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INTRODUCTION

Many of the performance limitations of an electric vehicle are due to the battery. Certainly the range, in some cases the acceleration and hill climbing capability, and to some extent the "fuel" costs, are all affected by the battery. Beyond these immediate effects, the long term cost of keeping an electric vehicle depends heavily on the cycle life of the battery. The longer a battery lasts, the longer the time over which one can amortize the cost of the battery.

Given an electric vehicle battery, there are two primary operations that affect the short term and long term performance of that battery: charging and discharging of the battery. Under the sponsorship of the DOE Electric and Hybrid Vehicle Program, the NASA-Lewis Research Center has been involved in quantifying battery performance as a function of the charging and discharging demands placed on the battery by electric vehicle propulsion systems. The questions that are addressed and discussed in this paper are: Which quick charging technique can shorten charge times and how does it affect energy efficiency? Is pulse charging with and without small discharging (depolarization) pulses an effective quick charging technique? Does the current waveform of an overnight charger affect the life of a battery? Does pulse discharging, characteristic of the demands placed on a battery by chopper speed controllers, affect battery performance? How does the electric vehicle's method of regenerative braking affect battery performance? Is it better to regenerate via a mechanical system like a flywheel or is it better to regenerate electrically? These are the questions we are attempting to answer. The answers will help us choose an electric vehicle propulsion system that not only will be inexpensive, small, light weight and durable but also a propulsion system that will treat the battery in a way that would efficiently extract energy from the battery without adversely affecting the battery's durability.

RESULTS

Many of the energy related questions have been answered but most of the durability questions are still awaiting completion of long term tests.

Charging

Rapid charging. The objective of these tests was to determine if electrochemical cells can be efficiently charged in less 1 hour (Ref. 1).

Two electrochemical systems, 300 A-h lead-acid and 300 A-h nickel-zinc cells, were tested. The charging current profile having promise was a high rate taper direct current (HRTDC) profile, which takes advantage of the high coulombic charge efficiency of a battery at low states-of-charge.

A typical charge curve is shown in Fig. 1. This happens to be for the nickel-zinc cell, however, data for lead-acid cells are similar. In the HRTDC method used, the initial charge current was 500 amperes. Periodically during the charge, the current was reduced in 50 ampere increments until the final charge current was 100 amperes. Excessive gassing or rate of temperature rise were the criteria used to reduce the current or end the charging.

During the first part of the charge, the stepdown in charge current was dictated by a rapid rise in temperature. In the middle of the charge, gassing became the dominate criteria. The termination of the charge was due to the battery approaching 10 or 20% coulombic efficiency as measured by the gassing rate.

Results of the HRTDC tests are shown in Table 1. The capacities removed from the two types of electrochemical cells during discharge were 71 and 63% of the rated capacity. The charging time was 53 minutes for the nickel-zinc system and 46 minutes for the lead-acid system, both less than an hour. The charge-discharge energy efficiency was 52% for the nickel-zinc cell and 64% for the lead-acid cell. Typically, the energy efficiency of a lead-acid cell that is charged overnight (i.e., about 8 hours), would be about 75% (Ref. 2), and a nickel-zinc somewhat higher (Ref. 3). We see that quick charging is possible, but one pays the price of lowered available capacity and a lowered energy efficiency.

Pulse charging. The variations in the performance of 300 A-h lead-acid cells, of the type and design found in electric vehicle delivery vans, were studied as a function of quick charging techniques other than the HRTDC method discussed above. The techniques varied from a baseline constant current charge to high frequency, pulse type charges with and without depolarization pulses (Ref. 4). Figure 2 shows schematically the type of charging pulses used and the nomenclature that is used to identify the pulses. The time averaged current and frequency for the wave shapes were equal, about 147 amperes and 60 Hz, respectively, yet the duty cycle and the magnitude of the charge and depolarization pulses vary.

All charges were terminated, as in the previous discussion, when either the gassing or temperature of the cells reached unacceptable levels.

