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SUMMARY

Computer programs used to calculate the performance of an electric vehicle must contain a battery model. A simple mathematical model is developed and evaluated in this report. The model is based on the time averaged current or power required from a battery during the operation of the electric vehicle. The time averaging technique used accounts for time varying discharge rates, rest times, and the electrical regenerative braking that are normally experienced by a battery in an electric vehicle.

The averaging battery model reported herein, has been verified through comparisons with test data gathered on batteries in the laboratory and from vehicles operated at test tracks. The averaging battery model accurately predicts the performance measured for lead-acid batteries operating in accordance with the power and current requirements of the various driving schedules specified in the SAE Recommended Practice, "Electric Vehicle Test Procedure - SAE J227a."

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INTRODUCTION

Every computer program used to calculate the range of an electric vehicle must contain a battery model of some sort. Many such models have been published (refs. 1 to 8). Some of the battery models are capable of following the changes in battery voltage and current during the discharge. Others only follow the change in the state-of-charge of the battery as the discharge progresses.

Irrespective of the type of model, it should predict the change in battery performance due to the effects of (1) time varying discharge rates, (2) rest periods, and (3) short charges between discharges such as those experienced by a battery during electrical regeneration in an electric vehicle. Battery models incorporating averaging techniques have been reported and used in the battery industry (refs. 9 and 10). The averaging battery model reported herein follows the state-of-charge of the battery. Also the averaging model reported herein is unique in that it can successfully account for the changes in battery performance due to the time varying discharge rates, rest periods and short charges (electrical regenerative braking) experienced by batteries in an electric vehicle.

Since lead-acid batteries have been extensively tested in the laboratory and in electric vehicles, this report deals exclusively with this electrochemical system. The application and evaluation of the averaging battery model is limited to battery discharge profiles expected from batteries in an electric vehicle operating under the SAE J227a schedules (ref. 11).

SYMBOLS

A-H_D	capacity (A-hr) discharged
$\text{A-H}_{\overline{W}}$	capacity (A-hr) withdrawn from battery during tests with regeneration

$A\text{-}\overline{H_{wo}}$	capacity (A-hr) withdrawn from battery during tests without regeneration
$A\text{-}H_R$	capacity (A-hr) at battery posts during regeneration phase of driving schedule
C	capacity (A-hr) available from battery
E	energy (J) available from battery
E_D	energy (J) discharged
$\overline{E_w}$	energy (J) removed from battery during tests with regeneration
$\overline{E_{wo}}$	energy (J) removed from battery during tests without regeneration
E_R	energy (J) at battery posts during regeneration phase of driving schedule
$F_I(t)$	state-of-charge (fraction) of battery on a capacity basis
$F_P(t)$	state-of-charge (fraction) of a battery on an energy basis
i_D	instantaneous discharge current, A
i_R	instantaneous regeneration current, A
$\overline{I}_D$	time averaged discharge current, A
p_D	instantaneous discharge power, W
p_R	instantaneous regeneration power, W
$\overline{P}_D$	time averaged discharge power, W
R_I	regenerative effectiveness on a capacity basis
R_P	regenerative effectiveness on an energy basis
t	time, hr
t_R	actual rest time, hr
T_{EFF}	effective rest time, hr
τ	time constant, hr

MODEL DESCRIPTION

The averaging battery model reported herein accounts for the time varying discharge rates encountered in electric vehicles, which can vary by a factor of up to 4, by averaging these discharge rates over the discharge time in question. The average discharge rate is then applied to a performance limit (Peukert or Ragone plots) determined from laboratory tests on the battery in question. Rest periods, which allow recuperation of a battery, are accounted for by including the rest period in the time averaging. Electrical regeneration, which extends the performance of a battery, is accounted for by incrementally increasing the state-of-charge of a battery by an amount proportional to the energy or capacity restored to the battery during regeneration.

