A SIMPLE METHODOLOGY FOR OBTAINING BATTERY DISCHARGE TIMES (AND VEHICLE RANGES) FOR ARBITRARILY STRUCTURED LOAD PROFILES*

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Introduction

At the National Battery Test Laboratory (NBTL) at Argonne National Laboratory (ANL), an easily applied methodology has been developed that allows battery discharge times (and vehicle ranges) to be approximated for arbitrarily-structured profiles of battery discharge. The methodology uses a Ragone plot (W h kg^{-1} *versus* W kg^{-1} plot) and a peak power *versus* depth of discharge (D.O.D.) plot. Both plots, which are relatively simple, are obtained in the standard test program at the NBTL. The only knowledge required of the application load profile is the peak and average specific power demands on the battery; the detailed structure of the load profile is not essential.

The use of this methodology provides several benefits over the direct application of a power profile to the battery. First, discharge times can be estimated for a host of specific application requirements without having to apply specific discharge profiles to the battery. As a result, a great deal of testing cost can be avoided, and discharge times for specific applications can be assessed, even though applying such discharges may be inconvenient or impossible.

Second, the use of this methodology allows a check for consistency of a test involving the actual application of a specific discharge profile. If the results of a test do not agree with the estimate obtained by this methodology, reasons for the variance can be immediately explored.

Finally, this methodology offers a convenient tool for sensitivity analyses in determining the impact on battery discharge times of various peak and average power demands on the battery. Trade-offs become quickly evident, and an insight into the relationship between peak and average power characteristics of a battery is provided.

This methodology will be illustrated by three examples involving simulated profile discharges of batteries. Other supporting data will also be cited.

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Examples

The first example involves the use of the SAE J227aD driving schedule as negotiated by an Improved ETVI electric vehicle (IETV-1). The dashed curve in Fig. 1 is the velocity *versus* time profile corresponding to the driving schedule. In this schedule, the vehicle is required to accelerate from zero to 72 kph (45 mph) in 28 s, cruise at 72 kph for 50 s, decelerate and brake to a stop in 19 s, and rest for 25 s; after the total time of 122 s, the schedule repeats. The average velocity for this schedule is 47 kph (29.5 mph), and a vehicle travels ~1.6 km (~1 mi) during one cycle of the schedule. The solid line in the Figure represents the power required by a 488 kg battery in IETV-1 negotiating the indicated velocity schedule. During vehicle acceleration, a peak specific power of ~47 W kg^{-1} is required from the battery. During cruise at 72 kph, a specific power of ~15 W kg^{-1} is required; and during the deceleration and braking, when regenerative braking is provided, a pulse of power up to ~31 W kg^{-1} is available to charge the battery. For the purpose of the methodology described in this paper, the power profile in Fig. 1 can be characterized as having a peak specific power of 47 W kg^{-1} and an average specific power of 15 W kg^{-1} without regenerative braking (12 W kg^{-1} with regenerative braking).

At the NBTL, this power profile is precisely applied to batteries under test, and a projected range is determined either by the number of profiles that a battery can deliver before it is completely discharged or by the product of the discharge time and the average velocity of the driving schedule. The range of the vehicle, however, can be approximated by this methodo-