Table 2 contains the results of these tests. As can be seen, the capacity removed and charge time are somewhat independent of the charging wave shape. In all cases the capacity removed was about 63% of the rated capacity and the charging time varied between 77 and 81 minutes. Of significance is the energy efficiency. Pulse charging resulted in a 9 to 19 percentage point drop in efficiency when compared to constant current charging.

Using as a baseline the Romanov pulse described in Fig. 2(c), the effects of frequency, duty cycle and the size of the depolarization pulse was measured. A summary of the data is presented in Table 3. Frequency had little effect on charge time, capacity removed or energy efficiency. Increasing the duty cycle to 94% from 50% did not significantly change the energy efficiency (66 to 71%), but allowed the charging time to be reduced by a factor of two with an 11% drop in capacity removed (193 to 171 A-h). The reduction in the charging time and the capacity removed was due to the increased time-averaged current. Increasing the size of the depolarization pulse decreased the energy efficiency and slightly increased the charging time with no change in the capacity removed.

From the data presented in Tables 2 and 3, relationships are evident between average charge current, capacity removed, charging time and energy efficiency. Pulse charging, as investigated, tends to have an energy efficiency of 60 to 70%, tends to deliver 63% of the rated capacity after being charged in about an hour and a half. Constant current charging has a higher energy efficiency at comparable delivered capacity and charge time.

Overnight charging. Charging current waveforms anticipated from slow overnight chargers were studied on a basis of their effect on the cycle life of small nickel-zinc cells (Ref. 5). These nickel-zinc cells offered a means of quickly evaluating the effect of overnight charger designs on the cycle life of an electrochemical system. The nickel-zinc cells were constructed in-house at Lewis Research Center and were sized to meet the constraints of the available chargers.

The study was aimed at measuring the effect on battery cycle life of four types of charging waveforms considered viable candidates for overnight chargers. The waveforms investigated were full wave rectified sinusoidal, 120 Hz phase control rectified, 1 kHz square wave and, as a baseline, constant current.

The cells were discharged at 2 amperes to 75% of rated capacity, and charged at an average current of 0.25 amperes with a 5% coulombic overcharge. This discharging/charging cycle was repeated until the cells failed to deliver 50% of the initial discharge capacity.

The effect of the four charging waveforms on the cycle life of the nickel-zinc cells is shown in Fig. 3. As can be seen, the full wave and 1 kHz waveforms have minimal effects on the cycle life of the nickel-zinc cells when compared to the baseline constant current charging method. Unfortunately, during the phase control rectified waveform charging tests, there was an equipment problem which caused a sustantial overcharge which may have led to premature failure. Failure analysis of the cells indicated that failure was due to internal cell shorting.

We conclude from these tests that waveforms have little effect on the cycle life of nickel-zinc cells. Inexpensive chargers which deliver full wave rectified current have little detrimental effect on cycle life when compared to the relatively expensive constant current or 1 kHz square wave chargers. Unfortunately, any conclusion on the effect of phase control rectified chargers would be inappropriate.

As yet unpublished data indicates there are no substantial differences in the energy efficiency of large lead-acid traction cells when these cells are charged using the four charging waveforms discussed above (Ref. 6).

Discharging

Chopper controlled discharges. The speed and acceleration of many electric vehicles are controlled by amature choppers. When operating, these choppers impose a chopped current demand on the electric vehicle battery. The peak current demand during the short "on" time may be several hundred amperes while the frequency can be as high as 500 Hz.

To measure the effect of chopper type discharges on the energy available from a battery, a series of discharge experiments were performed on several golf car batteries rated at 132.5 A-h (Ref. 1). In these experiments the energy available from the lead-acid battery was measured for chopped discharge currents having time-averaged current values of 100 to 300 amperes, peak-to-average current ratios up to 4 to 1 and pulse repetition frequencies up to 500 Hz. The battery energy removed under the chopped conditions was then compared to the energy removed from the same battery under a constant current discharge condition.

The results of these tests are shown in Fig. 4. The data presented here are corrected for electrolyte temperature. The final temperature of the battery during chopped discharge was 5^{o} to 10^{o} C higher than the constant current discharges.