Time varying discharge rates. - The model is based on time averaging the discharge rate of the battery and the comparison of this rate to the battery performance limits determined from controlled laboratory tests. These laboratory tests are constant current or constant power discharges which result in Peukert (A-hr versus A) or Ragone (J (W-hr) versus W) plots.

Typical battery Peukert and Ragone plots are given in figure 1. The equations that describe the two curves in figure 1 are

$$\text{Peukert:} \quad C = 499 i_D^{-0.308}$$

$$\text{Ragone:} \quad E = 5.047 - 1.254 \times 10^{-2} p_D + 3.045 \times 10^{-5} p_D^2 - 4.201 \times 10^{-8} p_D^3 + 2.775 \times 10^{-11} p_D^4 - 6.9552 \times 10^{-15} p_D^5$$

Here, C is the capacity limit in ampere-hours, i_D is the current in ampheres, E is the energy limit in megajoules and, p_D is the power in watts. The particular battery represented by figure 1 has been used in many of the tests used to judge the efficacy of the averaging battery model.

The averaging model expressed in its simplest form (for calculating the state of charge of a battery during time varying discharge rates), is given below

$$F_I(t) = 1 - \frac{\int_0^t i_D \, dt}{C}; \quad \bar{I} = \frac{\int_0^t i_D \, dt}{t} \tag{1}$$

$$F_P(t) = 1 - \frac{\int_0^t p_D \, dt}{E}; \quad \bar{P} = \frac{\int_0^t p_D \, dt}{t} \tag{2}$$

Since a battery can be discharged in a current controlled mode, or a power controlled mode, the applicable state-of-charge equation is dependent on the mode of discharge. Throughout this report there will be two state-of-charge equations developed. State-of-charge equations dealing with current as an independent variable are designated $F_I(t)$, while those equations dealing with power as an independent variable are designated $F_P(t)$. The choice of which to use will depend on whether current and its associated capacity (A-hr) limit or power and its associated energy (MJ) limit is the independent variable.

In equations (1) and (2), $F_I(t)$ or $F_P(t)$ is a measure of the state-of-charge of a battery at time t. Equation (1) is used to determine the state-of-charge of a battery when the discharge current (i_D) is known, i.e., when the current i_D is the independent variable. Equation (2) is used when the discharge power p_D is known. $\overline{I}_D$ and $\overline{P}_D$ are the time averaged current and power respectively at time t. C and E are the capacity (A-hr) and energy (MJ) limits respectively, obtained from plots similar to figure 1, at the time averaged current $\overline{I}_D$ or power $\overline{P}_D$.

Rest periods. - It is obvious that equations (1) and (2) tend to account for the rest periods if the appropriate integrations are performed to include times when no current or power is being drawn from the battery. Resting, in equations (1) and (2), reduces the values of $\overline{I}$ or $\overline{P}$. This reduction increases the value of C or E which results in an increase in $F_I(t)$ or $F_P(t)$. However, as reported in reference 9, experiments have shown that resting increases the state-of-charge rapidly at first followed by a gradual decrease in rate until a limit is reached asymptotically. As defined in equations (1) and (2), time-averaging the current or power during rests does'nt account for the aforementioned asymptotic behavior of a battery. Therefore, for completeness, the effect of resting as used in equations (1) and (2) must be modified.

An effective resting period, defined below, has been suggested in reference 9 as a means of discounting the actual rest period. The discounting allows for the initial rapid increase in the state-of-charge followed by a limit reached asymptotically.

$$T_{EFF} = \tau \left[1 - \exp\left(\frac{-t_R}{\tau}\right)\right] \tag{3}$$

Here T_{EFF} is the effective rest period to be used in calculating the average current or power, τ is a time constant and t_R is the actual resting time. The time constant (τ) indicated in reference 9 was determined to be 0.5 hour. As can be seen, the maximum effective resting period is 0.5 hour. In this report the efficacy of the averaging battery model is based on a comparison to tests which have rest times less than 1 minute. In this case there is little difference between T_{EFF} and t_R. For example, when t_R is 1 minute the value of T_{EFF} is only 2% smaller than t_R.