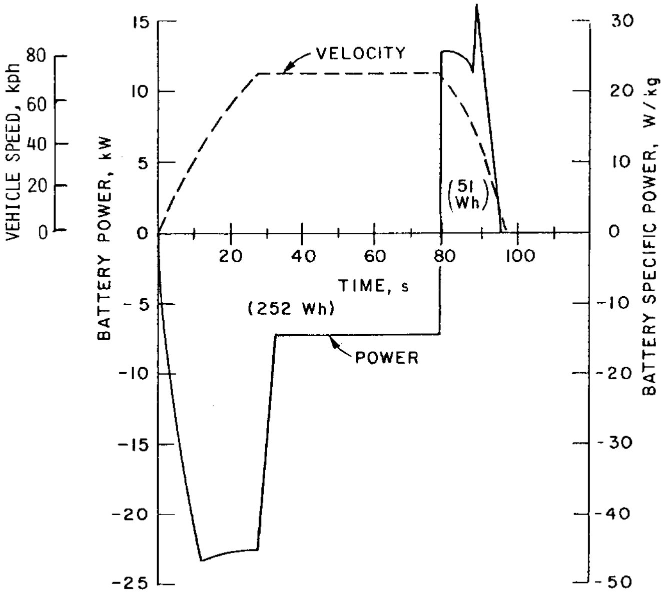

Fig. 1. Velocity *vs.* time schedule (— — —) for the SAE J227aD and the power (——) required by the IETV-1 to negotiate the velocity schedule.

logy, which combines the use of a Ragone plot and a peak power plot for the battery in the manner described below.

Figure 2 is a Ragone plot for the JCI EV2300 battery and shows the specific energy obtained as a function of the specific power level at which it is discharged. The plot has a vertical dashed line to represent the average specific power (15 W kg^{-1}) of the SAE J227aD/IETV-1 profile without regenerative braking. The corresponding specific energy is 34 W h kg^{-1}. The ratio of the specific energy to the specific power gives a discharge time as follows:

$$\frac{34\ \mathrm{W\ h\ kg^{-1}}}{15\ \mathrm{W\ kg^{-1}}} = 2.27\ \mathrm{h} \tag{1}$$

This discharge time is that expected if the battery did not become peak power limited before the discharge was completed. The extent to which the peak power capability of the battery limits the discharge time is obtained from Fig. 3, the plot of the specific peak power in W kg^{-1} as a function of D.O.D. for the EV2300 battery. The horizontal line at a specific power of 47 W kg^{-1} represents the envelope of the battery peak specific power demands of the SAE J227aD/IETV-1 profile. The line intersects the extrapolated peak power curve at a D.O.D. of ~93%. At this D.O.D., the battery is projected to fail to meet the peak power requirement of the profile, and the discharge would be terminated. Accordingly, the resultant discharge time is the product of the discharge time obtained from the Ragone plot and the D.O.D. at which the battery fails to deliver the peak power requirement, as follows:

$$\text{Resultant discharge time} = 2.27\ \mathrm{h} \times 0.93 = 2.1\ \mathrm{h} \tag{2}$$

Since the average velocity of the schedule is 47 kph, the resultant projected range is simply the product of the resultant time and the average velocity:

$$2.1\ \mathrm{h} \times 47\ \mathrm{kph} = 99\ \mathrm{km}\ (62\ \mathrm{miles}). \tag{3}$$

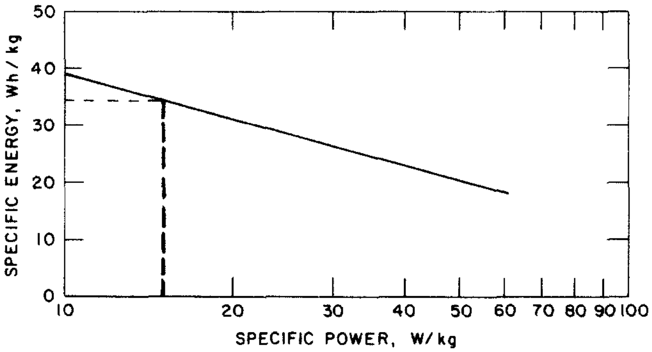

Fig. 2. Ragone plot showing specific energy as a function of specific power level of discharge for JCI EV-2300 modules. Vertical Dashed Line at 15 W kg^{-1} corresponds to the average power requirement of SAE J227aD/IETV-1.

