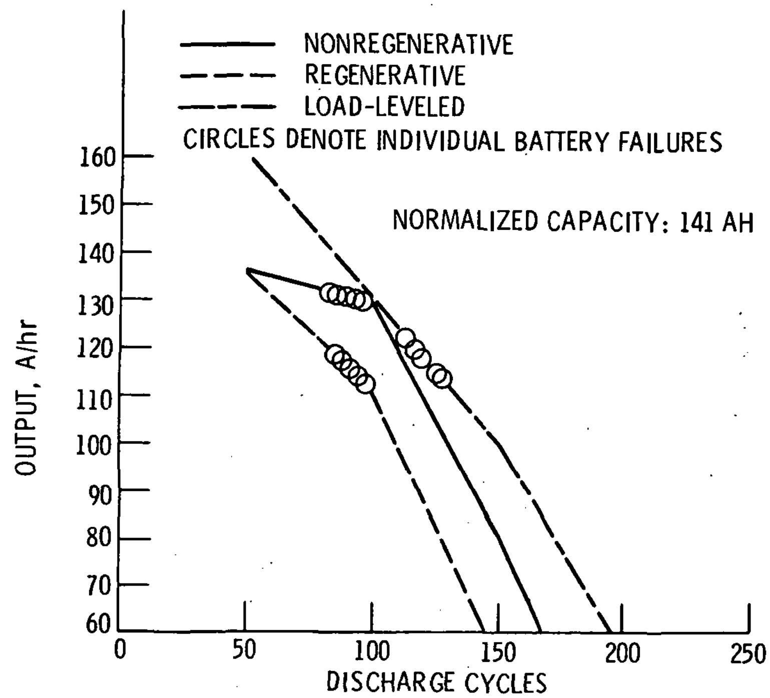


Figure 5. - EV 1000 six-battery test string, 50 cycle capacity to 3. 90 V/battery.

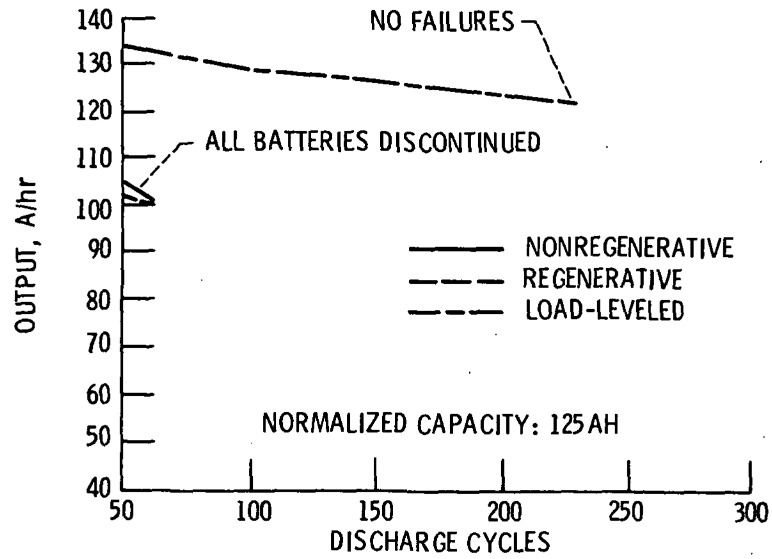


Figure 6. - 3KQ-11 three-battery test string, 50 cycle capacity to 3.9 V/battery.

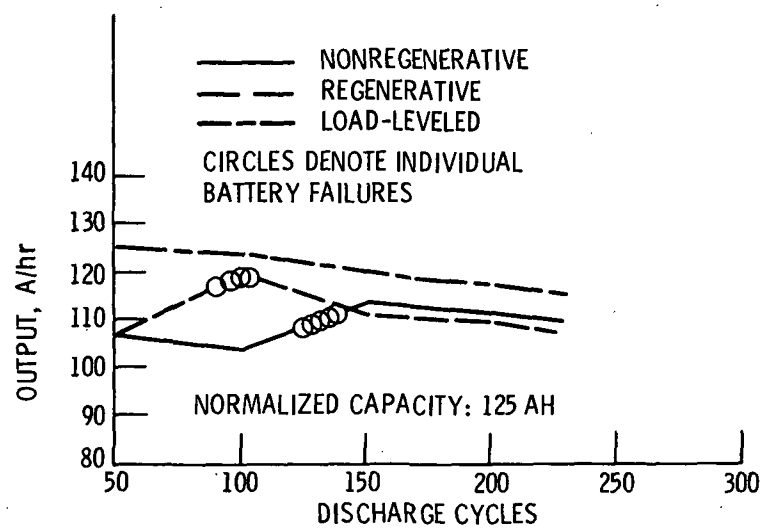


Figure 7. - 3KQ-11 six-battery test string, 50 cycle capacity to 3.9 V/battery.

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15. Supplementary Notes

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16. Abstract

Three types of state-of-the-art 6 V lead-acid batteries were tested at the Naval Weapons Support Center, Crane, Indiana. The primary objective of these tests was to determine the cycle life of lead-acid batteries as a function of the electric vehicle propulsion system design. Included in this objective was a comparison of cycle life, degradation rate and failure modes with different battery types (baseline versus state-of-the-art tubular and thin plate batteries). Also, in addition the effects of testing strings of three versus six series connected batteries on overall performance were investigated. The performance results of all three types does not raise expectations that an economically feasible battery system exists for the propulsion systems tested. Only the tubular plate batteries on the load-leveled profile were the cycle life results encouraging. These batteries attained 235 cycles with no signs of degradation and minimal capacity loss.

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