Regeneration. - During the deceleration of an electric vehicle, regeneration into the battery may occur. Energy from the moving vehicle is transferred through the propulsion system to recharge the battery. This energy replaces some of that previously removed from the battery and the state-of-charge must increase. How much of an increase will depend on the ability of the battery to convert regeneration energy into recoverable electrochemical energy. A measure of this ability to convert regeneration energy to recoverable electrochemical energy is defined, for purposes of this report, as regenerative effectiveness. Regenerative effectiveness is the fraction of the energy at the battery posts during regeneration that is recoverable during subsequent discharges. Regenerative effectiveness is also defined as a fraction of the recoverable capacity.

The equations for the state-of-charge (eqs. (1) & (2)) can be modified to incorporate regeneration as follows:

$$F_I(t) = 1 - \frac{\int_0^t i_D \, dt - R_I \int_0^t i_R \, dt}{C} \tag{4}$$

$$F_P(t) = 1 - \frac{\int_0^t p_D\,dt - R_P \int_0^t p_R\,dt}{E} \qquad (5)$$

Here regenerative effectiveness is R_I on a capacity (A-hr) basis and R_P on an energy (MJ) basis. The regeneration current is i_R, the regeneration power is p_R, while i_D and p_D are the discharge current and power, respectively. $F_I(t)$ and $F_P(t)$ are the state-of-charge of the battery at time t. C and E are as defined in equations (1) and (2) for $\bar{I}$ and $\bar{P}$, respectively. The regeneration current i_R and power p_R are not used in calculating $\bar{I}$ or $\bar{P}$. The regeneration period is considered a rest period.

Conventional wisdom dictates that the regenerative effectiveness on an energy basis should be less than one (1). The voltage of a battery is higher during charge than during discharge. Assuming 100% coulombic efficiency, i.e., every electron at the battery posts during regeneration charge will be available during a subsequent discharge, the regenerative effectiveness will be equal to the ratio of the voltage during discharge and the voltage during charge. This ratio is always less than one. The regenerative effectiveness on an amphere-hour basis, occasionally called coulombic efficiency, should also be less than one. The electrons passing through a battery during regeneration not only charge the active material in the battery but also find their way into the production of H_2 and O_2 gases. The gassing rate can be high during the high currents experienced during regeneration.

Commensurate with conventional wisdom, regenerative effectiveness values less than one have been used by others. Nelson (ref. 12) has used 0.70 for what he terms the turnaround efficiency of regeneration. Yet, as will be seen below, regenerative effectiveness values equal to or greater than one have been observed in laboratory tests on lead-acid batteries.

Regenerative effectiveness values were calculated from published results of laboratory tests on lead-acid batteries. As reported in reference 1, lead-acid batteries were tested under three discharge power-time profiles simulating battery requirements for an electric vehicle driven according to the three schedules, "B", "C", and "D" specified in reference 11. In these tests the battery was completely discharged twice under each of the three power profiles. Once with regeneration and again when regeneration was not included.

In another series of tests (as reported in ref. 13) a lead-acid battery was tested under one discharge power-time profile simulating the battery requirements of an electric vehicle driven according to the "D" schedule specified in reference 11. In these tests the battery was completely discharged twice, once with regeneration and again with regeneration not included. In both referenced works the energy removed from the battery and the energy at the battery posts during regeneration was reported or can be easily calculated from given data. A golf car lead-acid battery of the same design was used in both referenced works. From the reported data, the regenerative effectiveness on an energy basis (R_P) can be calculated from the following relationship.

$$R_P = \frac{\overline{Ew} - \overline{Ewo}}{E_R} \qquad (6)$$

Here $\overline{Ew}$ is the energy removed from the battery at the end of discharge for the test which included regeneration, while $\overline{Ewo}$ is the energy removed during the tests without regeneration. E_R is the total energy at the battery posts during regeneration at the end of discharge.