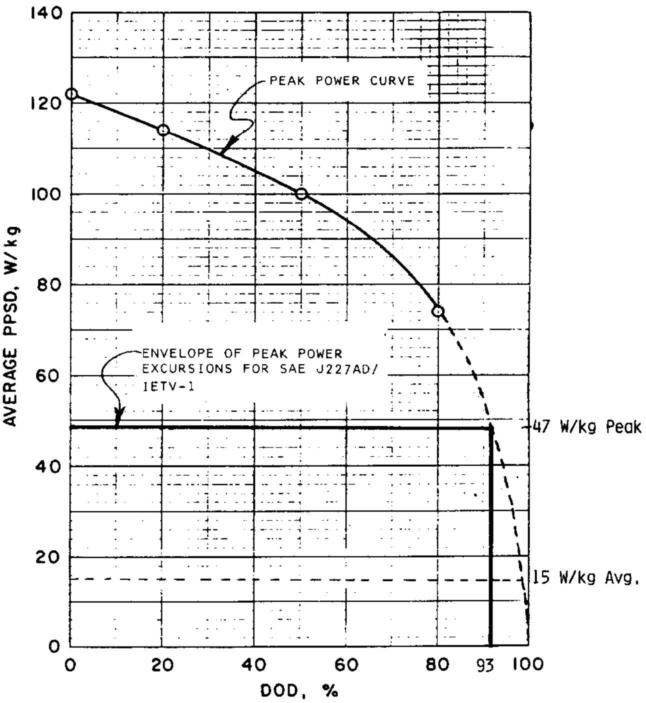

Fig. 3. Specific peak power (PPSD) *vs.* depth of discharge (D.O.D.) average for JCI EV-2300 modules with peak and average power requirements for the SAE J227aD/ IETV-1.

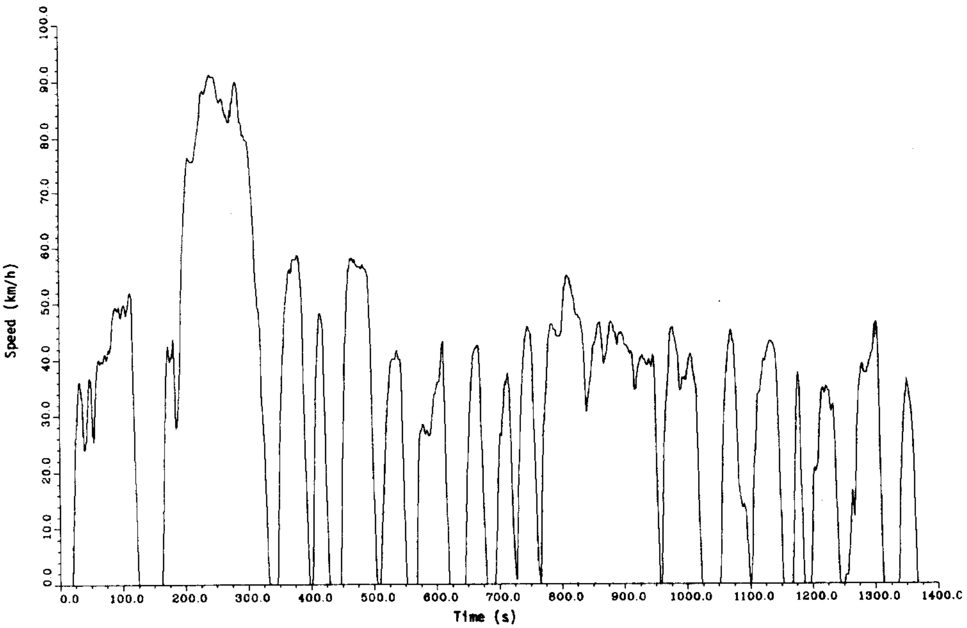

Fig. 4. Velocity *vs.* time schedule for the Federal Urban Driving Schedule (FUDS).

Application of the actual power profile to discharge the battery resulted in a range projection of 91 km.

