AUTONORMALIZATION OF BATTERY TEST DATA TO SIGNIFICANTLY REDUCE IMPACT OF BATTERY AGING ON TEST RESULTS*

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Batteries show varying rates of capacity decline as they are charged and discharged cycled (see Fig. 1). As a consequence, data from any test implicitly contain an effect of cycle history, which may be different for each battery at the time that a test is conducted. Batteries, alike in all other respects, may yield different results when subjected to the same test simply because of a difference in history. Similarly, an identical test applied to the same battery at different times in its history may yield different results. A method of normalization employed at the National Battery Test Laboratory, called "autonormalization", can be used to adjust, or normalize, test results to the original capacity, the rated capacity, or any point of reference for the battery. The use of this methodology effectively eliminates the effect of

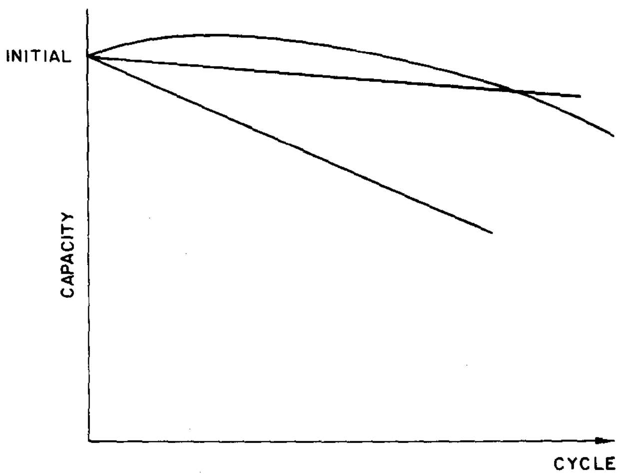

Fig. 1. Capacity as a function of cycle life for three different types of batteries.

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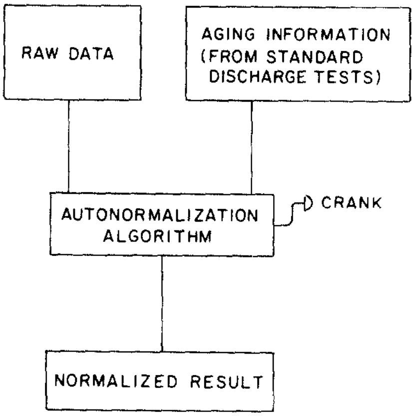

Fig. 2. "Cranking" raw data and aging information through autonormalization algorithm provides normalized result.

aging on the test results. As a consequence, improvements in the reproducibility of test results are achieved, and more meaningful and rational comparisons among, and within, battery types can be made.

As illustrated in Fig. 2, raw data combined with aging information (obtained from a standard discharge test) are "cranked" through the autonormalization algorithm to obtain normalized results virtually free of aging effects. The autonormalization algorithm (with normalization to rated capacity) is as follows:

$$\text{Normalized Result} = \text{Prevailing Raw Result} \times \frac{\text{Rated Capacity}}{\text{Prevailing Capacity}}$$

where:

the normalized result is virtually free of aging effects;

the prevailing raw result is the apparent result from a given measurement;

the rated capacity is the point to which normalization is desired;

the prevailing capacity is the capacity measured at a standard rate (*e.g.*, $C_3/3$ h rate) on a cycle closely following the prevailing test; and

the term $\frac{\text{Rated Capacity}}{\text{Prevailing Capacity}}$ is defined as the "normalization factor".

The use of this algorithm assumes that all other test conditions, such as charging and operating temperature, are consistent.

