TEST PROGRAMS AT THE NATIONAL BATTERY TEST LABORATORY*

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Introduction and background

The National Battery Test Laboratory (NBTL) was established at Argonne National Laboratory (ANL) in 1976 as a facility for studying advanced electric storage batteries. The facility tests batteries developed under Department of Energy (DOE) programs and for private sponsors. The batteries tested are for utility load leveling, propulsion of electric and hybrid vehicles (EHVs), solar energy storage, and other related applications.

The NBTL serves five key roles in battery development programs:

(i) It serves as a facility for testing cells and batteries at various stages of development.

(ii) It provides a centralized and independent facility for comparing and evaluating the performance of various types and brands of batteries under uniform operating conditions.

(iii) It permits the testing of battery performance under simulated operating conditions before field demonstration.

(iv) It provides data for battery analyses and improvement.

(v) It serves as a facility for battery charge, discharge, and thermal studies.

Almost concurrently with the establishment of the NBTL, DOE formed the National Battery *ad hoc* Advisory Committee (NBAC) to provide advice on various matters pertaining to battery development. The NBAC comprised representatives from battery developers, battery users (including electric utilities and manufacturers of electric vehicles), the Electric Power Research Institute, academia, national laboratories, and governmental laboratories. The Standards and Specifications Subcommittee of the NBAC provided advice on standard tests for batteries. The bulk of the tests in the standard test program at the NBTL were formulated with the aid of this subcommittee.

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In 1983, DOE appointed a working task force for EHV battery tests, comprising DOE-supported personnel directly involved with battery and vehicle testing and evaluation. This task force has supplemented the standard tests that were developed with the aid of the NBAC, which was dissolved in 1984.

The objectives of the standard test program at the NBTL are as follows:

(i) To determine and document the capabilities of batteries over a spectrum of meaningful test conditions.

(ii) To track the progress in battery development programs.

(iii) To provide data for battery analyses and modeling.

In addition to these objectives, the standard test program serves as the foundation for further investigations involving special tests, parametric studies, and post-test analyses of batteries. Problems uncovered during the standard test program are explored in a more focused manner during these

TABLE 1

Standard tests performed at NBTL

Item no.	Type of test	Purpose
1	Capacity at $C_3/3$ h rate	Capacity verification or baseline capacity check.
2	Capacity at 10, 20, 30, 40, 50, 60 W kg^{-1}	To provide data for Ragone plot, which, in conjunction with the peak power *vs.* depth-of-discharge (DOD) data below, can be used to project EV range in general.
3	Peak power *vs.* DOD	To measure capability of battery at various DOD to deliver power for vehicle acceleration or other power demands.
4	Range on SAE J227aD/ IETV-1 with and without RB	To project range of an electric vehicle (IETV-1) under the SAE J227aD urban driving condition and to measure the impact of regenerative braking (RB) on vehicle range.
5	Sustained hill-climb test	To determine maximum DOD at which a battery will provide a specified power level sustained for a given period of time.
6	Capacity at low temp. & capacity at elev. temp.	To assess general temperature sensitivity of battery system.
7	Self-discharge rate	To assess energy loss suffered by a battery during prolonged stand periods.
8	Partial DOD test series	To uncover any apparent "memory" effects.
9	Life at 80% DOD	To project cycle life under deep discharge conditions.
10	Determination of Coulombic Eff., Energetic Eff., Thermal Behavior	Self-explanatory — measured under different conditions.

special tests and studies. Such studies involve, for example, determining the impact of temperature on battery cycle life; the effect of pulsed current discharges on battery performance, life, and internal morphology; and equivalent circuit models for the internal inductance and resistance of batteries.

Standard tests at NBTL

The standard tests in use at the NBTL are listed in Table 1 along with a brief statement of purpose for each test.

Item 1 is a capacity verification test at the $C_3/3$ h rate. As explained in my paper later in this session, this test is also repeated periodically during a test program to provide baseline capacity data for normalizing the test data.

During the tests in item 2, watt-hour and ampere-hour capacities are determined for discharges at various levels of constant specific power. Plotting the specific energy obtained from a battery as a function of the specific power upon discharge results in Ragone curves, as illustrated for various battery systems in Fig. 1. As explained in my paper in Session 5, a Ragone plot, in conjunction with the peak power plot described next, can be