In the above example, the peak to average power of the profile was a little over 3 to 1, and the impact of the peak power demand on the discharge time (obtained from the Ragone plot) resulted in only a seven percent reduction in range over the projection based upon the average power only. The next example involves a power profile having a peak to average power ratio of approximately 9 to 1, and the effect of peak power on discharge time is considerably greater.

The Federal Urban Driving Schedule (FUDS) is illustrated in Fig. 4. As can be seen, the profile is highly structured and has a long period of 1371 s (0.38 h). A single high velocity (>88 kph (55 mph)), preceded by a high acceleration, exists at approximately 200 s. The average velocity of the schedule is 31.4 kph (19.6 mph); therefore, a vehicle travels ~12 km (7.5 miles) before the schedule repeats. The battery power profile required, if the IETV-1 could traverse the FUDS, is illustrated in Fig. 5. This power profile is, of course, more structured than the velocity profile, and a reasonably sophisticated computer control system is required to apply the profile with strict fidelity. Note that near 200 s (the time of the high velocity point described above) a peak specific power of ~89 W kg^{-1} is required. Although high peak power is required in the profile, an average power of only ~9.9 W kg^{-1} is required; therefore, for the purpose of this methodology, the demands on the battery can be characterized as having a peak specific power of 89 W kg^{-1} and an average specific power of 9.9 W kg^{-1}.

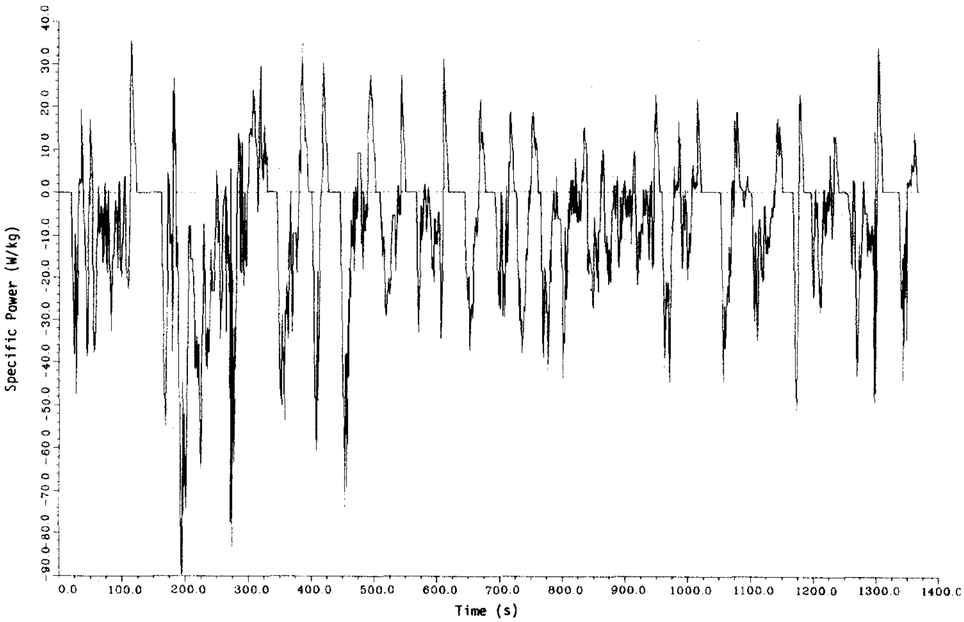

Fig. 5. Power *vs.* time profile required of the IETV-1 to negotiate the FUDS in Fig. 4.