The first example in the use of the autonormalization methodology is illustrated in Table 1. Data were obtained from an Ni/Fe battery module that was being characterized to determine its available specific energy (W h/kg) as a function of the specific power level (W/kg) applied on discharge. Constant power discharges at 15 W/kg and 30 W/kg were applied on cycle 26 (2 September 1979) and on cycle 52 (18 October 79), respectively. The

TABLE 1

Specific energy as a function of specific power for an Ni/Fe module rated at 220 A h

Cycle number	Date	Specific power level of discharge (W/kg)	Raw specific energy (W h/kg)	Prevailing capacity* (A h)	Normalization factor (A h/A h)	Normalized specific energy** (W h/kg)
26	02 Sept 79	15	47.5	211	$\frac{220}{211}$	49.5
52	18 Oct 79	30	42.8	213	$\frac{220}{213}$	44.2
270	21 Feb 80	10	37.9	160	$\frac{220}{160}$	52.1
275	23 Feb 80	20	35.1	160	$\frac{220}{160}$	48.3
278	28 Feb 80	30	32.6	160	$\frac{220}{160}$	44.8

*Measured during a separate $C_3/3$ h discharge performed on a following cycle.
**Normalized to the 220 A h capacity of the module.

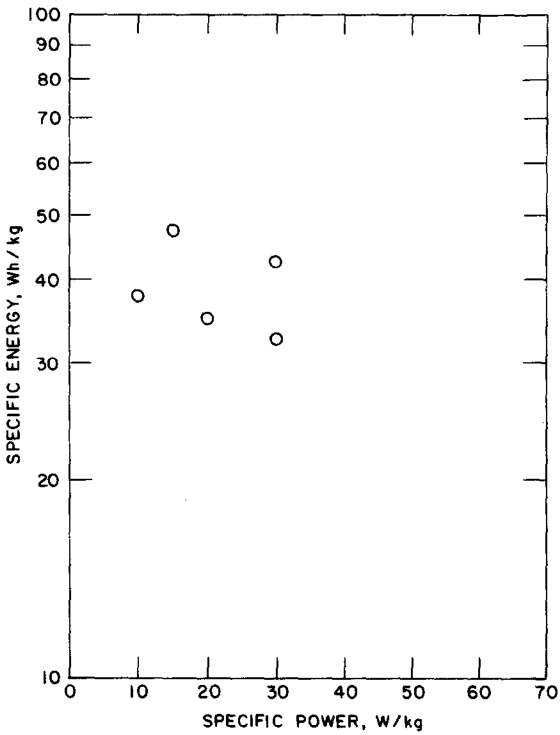

Fig. 3. Specific energy as a function of specific power obtained from a Ni/Fe module. (Data are not normalized.)

discharges yielded corresponding raw specific energies of 47.5 and 42.8 W h/kg, listed in column 4. The prevailing capacities, listed in column 5, were measured for $C_3/3$ h discharges on a cycle following the test cycles 26 and 52. These capacities are only slightly less than the rated capacity of the module; therefore, the normalization factors in column 6 are not far from unity. Application of the normalization factors to the raw data in column 4 yields normalized specific energies of 49.5 W h/kg for cycle 26 and 44.2 W h/kg for cycle 52 listed in the last column.

Later in the test program, at cycles 270, 275, and 278, constant power discharges of 10, 20, and 30 W/kg were applied. The raw results given in column 4 were obtained. Note, in particular, that the raw result for 30 W/kg on cycle 278 is considerably less than that obtained on cycle 52. The prevailing capacity of the module on a cycle following the 30 W/kg measurement was found to be 160 A h, listed in column 5. The 160 A h result indicates that the capacity of the battery at this point had declined to less than 73% of rated. Adjusting the raw result by a factor of 220 A h/160 A h (column 6) yields the normalized specific energy of 44.8 W h/kg for cycle 278, which compares favorably with the normalized 44.2 W h/kg obtained on cycle 52. One expects that the remaining normalized points can be meaningfully compared as well, as next illustrated.