As seen, the chopped discharges exhibited a substantial reduction in available energy at low specific powers. At high specific powers, the chopped energy approaches the constant current energy. In some cases, the energy removed during chopped discharges exceeded that for constant current discharges. This increase were primarily due to the increased discharge capacity which had been observed for chopper discharges. The increased capacity more than compensated for the increased I^2R heating losses present during chopped discharges.

There are ongoing efforts in this area. An in-house NASA Lewis effort on the chopper discharge effects on nickel-zinc cells is nearing completion (Ref. 8). Also, a contracted effort with TRW at Redondo Beach is directed toward evaluating the effects of chopper discharges on the life expectancy of lead-acid batteries.

Regenerative braking. The objectives of these tests are two-fold. First, to verify that electrical regenerative braking can increase the range of an electric vehicle in a mathematically predictable manner. Though an increase in the range of an electric vehicle with regenerative is expected, we also are attempting to predict this increase by the application of battery performance models. The second objective is to quantify any effect regeneration may have on the cycle life of a battery.

Soon to be published test results show that electrical regeneration does indeed increase the range of an electric vehicle (Ref. 9). Reference 10 describes a battery model developed at NASA-Lewis which reasonably predicts the battery performance.

Table 4 shows the results of the laboratory tests and model predictions for a golf car battery rated at 132.5 A-h. During the laboratory tests the discharge current was programmed to those values expected in electric vehicles following the various SAE J227a driving schedules (B, C, and D).

The laboratory experiments show a range increase due to electrical regeneration of 15% for the D schedule and 25% for the B schedule, while the model predictions show an increase of 10% for the D schedule and 16% for the B schedule. Also, as shown in Table 4, the maximum deviation between laboratory test data and mathematical predictions is 10%.

To complement the on-going in-house effort at NASA-Lewis, a contracted effort has recently been initiated with the Naval Weapons Support Center in Crane, Indiana. The objective of this effort is to determine the cycle life of lead-acid batteries as a function of electric vehicle propulsion system design. The benefit of electrical regeneration (i.e., increasing the range of an electric vehicle), is well documented. The effect of electrical regeneration on the cycle life of a battery is not known. The possibility of electrical regeneration reducing the cycle life to an extent that it may overshadow an increase in range needs to be clarified. There is also a need to clarify the benefits of a mechanical regenerative propulsion system (i.e., flywheel) over an electrical regenerative propulsion system. The increased complexity of a mechanical regenerative system must be compensated for by an increase in vehicle performance (range) or an increase in battery cycle life over that observed for an electrical regenerative propulsion system. In our contracted effort we will be investigating the effect on three different types of lead-acid batteries of three different types of electric vehicle propulsion systems. The batteries are: (1) golf car batteries, (2) thin plate high energy batteries, and (3) long life tubular batteries. The propulsion systems are: (1)

nonregenerative, (2) electrical regenerative, and (3) mechanical regenerative.

SUMMARY

A battery can be recharged rapidly (i.e., in less than an hour), but one pays the price of lowered output capacity and lowered energy efficiency. Pulse charging does not decrease charge time when compared to constant current charging but does decrease the energy efficiency. Depolarization pulses do not reduce charge times or increase charging energy efficiency. A relatively inexpensive, full wave rectified, overnight charger is as good as an expensive, complicated, constant current charger when both are compared on the basis of cycle life and energy efficiency. Chopper type discharging decreases the energy available from a battery especially at low power levels and may increase the energy available at high discharge rates. Electrical regeneration does improve the range of an electric vehicle in a mathematically predictable manner.

On-going programs at NASA-Lewis will help clarify the effects of propulsion system design concepts on the cycle life of batteries.