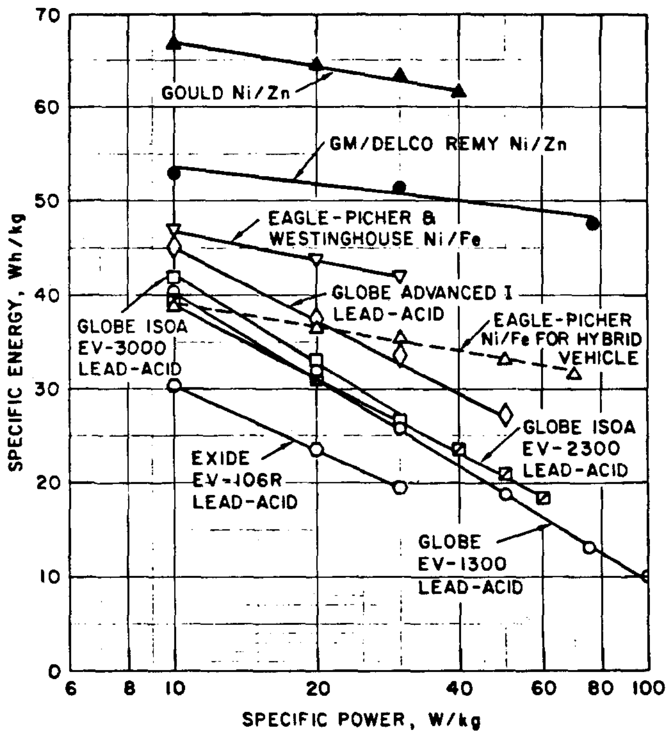

Fig. 1. NBTL-derived Ragone plot showing specific energy as a function of specific power level of discharge for several types of aqueous mobile batteries.

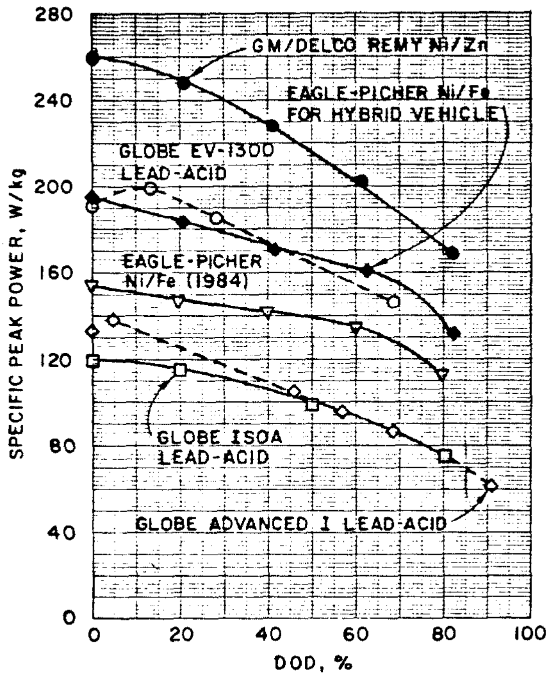

Fig. 2. Specific peak power as a function of depth of discharge (DOD) for several types of aqueous mobile batteries as measured in the NBTL.

used to project discharge times (and vehicle ranges) for virtually any type of discharge load profile.

Item 3 is used to measure the capability of a battery to deliver peak power at various DODs. Examples of peak power *versus* DOD curves for various types of batteries are plotted in Fig. 2. Such plots can also be used for determining the relative DOD at which a battery will fail to provide a required power demand.

Item 4 measures the range of the improved ETV-1 electric vehicle (IETV-1), with and without regenerative braking, negotiating the SAE J227aD urban driving schedule. Results from such simulated power profile discharges for various types of batteries are given in Fig. 3. As shown in my paper in Session 5, these range projections can be estimated by the combined use of the Ragone and peak power curves.

Item 5 is a sustained hill-climbing test to determine at what DOD a battery can support a discharge at a specific power of 45 W kg^{-1}, which approximates the power level required to sustain the IETV-1 at 48 kph (30 mph) on a 6% grade. A typical result from this test is illustrated in Fig. 4. The dashed line at six minutes indicates that this battery could support a six-minute sustained hill climb (or power demand of 45 W kg^{-1}) at any DOD up to 67%.

Item 6 is an exploratory test to assess the temperature sensitivity of battery capacity.

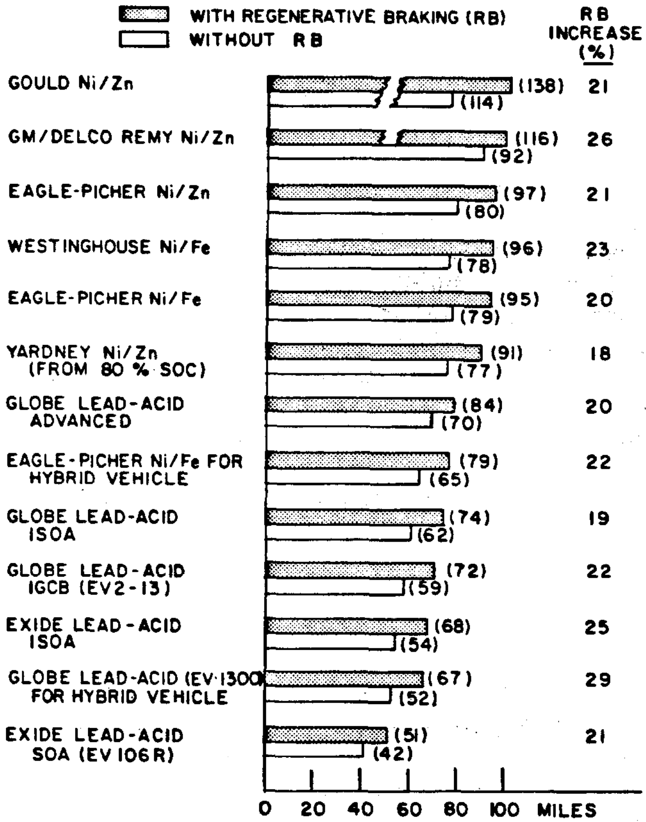

Fig. 3. Projected number of miles traveled in one complete discharge of a 488 kg battery powering the IETV-1 electric vehicle performing the SAE J227aD urban driving schedule.