As in the previous example, an estimate of the range of the IETV-1 equipped with the EV2300 battery, but negotiating the FUDS, starts with the Ragone plot for the battery. This plot is reproduced in Fig. 6, with a vertical line corresponding to the 9.9 W kg^{-1} average specific power requirement of the FUDS/IETV-1. This line intersects the plot at 38 W h kg^{-1}, the specific energy expected for a discharge at this specific power level. The ratio

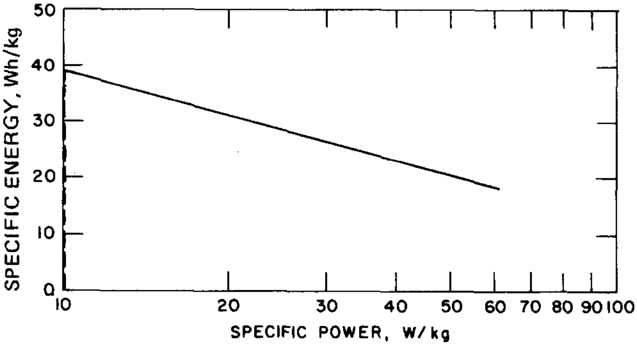

Fig. 6. As for Fig. 2, except with a vertical dashed line at 10 W kg^{-1} (~9.9) corresponding to average power requirement of the FUDS/IETV-1.

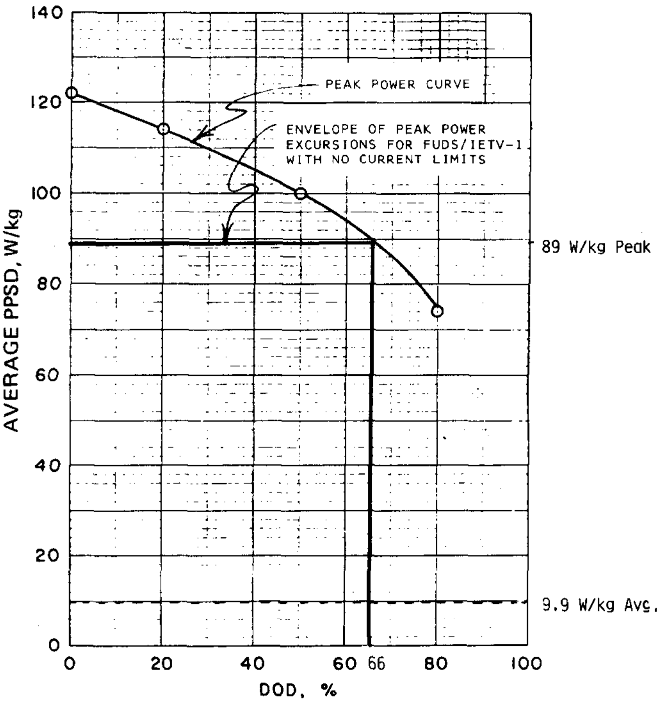

Fig. 7. As for Fig. 3, except with peak and average power requirements for the FUDS/ IETV-1 with no current limits.

of this specific energy to the specific power yields an expected discharge time of

$$\frac{38 \text{ W h kg}^{-1}}{9.9 \text{ W kg}^{-1}} = 3.84 \text{ h} \tag{4}$$

if the battery is not peak power limited. The extent to which the peak power limits the battery is determined, as before, from the peak power *versus* D.O.D. curve, reproduced in Fig. 7, with a horizontal line at 89 W kg^{-1} corresponding to the peak specific power of the FUDS/IETV-1. This line intersects the peak power plot at a D.O.D. of 66%, which is the point at which the discharge will be terminated because the battery can no longer supply the peak power demand. As before, the resultant discharge time is the product of the time from the Ragone plot and the D.O.D. from the peak power plot as follows

$$\text{Resultant discharge time} = 3.84 \text{ h} \times 0.66 = 2.53 \text{ h} \tag{5}$$

The resultant time multiplied by the average velocity of the schedule yields the projected range as follows:

$$2.53 \text{ h} \times 31.4 \text{ kph} = 79.4 \text{ km (49.7 miles)}. \tag{6}$$

Discharging the battery directly with the FUDS/IETV-1 power profile yielded a projected range of 84.8 km ± 12 km.