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TABLE 1. - HIGH RATE TAPER DIRECT CURRENT CHARGE

Type of cell	Rated capacity, A-h	Charge time, min	Capacity removed		Energy efficiency, %
			A-h	% rated	
Nickel zinc	300	53	214	71	52
Lead-acid	300	46	189	63	64

TABLE 2. - PULSE CHARGING OF 300 A-H LEAD-ACID CELLS

Type of charge	Time averaged current, amp	Charge time, min	Capacity removed		Energy efficiency, %
			A-h	% rated	
Constant current	147	80	193	64	80
Positive pulse	149	77	191	64	71
Romanov pulse	147	81	193	64	66
McCulloch pulse	147	77	187	62	61

TABLE 3. - PULSE CHARGING VARIABLES 300 A-H LEAD-ACID CELL

Variable	Time averaged current, amp	Charge time, min	Capacity removed		Energy efficiency, %
			A-H	% rated	
Frequency, Hz					
8	140	86	200	67	67
60	147	83	198	66	65
200	149	80	196	65	67
400	148	80	193	64	67
Duty cycle, %					
50	146	81	193	64	66
75	225	49	183	61	69
94	288	36	171	57	71
Size of depolarization pulse, amps					
0	149	77	191	64	71
15	146	81	193	64	66
35	133	88	190	63	59

TABLE 4. - REGENERATIVE BRAKING TEST RESULTS WITH A132.5 A-H LEAD-ACID BATTERY

SAE J227a driving schedule	Laboratory measured range*					Mathematically predicted range*					Deviation of predicted from measured	
	Without regen		With regen		Regen increase, %	Without regen		With regen		Regen increase, %	Without regen, %	With regen, %
	kM	mi	kM	mi		kM	mi	kM	mi			
B	164	102	204	127	25	158	98	183	114	16	-3.9	-10
C	100	62	119	74	19	101	63	114	71	13	+1.6	-4.1
D	64	40	74	46	15	66	41	72	45	10	+2.5	-2.2

*Ranges based on; 0.23 kM/B schedule; 0.60 kM/C schedule; 1.71 kM/D schedule.

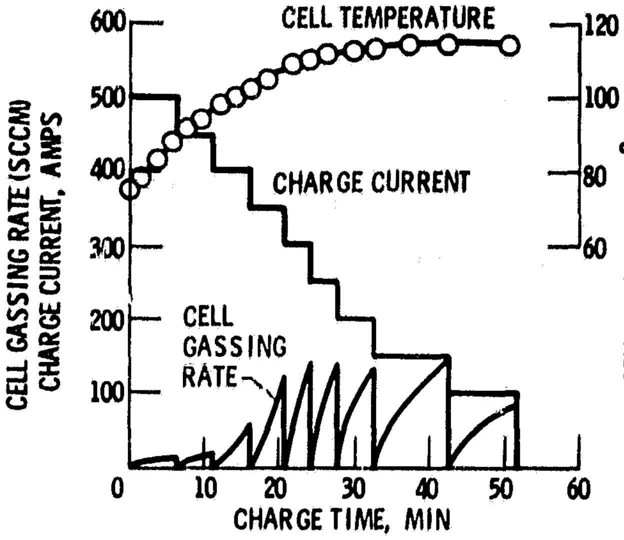

Figure 1. - High rate taper direct current charge of 300 A-H nickel-zinc cell.

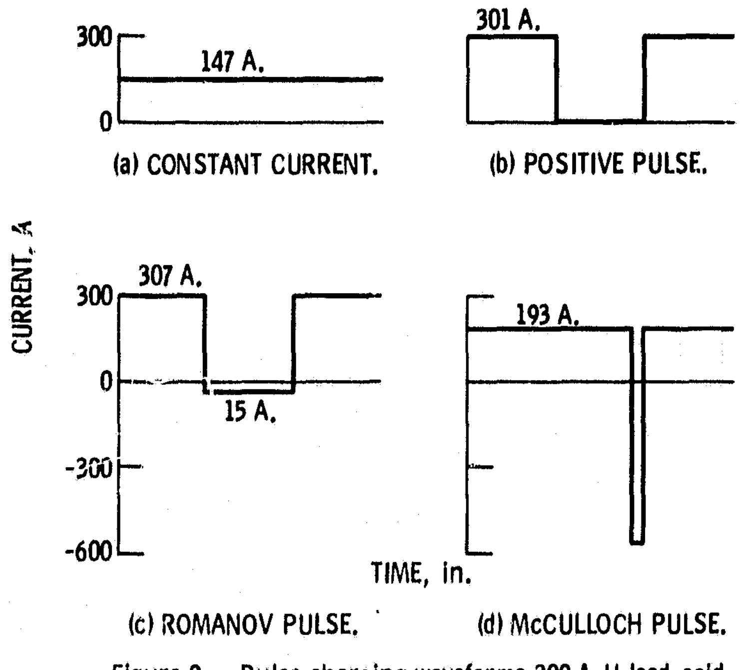

Figure 2. - Pulse charging waveforms 300 A-H lead-acid cell.