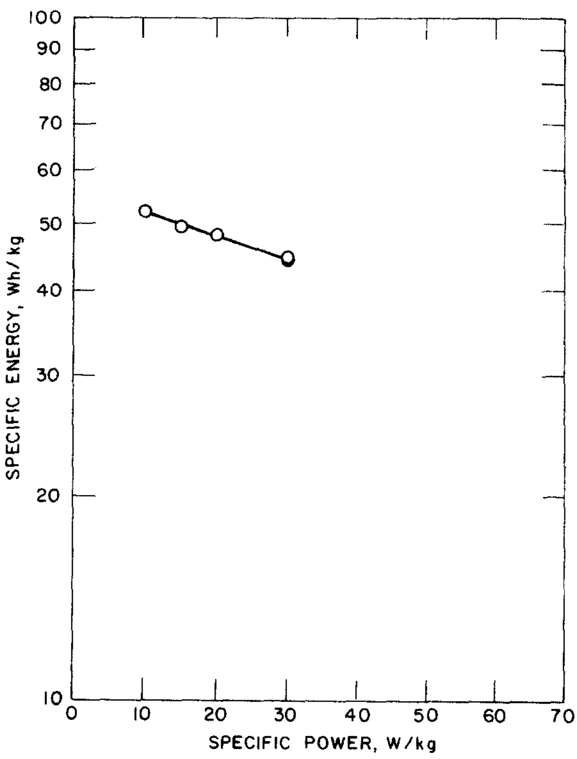

Fig. 4. Normalized version of data shown in Fig. 3.

Figure 3 shows a plot of specific energy as a function of specific power for the raw (un-normalized) data of column 4 in Table 1. This plot shows the scatter in the data due to the aging of the battery. One might question whether these measurements were from the same battery. Figure 4 shows the normalized specific energy (column 7) as a function of specific power. These measurements, which take into account aging effects, appear to be from the same battery and are self-consistent. One could consider this plot to be a characterization of the specific energy as a function of specific power based upon, or normalized to, the rated capacity of the battery.

In a similar manner, specific energy as a function of specific power was measured for three separate Ni/Zn battery modules of the same design from the same developer. The raw data are plotted in Fig. 5. These data make it appear that the modules are different; however, normalization of the data from this Figure resulted in the plot in Fig. 6. The plot shows that the battery modules are comparable in performance when the effects of aging are eliminated by the autonormalization process.

In one final example, normalized test results for projected electric vehicle (EV) range are tabulated in Table 2. In this case, simulated driving profile discharges were applied at two different times in the life of a lead–

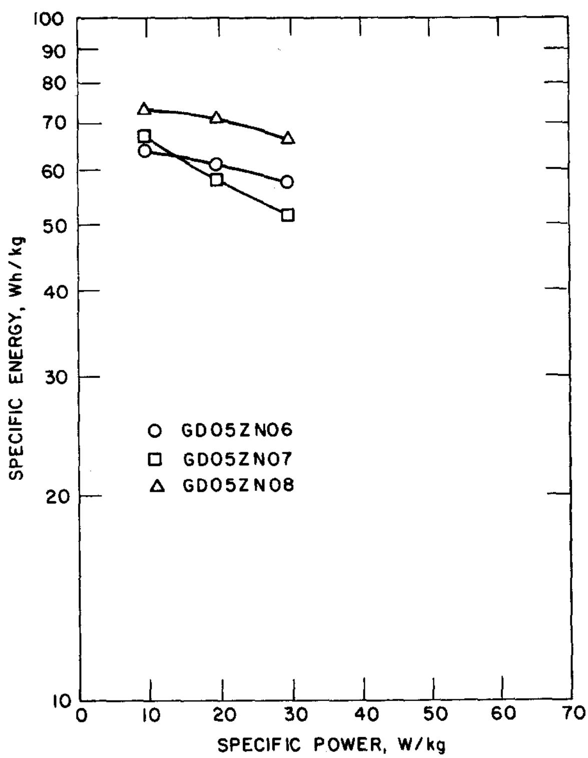

Fig. 5. Specific energy as a function of specific power for three Ni/Zn modules. (Data are not normalized.)