The calculated regenerative effectiveness values are shown in table I for the tests reported in references 1 and 13. In table I, column two refers to the SAE J227a schedule used in tests. Though both workers tested the same type of battery on the SAE J227a 'D' schedule, the power-time profiles (shown in fig. 2) were different. The differences reflect different electric vehicle designs and different interpretations of the testing procedures outlined in reference 11. One of the power-time profiles has a peak discharge power almost twice that of the other. The regenerative powers also differ in magnitude and duration. Even with these differences, the regenerative effectiveness is greater than one. In all the SAE J227a schedules and in both referenced works the value of regenerative effectiveness is greater or equal to one.

From data presented in reference 13, the regenerative effectiveness on a capacity (A-hr) basis can be calculated. Regenerative effectiveness on a capacity basis is defined as

$$R_I = \frac{(A\text{-}H\overline{w}) - (A\text{-}H\overline{wo})}{(A\text{-}H_R)} \qquad (7)$$

Here $(A\text{-}H\overline{w})$ is the capacity (A-hr) removed from the battery at the end of discharge for the test that included regeneration $(A\text{-}H\overline{wo})$ for the test without regeneration and $(A\text{-}H_R)$ the total capacity at the battery posts during regeneration at the end of discharge. In these tests, the capacity difference between the tests with and without regeneration $(A\text{-}H\overline{w}) - (A\text{-}H\overline{wo})$, was 46 ampere-hours, while the capacity during the regeneration periods $(A\text{-}H_R)$ was only 31 ampere-hours. The resultant regenerative effectiveness, R_I, is 1.48.

A reasonable explanation for regenerative effectiveness values greater than one has been given in reference 13. Rowland, et. al, indicate that during regeneration there is an abnormally high increase in sulfate ion ($SO_4^{=}$) concentration (specific gravity) in the pores of the positive plate. This abnormally high ion concentration increases the state-of-charge of the battery by allowing more complete subsequent discharges to a cut-off voltage.

USE AND VERIFICATION OF BATTERY MODEL

The efficacy of the averaging battery model was judged by comparing predictions against test data. The test data were limited to these obtained for batteries operating in a manner expected in an electric vehicle following the various schedules specified in reference 11. The battery power-time and current-time profiles for each of the schedules are repetitive and short, lasting no longer than 122 seconds. The equations used to calculate the number of profiles possible, for one complete discharge of the battery, are given below.

$$\text{Number of profiles} = \frac{C}{(A\text{-}H_D)/\text{profile} - (A\text{-}H_R)/\text{profile}} \tag{8}$$

$$\text{Number of profiles} = \frac{E}{E_D/\text{profile} - E_R/\text{profile}} \tag{9}$$

The above equations are equations (4) and (5) simplified to reflect the repetitive nature of the power-time and current-time profiles. Regenerative effectiveness (R_p or R_I) is set equal to one, and the effective rest time (T_{EFF}) is equal to the actual rest time (t_R).

Experimental data indicates a range of values for regenerative effectiveness (table I), however, the averaging model is somewhat insensitive to the value of regenerative effectiveness. A 25% increase in R_p or R_I affects the results of calculations by less than 8%. Therefore, equations (8) and (9) assume a regenerative effectiveness of 1.0 in all cases. The effective rest time, equation (3), is not influential, since rest times are always less than 45 seconds. The values $(A\text{-}H_D)$/profile and $(A\text{-}H_R)$/profile are the discharge capacity and regenerative capacity per profile, respectively. C is the capacity available at the time averaged discharge current. The capacity available is determined from data similar to that in figure 1. E_D/profile, E_R/profile and E have similar definitions but on an energy basis.

Table II contains a summary of the comparisons of laboratory and vehicle test track data to the calculated data using the averaging battery model. Column one contains the type of experimental data, whether laboratory tests or vehicle tract tests, together with the appropriate references, and a brief description of the test or vehicle involved. Column 2 contains the applicable SAE J227a schedule, "B", "C", or "D", with (w) or without (wo) electrical regeneration. Column 3 contains the number of profiles completed at the time the battery was no longer able to function under the prescribed profile. Column 4 contains the prediction using the averaging model. Column 5 contains the percentage error between tests and calculations.