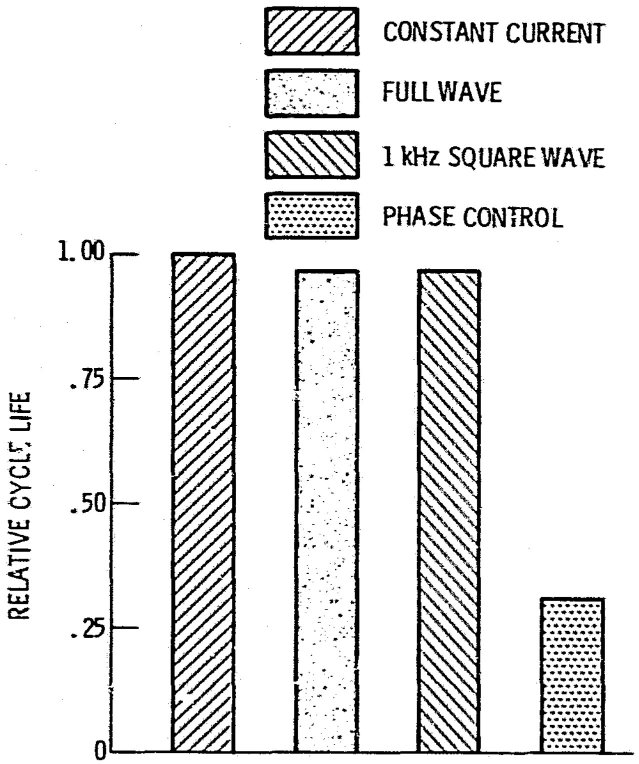

Figure 3. - 'Overnight' charge waveform effects on cycle life of 5 A-H nickel-zinc cells.

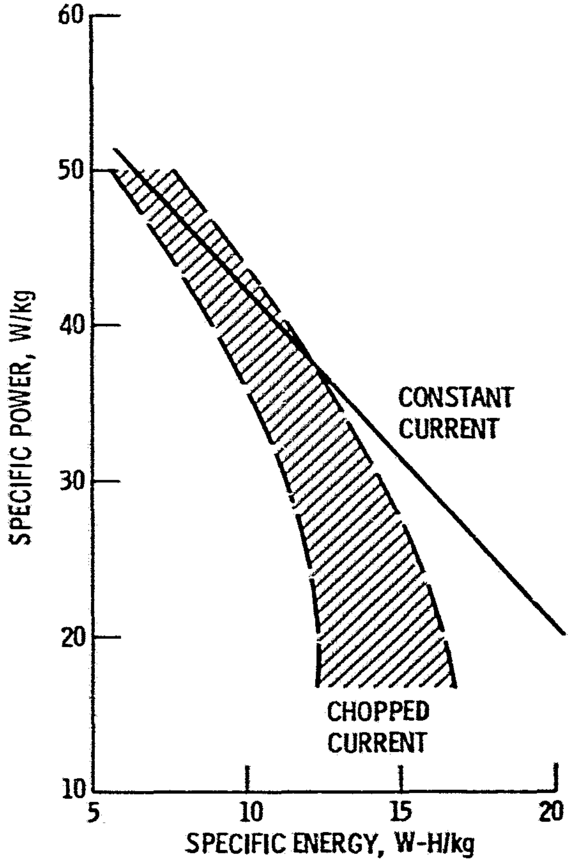

Figure 4. - Energy available from 132.5 A-H lead-acid battery.