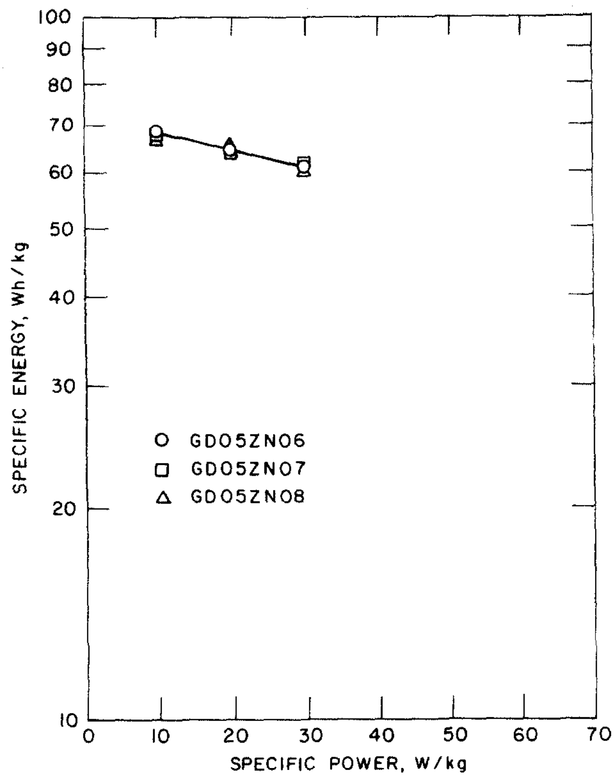

Fig. 6. Normalized version of data shown in Fig. 5.

TABLE 2

Projected EV range obtained at two different points in cycle life for a lead–acid battery module rated at 249 A h

Cycle number	Date	Raw projected range (km)	Prevailing* capacity (A h)	Normalization factor (A h/A h)	Normalized projected range** (km)
71	30 Jul 79	122	240	$\frac{249}{240}$	127
199	24 Oct 79	78	152	$\frac{249}{152}$	128

*Measured during a separate $C_3/3$ h discharge performed on a following cycle.
**Normalized to the 249 A h rated capacity of the module.

acid battery rated at 249 A h. At cycle number 71, on 30 July 1979, the discharge yielded a projected range of 122 km (un-normalized). The prevailing capacity of the battery measured during a $C_3/3$ h discharge on a cycle following cycle 71 was 240 A h. Therefore, the projected range normalized to the rated 249 A h capacity was (249/240) × 122 km, or 127 km. At cycle number 199, on 24 October 1979, the simulated driving profile discharge was repeated. A range of only 78 km, based upon the raw data, was obtained; however, the prevailing capacity of the battery at the $C_3/3$ h rate had declined to 152 A h. Therefore, the projected range normalized to the 249 A h rated capacity of the battery was (249/152) × 78 km = 128 km, in very good agreement with the normalized range of 127 km achieved on cycle 71. Hence, even though a capacity change of about 40% had occurred, the results of the simulated driving profile tests are meaningfully comparable.

The methodology is particularly beneficial when a series of parametric variation tests is conducted to measure small changes in battery capacity. Such a case was the measurement of the impact of pulsed discharge frequency and duty cycle upon the capacity of a battery. In many cases, without autonormalization, the effects of battery aging had a greater impact on the test result than the parameter being varied. Accordingly, test results were affected by the order in which the tests were conducted. The use of autonormalization was essential to obtain consistent results independent of the order in which the tests were applied.

In conclusion, the use of autonormalization is essential to a test program because it significantly reduces the influence of battery aging on the test results. The following three improvements are possible with autonormalization:

(i) results are independent of the order in which tests are conducted;

(ii) data are self-consistent;

(iii) more meaningful comparisons among, and within, battery types are obtained.

Acknowledgements

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