As can be seen, the agreement between tests and calculations is good. Only 3 out of the 14 laboratory tests reported have an error greater than ±5%. However, in the track test comparisons, 2 out of the 10 reported tests have an error greater than ±8%.

The actual data used and methods employed to extract needed information from references are presented in the appendix.

CONCLUDING REMARKS

Through time averaging the current or power, an effective means of predicting the performance of a lead-acid battery is demonstrated. The effectiveness of this battery model was tested on battery discharge profiles expected during the operation of an electric vehicle following the various SAE J227a schedules. The averaging model predicts the performance of a battery that is periodically charged (regenerated) if the regeneration energy is assumed to be converted to retrievable electrochemical energy on a one to one basis.

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TABLE I. - REGENERATIVE EFFECTIVENESS

Reference	SAE J227a schedule	Total energy out, E_w[a,b]		Total energy out, E_{wo}[a,b]		Total regeneration energy,[a,b] E_R		Regeneration effectiveness, R_p[b]
		MJ	W-H	MJ	W-H	MJ	W-H	
1	B	4.45	1236	3.77	1048	0.655	182	1.03
1	C	4.10	1139	3.46	960	.644	179	1.00
1	D	3.04	845	2.60	722	.389	108	1.13
13	D	3.65	1013	2.75	763	.713	198	1.26

[a] Per 6-volt battery.
[b] Equation (6).

TABLE II. - COMPARISON OF TEST AND CALCULATED RESULTS

	SAE J227a schedule[a]	Test results	Calculated results	Error, percent
		Profiles	Profiles	
Laboratory tests				
Controlled power				
Ref. 1	B$\overline{wo}$	424	437	+3.1
	B$\overline{w}$	500	512	+2.4
	B'	374	373	0
	C$\overline{wo}$	187	181	+3.3
	C$\overline{w}$	222	214	+3.6
	C'	159	145	-8.8
	D$\overline{wo}$	47	50	+6.4
	D$\overline{w}$	55	57	+3.0
	D'	40	41	+2.5
Ref. 13	D$\overline{wo}$	53	54	+1.8
	D$\overline{w}$	71	68	-4.2
Controlled current				
Ref. 14	B$\overline{wo}$	369	405	+9.8
	C$\overline{wo}$	184	193	+4.9
	D$\overline{wo}$	49	48	-2.0
Track tests				
Ref. 15 (Change-of-Pace)	B$\overline{wo}$	133	133	0
	C$\overline{wo}$	83	87	+4.8
Ref. 16 (Contactor)	B$\overline{wo}$	152	132	-13.2
	C$\overline{wo}$	66	63	-4.5
Ref. 17 (DJ5-E)	B$\overline{wo}$	173	182	+5.2
Ref. 18 (R-5)	B$\overline{wo}$	337	337	0
Ref. 19 (Ripp-Electric)	B$\overline{wo}$	326	350	+7.4
	B$\overline{w}$	364	375	+8.5
	C$\overline{wo}$	171	177	+3.5
	C$\overline{w}$	224	206	-8.0

[a] SAE J227a driving schedules: $\overline{wo}$ = without regeneration; $\overline{w}$ = with regeneration; prime = discharge profile did not include coast, brake, or rest times as specified by SAE J227a.

APPENDIX A

This appendix discusses the methods of extracting needed data from references and the methods employed in using these data to predict battery performance via the averaging model presented in the main body of the report.

Reference 1. - This reference describes laboratory tests performed on a number of golf car lead-acid batteries. These batteries were discharged in accordance with a repeated power-time profile, which simulates the discharge power requirements of a battery in a vehicle operating in accordance with the schedules specified in reference 11. The performance of the battery was measured when regeneration was implemented and when regeneration was not implemented. In addition, the battery performance was measured in unique tests where the battery was only discharged at the power levels required for the acceleration and cruise phases. All coast, brake, and rest phases were deleted from the SAE J227a schedules.