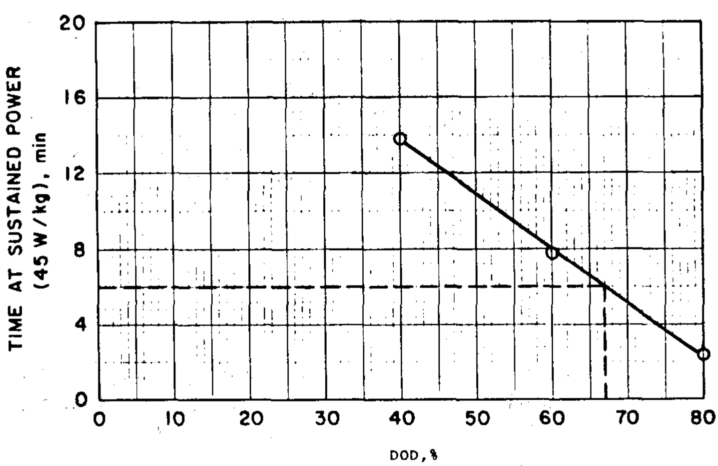

Fig. 4. Sustained hill-climbing power test for Globe EV-2300 lead–acid modules.

Item 7 is a simple measure of the amount of capacity loss incurred by a battery if left standing for a period of about one week on open circuit after charge.

Item 8 is another simple exploratory test to uncover any apparent "memory" effects of a battery. A memory effect occurs if a battery is used at a fraction of its nominal capacity for a period of time and fails to immediately provide its nominal capacity when 100% DOD is attempted. This standard test consists of a series of six discharges at 50% DOD followed by a DOD of 100%. The number of cycles required for a battery to achieve within one percent of its nominal capacity is noted.

Should any unusual behavior be discovered in the tests for items 6 - 8, a more extensive test program is initiated to fully investigate this behavior.

Item 9 determines the cycle life for batteries discharged to 80% DOD. Generally, the discharge is performed at the $C_3/3$ h rate; however, life cycle testing on some systems is performed at the $C_2/2$ h rate, at constant power rates, or under simulated driving profiles.

Item 10 lists just three of the many parameters that are routinely measured and quantified during NBTL testing.

Discussion

The above is a brief description of the standard test program at the NBTL. During the eight years that this program has been in effect, the procedures have been modified, and continue to be modified, to meet the needs of the DOE battery development programs. Industrial sponsors may have unique testing requirements; however, the standard test program serves as a useful basis for developing their test programs.

These test procedures have worked well. Together with scaling and normalization techniques developed at the NBTL, the standard tests have allowed accurate projections to be made of battery performance for different applications. In Fig. 5, a comparison is made between NBTL projections of vehicle range and range achievements for batteries tested in a vehicle (at the Jet Propulsion Laboratory) over various types of driving conditions. The data above 30 mph are for constant velocity; below 30 mph, data for the SAE J227 a C and D schedules are indicated at their approximate average velocities. As can be seen, the agreement between the calculated and achieved ranges is quite good.

Conclusion

The standard test procedures described in this paper are useful to:
(i) assess the capabilities of batteries over a variety of test conditions,
(ii) track the progress of battery development programs, and
(iii) provide data for battery analyses and modeling.

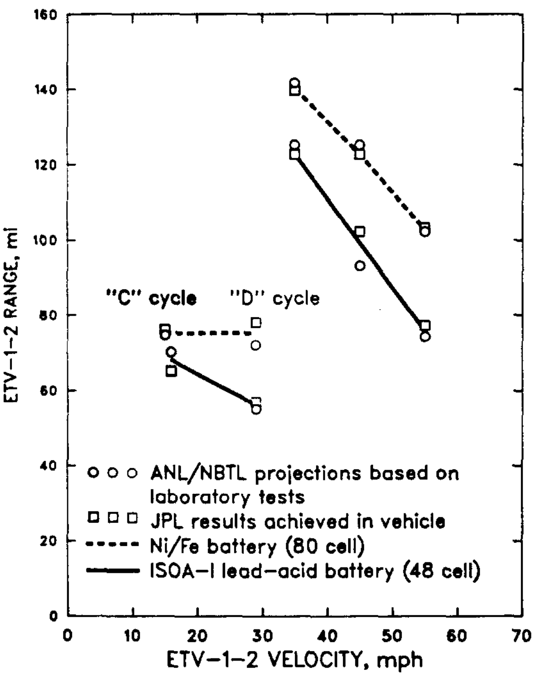

Fig. 5. ETV-1 vehicle range projections based on NBTL test results, compared with range achieved in vehicle on dynamometers at JPL.

In addition, data on battery performance garnered in this test program have been used to accurately project battery performance in an intended application.

Acknowledgements

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