(The ±12 km deviation in range results from the one high peak power demand during the driving schedule. If the battery can provide this power peak, it can always comply with the remaining power demands of the profile. As a result, the discharge will generally be terminated by the peak power point of 89 W kg^{-1}, which occurs only once every 12 km. Hence, the range results are quantified by this value.)

The final example discussed is a variation of the previous example and shows the value of this methodology as a tool for evaluating the impact on range when the peak power demand is varied. In this case, the current is limited electronically to values less than 400 A. Under this condition, IETV-1 cannot actually negotiate the FUDS except on a "best effort" basis, but this approach is commonly used when any vehicle cannot meet the demanding peak acceleration and velocity requirements of the FUDS.

With the 400 A limitation, the average power requirement is reduced slightly to 9.7 W kg^{-1} from the 9.9 W kg^{-1} in the previous example. Since the change in average power demand is small, the same expected duration of discharge of 3.84 h from the Ragone plot will be used for the purpose of this example.

The impact of the peak power on the expected duration of the discharge is depicted in Fig. 8. (Since the peak current is limited to a fixed value the envelope of the peak power demand slopes as the voltage declines during the discharge.) The intersection with the peak power curve occurs at a D.O.D. of 88%. Accordingly, the resultant discharge time is

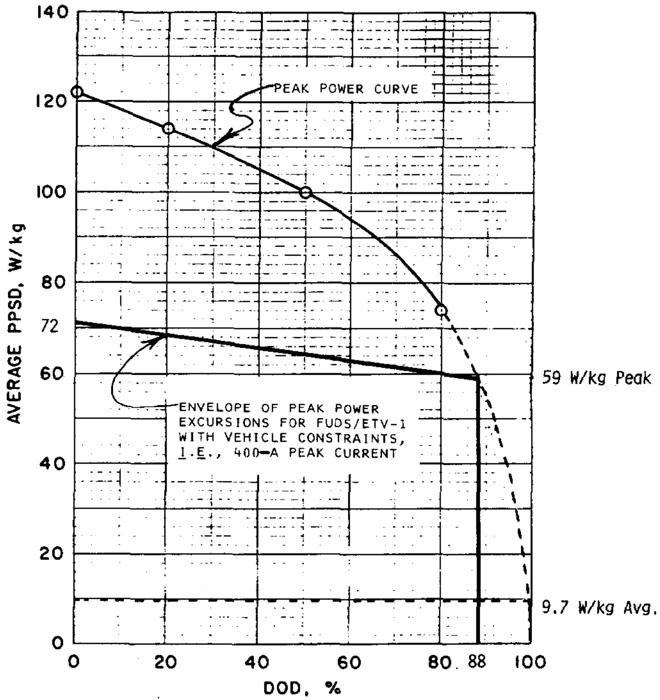

Fig. 8. As for Figs. 3 and 7, except with the peak and average power requirements for the FUDS/IETV-1 with currents limited to values less than 400 A.

$$3.84 \text{ h} \times 0.88 = 3.38 \text{ h} \tag{7}$$

and the estimated range is

$$3.38 \text{ h} \times 31.4 \text{ kph} = 106 \text{ km (66 miles)} \tag{8}$$

Hence, as a result of a drop in the peak power demand, an increase in range from 79.4 km to 106 km (34%) over the previous illustration is projected, even though practically no change in average power demand occurred.

Direct application of the simulated load profile without regenerative braking was not undertaken; however, the profile with regenerative braking was applied, with the following result compared with that projected by this methodology:

Range with regenerative braking (km)	
By this methodology	By applying profile
126 (79 miles)	133 ± 12 (83 ± 7.5 miles)

Again the values are in good agreement, and one would expect similar agreement for the case without regeneration braking.