Equation (9) in the main body of the text was used to predict the number of profiles possible. Data presented in reference 1 contain the actual power-time profiles for each of the SAE J227a schedules. From these data the energy and average power values needed to implement equation (9) were obtained and are presented in table III. The power versus energy plot in figure 1(a) was used for the limiting values of energy E in equation (9).

Reference 13. - This reference describes laboratory tests performed on one golf car lead-acid battery. This battery was discharged following a repeated power-time profile simulating the battery demands of a vehicle following the SAE J227a "D" schedule, with and without regeneration.

Equation (9) was used to calculate the number of profiles. Data presented in reference 13 contain the measured energy removed from the battery over a complete discharge and the total energy at the battery posts during regeneration, which allowed easy calculations for E_D/profile and E_R/profile in equation (9). The data needed to apply equation (9) are given in table IV. The limiting energy, E, was obtained from figure 1(a).

Reference 14. - This reference describes laboratory tests on a golf car lead-acid battery. The battery was discharged on a repreated current-time profile approximating the demand placed on a battery by a vehicle being driven in accordance with the SAE J227a "B", "C", and "D" schedules specified in reference 11. No effect of regeneration was measured.

Equation (8) was used to calculate the number of profiles possible, since the laboratory tests were current controlled. The necessary values of capacity and current were obtained by a numercial integration of the current-time profiles presented in reference 14. The limiting value of capacity, C, was obtained from figure 1(b). The data used in applying equation (8) are given in table V.

References 15 to 18. - The data presented in these references were from track tests of four electric vehicles, driven according to the schedules specified in reference 11. Equation (8) was used to calculate the number of profiles possible. Since, only total capacity removed from the battery was reported, the capacity removed per profile, used in equation (8), was the total capacity divided by the reported number of profiles completed. The average current was calculated by dividing this capacity per profile by the time it took to complete one profile. Table VI contains all the needed information for applying equation (8). The data presented in table VI for

"Capacity Limit C" were obtained by using the average discharge current, $\bar{I}$, in the appropriate equation used to describe the Peukert curve. These equations were generated from data supplied by the battery manufacturers. The equations are given below.

Reference 15 $C = 302i_D^{-0.193}$
Reference 16 $C = 499i_D^{-0.308}$
Reference 17 $C = 2218i_D^{-0.456}$
Reference 18 $C = 499i_D^{-0.308}$

Reference 19. - This reference contains information on the performance of an electric vehicle and its batteries during track tests. Since this reference contains information on the energy flow to and from the battery, equation (9) was used to calculate the number of profiles possible. The electric vehicle tested contained 20 6-volt batteries; therefore, all data presented in reference 14 were divided by 20 so that the limiting energy, E, presented in figure 1(a) could be used.

The data used in applying equation (9) are presented in table VII. The energy per profile reported in table VII is the average of all tests reported in reference 19, even the incomplete tests.

TABLE III. - POWER AND ENERGY FROM LABORATORY TESTS IN REFERENCE 1

SAE J227a schedule[a]	Test results profiles	Discharge energy per profile,[b] E_D/profile		Regeneration energy per profile,[b] E_R/profile		Net energy per profile,[b] (E_D-E_R)/profile		Average power,[b] $\bar{P}_D$, W	Energy limit,[b,c] E		Calculated profiles[d]
		KJ	W-H	KJ	W-H	KJ	W-H		MJ	W-H	
B$\overline{wo}$	424	8.89	2.47	----	-----	8.89	2.47	124	3.89	1080	437
B$\overline{w}$	500	8.89	2.47	1.31	0.365	7.60	2.11	124	3.89	1080	512
B'	374	8.89	2.47	----	-----	8.89	2.47	234	3.32	922	373
C$\overline{wo}$	187	18.47	5.13	----	-----	18.47	5.13	231	3.33	926	181
C$\overline{w}$	222	18.47	5.13	2.92	.810	15.55	4.32	231	3.33	926	214
C'	159	18.47	5.13	----	-----	18.47	5.13	485	2.69	746	145
D$\overline{wo}$	47	55.04	15.29	----	-----	55.04	15.29	431	2.75	764	50
D$\overline{w}$	55	55.04	15.29	7.20	2.00	47.84	13.29	451	2.75	764	57
D'	40	55.04	15.29	----	-----	55.04	15.29	706	2.26	629	41

