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Key Results of Battery Performance and Life Tests at Argonne National Laboratory

W. H. DeLuca, K. R. Gillie, J. E. Kulaga, J. A. Smaga,
A. F. Tummillo, and C. E. Webster

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Chemical Technology Division
Electrochemical Technology Program
Argonne National Laboratory
Argonne, IL 60439

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ABSTRACT

Advanced battery technology evaluations are performed under simulated electric vehicle operating conditions at Argonne National Laboratory's & Diagnostic Laboratory (ADL). The ADL provides a common basis for both performance characterization and life evaluation with unbiased application of tests and analyses. This paper summarizes the performance characterizations and life evaluations conducted in 1991 on twelve single cells and eight 3- to 360-cell modules that encompass six battery technologies (Na/S, Li/MS, Ni/MH Zn/Br, Ni/Fe, and Pb-Acid). These evaluations were performed for the Department of Energy, Office of Transportation Technologies, Electric and Hybrid Propulsion Division. The results measure progress in battery R&D programs, compare battery technologies, and provide basic data for modeling and continuing R&D to battery users, developers, and program managers.

INTRODUCTION

The Analysis & Diagnostic Laboratory (ADL), established at Argonne National Laboratory (ANL) by the Department of Energy (DOE) in 1976, is a facility for studying advanced battery systems. It includes a versatile computer-operated test laboratory to conduct battery evaluations, under simulated application conditions and a post-test analysis laboratory to determine, in a protected atmosphere if needed, component compositional changes and failure mechanisms. The ADL evluates battery systems using standardized tests and analyses on a common, unbiased basis. The experimental data and their analyses, in combination with post-test examinations of these advanced battery systems, help identify factors that limit system performance and life and the most-promising R&D approaches for overcoming these limitations.

The ADL facilities have been used to evaluate battery systems of various types and sizes for DOE, Electric Power Research Institute (EPRI), and private industry. Over 3000 cells, ranging from individual 4-Wh cells to 360-cell, 22-kWh batteries and representing 12 battery technologies from over 18 developers, have undergone performance characterizations and life evaluations for load-leveling, electric vehicle (EV) propulsion, and standby power applications.

During 1991, EV battery evaluations were performed for the DOE Office of Transportation Technologies, Electric and Hybrid Propulsion Division (OTT/EHP). Performance characterizations and/or life evaluations were conducted on eight modules and twelve cells representing six battery technologies (Na/S, Li/MS, Ni/MH Zn/Br, Ni/Fe, and Pb-Acid) from seven battery developers. The evaluations performed and results obtained are discussed below.

STANDARDIZED AND SPECIAL TESTS

Standardized tests have been developed to characterize the performance of batteries for EV propulsion applications. Performance characterization includes the verification of rated capacity and the measurement of (1) available energy vs. constant-current (CI) and constant-power (CP) discharge (DOD) for acceleration capability, (3) self-discharge losses vs. stand time, (4) sustained hill-climbing capability, and (5) projected ranges for various vehicles and driving schedules. All of the standardized performance and life tests are conducted on mature technologies, but only subsets of these tests are used on research cells because a shorter life and/or limited performance is anticipated. Life testing is typically conducted with 100% capacity discharges with a simulated driving power profile. The driving profiles used in these performance characterizations and life evaluations include:

1. Simplified Federal Urban Driving Schedule (SFUDS) for the improved van of the Dual System Electric Propulsion (DSEP) Program (SFUDS/IDSEP)
2. SAE J227aC urban driving schedule for the General Motors G-Van (J227aC/G-Van)
3. SAE J227aC urban driving schedule for the Chrysler TEVan (J227aC/TEVan)
4. SAE J227aD urban driving schedule for the improved ETV-1 vehicle (J227aD/IETV-1)

William H. DeLuca
Author Name

The power profile for each of the above driving schedules was obtained from a vehicle test laboratory and is based on data either recorded during EV road tests or generated by a computer EV-simulation program. Each power profile was normalized to the weight of the battery that was used to propel the vehicle. To determine the power levels that must be imposed on a single cell or module for driving profile discharges, the mass of the cell or module is multiplied by the specific power profile. With this methodology, the battery mass originally installed in the vehicle remains constant. For high-temperature cells and modules, a weight burden is added to the measured weight to include a share of the weight for a thermal enclosure, heaters, interconnectors, etc. In some cases, this burden is >85% of the cell weight.

A computer-control and data-acquisition system is used to cycle and monitor the cells and modules during testing at the ADL. The signals measured and recorded include module voltage and current, voltage and temperature of each cell (if available), and ambient temperature of the laboratory test enclosure. When possible, battery temperatures are measured within the cell cases; otherwise, a surface measurement is made on the cell case. The energy (Wh) and coulombic charge (Ah) transferred during each charge and discharge period are calculated by the computer from the voltage and current signals of the cell or module. All the signals are quantified, computations performed, and data recorded at one-second intervals for driving profile discharges and approximate one-minute intervals for CI and CP discharges. Cell and module internal resistance, IR-free voltage, and peak power vs. DOD data are derived from the measured values of cell and module voltage and current during driving profile discharges. During life testing, the effect of age on these parameters is evaluated.