TABLE 1

Additional supporting data for Ragone, peak power methodology

IETV-1 Battery & schedule	Required specific power (W kg^{-1})		Expected duration (h) of discharge at avg power (from Rag. Plot)	×	Percent available D.O.D. at required peak power (from PP Plot)	×	Average velocity (kph)	=	Range (km)	
	Avg	Peak							Estimate*	Measured**
EPI Ni/Fe SAEJ227aD	15	47	44/15 = 2.93	×	0.92	×	47	=	127	126
GM/DR Ni/Zn SAEJ227aD	15	47	53/15 = 3.5	×	0.98	×	47	=	161	147
GM/DR Ni/Zn FUDS	9.9	89	54/9.9 = 5.45	×	0.97	×	31	=	164	NA†

*Using methodology of this paper.

**By directly applying power profile to battery.

†Not available.

Table 1 cites additional results of the application of the method to Ni/Fe and Ni/Zn batteries. Column 1 lists the battery and the driving schedule. Columns 2 - 5 list the values used in the calculations. For comparison, the last two columns contain the range as estimated from this methodology, and from that obtained directly by applying the simulated profile to the battery. Unfortunately, for the case of the GM/DR Ni/Zn battery with the FUDS, no data are available for the range measured directly with the simulated profile; however, a representative of Delco Remy indicated that, in their experience, a vehicle with their Ni/Zn battery achieved almost the same range in negotiating the FUDS as in negotiating the SAE J227aD schedule. The reason for the similarity in ranges under the two different schedules is that the Ni/Zn battery is not highly sensitive to peak power demands, and the decrease in average power requirements of the FUDS nearly compensates for the increased peak power demands. Other battery systems tend to suffer greater impacts from peak power demands.

Discussion

Good agreement is evident between the results obtained by the use of this methodology and those obtained by direct application of discharge profiles. This agreement suggests that, as far as a battery is concerned, the dominant characteristics of an application requirement are the peak and average power demands. The detailed structure of the power profile appears to be of secondary importance. Hence, discharge times (and vehicle ranges) may be estimated simply from these two parameters and the peak and average power characteristics of a battery.

In those cases where the peak to average power level is high, a battery will fail at an early D.O.D. because of peak power limitations. In the NBTL, when a profile with high-peak-to-average power is applied and the end of discharge occurs, constant power discharges are often continued beyond that point at the average power level of the profile to measure the energy remaining in the battery. In all cases, the energy remaining in the battery, in addition to that obtained during the profile, is very close to that projected from the Ragone plot, without the peak power adjustment. In other words, under the high-peak-to-average power requirement, a great deal of energy may be left in a battery when it fails to meet the power demands of the application, and the amount of residual energy can be predicted by using this methodology. This observation suggests that a useful and rational definition of depth of discharge for a battery may be as follows:

$$\text{D.O.D.} = \frac{\text{Energy obtained from battery under any discharge condition}}{\text{Energy available from battery under the corresponding average power conditions}}$$

Such a definition recognizes that, with load profiles having high-peak-to-average power requirements, only a fraction of the available energy may be used. As such, the impact of the power demands on battery operation are clearly and meaningfully manifested by this definition.

Conclusion

As illustrated in this paper this methodology can be used to estimate battery discharge times (and vehicle ranges) for various applications having a range of peak and average power requirements. Also, a consistency check can be provided for tests involving the application of a discharge profile to a battery. In the field, if the peak and average demands on the battery can be measured for actual use patterns, an estimate of the range expected from a battery can be compared with that achieved. If these results are different, the reasons can be investigated so that vehicles can provide more nearly the ranges expected.

The methodology is simple to apply and lends itself to projecting discharge times for a host of application requirements. The only knowledge required of the application is its peak and average power demands. As a result, a multitude of missions can be analyzed conveniently without having to subject a battery to the actual requirements.

Finally, this methodology is a useful tool for sensitivity analyses when the impact on discharge time of various peak and average power demands can be quickly and economically assessed. Consequently, the importance of Ragone and peak power plots in characterizing a battery is made clear.

Acknowledgements

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