[a] $\overline{wo}$ = without regeneration; $\overline{w}$ = with regeneration; prime = Same as Table II.

[b] Per 6-volt battery.

[c] Determined from figure 1(a).

[d] Eq. (9).

TABLE IV. - POWER AND ENERGY FROM LABORATORY TESTS IN REFERENCE 13

SAE J227a schedule[a]	Test results profiles	Discharge energy per profile,[b] E_D/profile		Regeneration energy per profile,[b] E_R/profile		Net energy per profile,[b] (E_D-E_R)/profile		Average power,[b] $\bar{P}_D$, W	Energy limit,[b,c] E		Calculated profiles[d]
		KJ	W-H	KJ	W-H	KJ	W-H		MJ	W-H	
D$\overline{wo}$	53	51.84	14.40	-----	----	51.84	14.40	425	2.80	779	54
D$\overline{w}$	71	51.37	14.27	10.04	2.79	41.33	11.48	421	2.81	781	68

[a] $\overline{wo}$ = without regeneration; $\overline{w}$ = with regeneration.

[b] Per 6-volt battery.

[c] Energy limit obtained from figure 1(a).

[d] Eq. (9).

TABLE V. - CURRENT AND CAPACITY FROM LABORATORY TESTS IN REFERENCE 14

SAE J227a schedule[a]	Test results profiles	Discharge capacity per profile, $(A\text{-}H_D)$/profile, A-H	Average current, $\bar{I}_D$, A	Capacity limit,[b] C, A-H	Calculated profiles[c]
B$\overline{wo}$	369	0.469	23	190	405
C$\overline{wo}$	184	.843	38	163	193
D$\overline{wo}$	49	2.69	79	130	48

[a] $\overline{wo}$ = without regeneration.
[b] Capacity limit determined from figure 1(b).
[c] Eq. (8).

TABLE VI. - CURRENT AND CAPACITY FROM TRACK TESTS

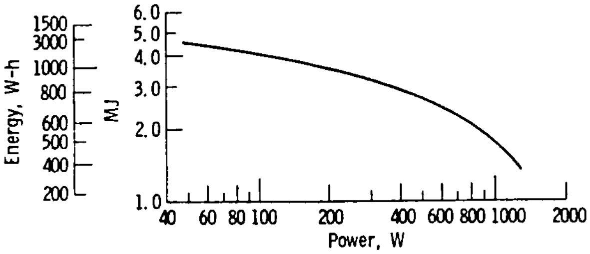
Reference	Vehicle identification	SAE J227a schedule[a]	Test results: Profiles	Test results: Capacity removed, A-H	Discharge capacity per profile, $(A\text{-}H_D)$/profile, A-H	Average current, $\bar{I}$, A	Capacity limit,[b] C A-H	Calculated profiles[c]
15	Change-of-pace	B$\overline{wo}$	133	140	1.05	53	140	133
		C$\overline{wo}$	83	127	1.53	69	133	87
16	Contractor	B$\overline{wo}$	152	167	1.10	55	145	132
		C$\overline{wo}$	66	132	2.00	90	125	63
17	DJ5-E	B$\overline{wo}$	173	284	1.64	82	298	182
18	R-5	B$\overline{wo}$	337	181	.537	27	181	337

[a] $\overline{wo}$ = without regeneration.
[b] Refer to text in Appendix A for Peukert Equation needed to calculate C@I.
[c] Eq. (8).

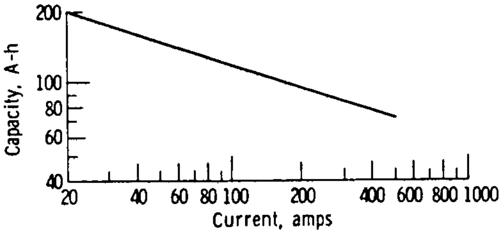
TABLE VII. - POWER AND ENERGY FROM TRACT TESTS IN REFERENCE 19 (RIPP-ELECTRIC)

SAE J227a schedule[a]	Test results profiles	Discharge energy per profile,[b] E_D/profile		Regeneration energy per profile,[b] E_R/profile		Net energy per profile,[b] (E_D-E_R)/profile		Average power,[b] $\bar{P}_D$, W	Energy limit,[b,c] E		Calculated profiles[d]
		KJ	W-H	KJ	W-H	KJ	W-H		MJ	W-H	
B$\overline{wo}$	326	10.66	2.96	----	-----	10.66	2.96	148	3.73	1037	350
B$\overline{w}$	364	10.66	2.96	1.21	0.336	9.45	2.62	148	3.73	1037	395
C$\overline{wo}$	171	18.72	5.20	----	-----	18.72	5.20	234	3.32	922	177
C$\overline{w}$	212	18.72	5.20	2.65	.735	16.07	4.47	234	3.32	922	206

[a] $\overline{wo}$ = without regeneration; $\overline{w}$ = with regeneration.
[b] Per 6-volt battery.
[c] Energy limit obtained from figure 1(a).
[d] Eq. (9).



(a) Ragone plot.



(b) Peukert plot.

Figure 1. - Performance limits of a 6 volt lead-acid battery.

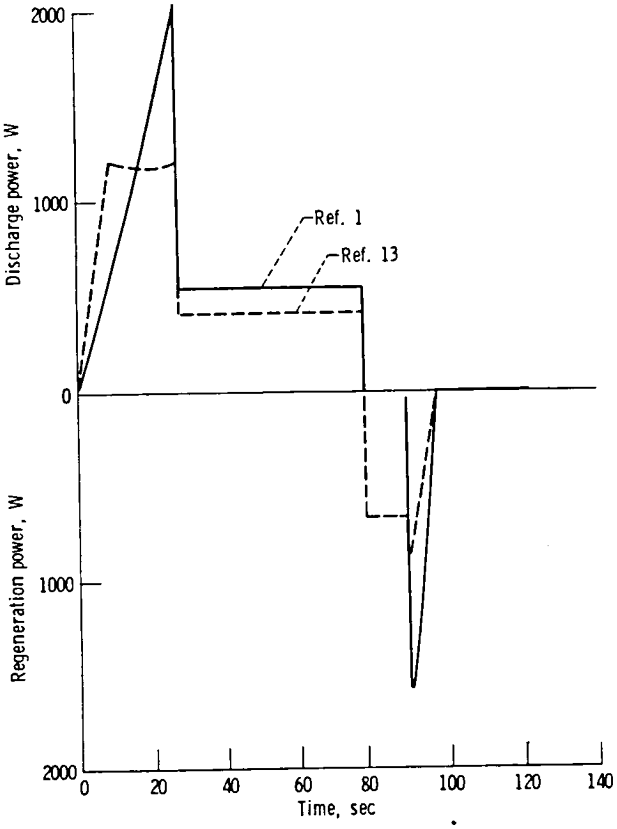


Figure 2. - Power-time profile for 6 volt golf car battery under SAE J227a "D" schedule.

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16. Abstract

A battery model is developed based on time averaging the current or power, and is shown to be an effective means of predicting the performance of a lead-acid battery. The effectiveness of this battery model was tested on battery discharge profiles expected during the operation of an electric vehicle following the various SAE J227a driving schedules. The averaging model predicts the performance of a battery that is periodically charged (regenerated) if the regeneration energy is assumed to be converted to retrievable electrochemical energy on a one-to-one basis.

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