TEST RESULTS

Table 1 lists the general specifications and performance of each EV battery technology evaluated at the ADL during 1991. Composite plots of specific energy and specific peak power for each technology are given in Figs. 1 and 2, respectively. The values of specific energies were measured using CP discharges to 100% DOD. The values of specific peak power were derived from driving profile discharge data and are plotted as functions of DOD based on available energy for the average power discharge rate. Results of the standardized hill-climb capability test are given in Fig. 3. The time that each battery is capable of propelling an electric car (IETV-1) up a hill (7% grade) at 30 mph (45 W/kg load) is plotted as a function of DOD achieved at a 15 W/kg rate. The results of the extended open-circuit stand test, plotted in Fig. 4, show the effects of self-discharge vs. time for each of the battery technologies examined. The data for the high-temperature systems (Na/S and Li/MS) do not reflect enclosure thermal losses. The results for each technology are discussed below.

SODIUM/SULFUR TECHNOLOGY - Two Na/S systems are undergoing evaluation. One is a one-half sized (22-kWh) Na/S EV battery fabricated by ASEA Brown Bouverie (ABB). This 240-Ah, 90-V battery was shipped to ANL at operating temperature (310°C) with thermal and safety management systems in May 1990. It contains 360 cells (30-Ah rating) configured into three series-connected banks, each containing eight parallel-connected strings of 15 series-connected cells. Performance characterization tests were completed, and life testing initiated in October 1990 after the battery had been operated for 160 cycles. This battery system exhibited the highest specific energy (and provided the greatest simulated vehicle driving range) of any battery technology examined to date. Because the internal heat losses were low, the cooling system was not used during driving profile discharges. An average heater power of 176 W was needed to maintain a battery temperature of ~310°C over an open-circuit period of 72 h to compensate for enclosure heat loss. This heat loss would cause a capacity decline, or self-discharge loss, of about 0.8%/h if the battery were used to power its heaters. After 186 cycles (October 1990), the battery underwent a temperature freeze/thaw cycle to repair its positive voltage output terminal, which had become disconnected inside the thermal enclosure. The battery retained about 97% of its initial 238-Ah capacity at that time. After heating the battery to operating temperature, a cell in its center section was found to have low capacity. This cell and a corresponding cell in each of the parallel-connected strings in this battery section were short-circuited by ABB. This reduced the battery to 352 cells and 88 V. Life testing was resumed in November 1990. The center section had been limiting battery performance prior to the terminal failure. Because the discharges were now terminated on overall battery voltage instead of individual section voltages, an increase in Ah capacity of ~2% was obtained. This offset the decrease in battery voltage due to the shorted cells and SFUDS range (154 miles) was maintained.

Life testing of the ABB battery was terminated in August 1991 because the battery operating temperature could not be maintained at 310°C. The module had completed 589 cycles and retained ~81% of its initial 238-Ah capacity when the temperature started to decline. On cycle 591, the temperature dropped below the limit level (290°C) even with the heaters energized continuously. At that time, the outer thermal jacket surface temperature was 45°C, and one bottom surface location reached 90°C. The battery was returned to ABB for post-test analysis. A cursory inspection when the battery was opened revealed that three cells had failed and a hole had formed in the thermal enclosure wall below one of them, apparently the result of sodium-polysulfide corrosion. Researchers at ABB are conducting a more detailed post-test analysis and will report their findings.

An 8-V Na/S module from Chloride Silent Power Ltd. (CSPL, England) has been under test since June 1990. The module contains 120 10-Ah cells, configured into 30 parallel-connected strings of four series-connected cells. This module is of the same design and assembly as the 24 series-connected modules in the battery system for the ETX-II vehicle (a light-duty van based on the Ford Aerostar). Performance characterization tests were completed and life tests initiated in October 1990. Test results indicated that the performance of this module is similar to that of the ABB battery. However, the CSPL module has a lower peak power due to its higher internal resistance. Life tests are continuing, and the module has successfully completed >700 cycles and retains ~85% of its initial 292-Ah capacity (3-h rate). This decline in capacity indicates the loss of four 4-cell strings. The resistance of the module has increased with life (from 5.5 to 7.1 mΩ), causing the available energy for SFUDS discharges to decline by almost 20% (<80% of initial energy is end-of-life).

LITHIUM/MONOSULFIDE TECHNOLOGY - Two Li/MS cells were delivered to ANL for baseline performance testing under the R&D development contract with SAFT America, Inc. (Cockeysville, Md). The first cell was placed on test in May 1991, and a test was conducted to determine its performance as a function of temperature (465 to 485°C). The results showed that cell capacity, internal resistance, and IR-free voltage were very sensitive to temperature. To further evaluate this effect, the cell was removed from test after 30 cycles to undergo post-test analyses. It still retained 98% of its initial capacity at that time. These analyses showed that increased compression was needed to improve cell performance and reduce its sensitivity to temperature. A second cell was placed on test in July 1991 with an improved clamping fixture to allow more compression on the cell electrode area. Performance characterization was conducted at a temperature of 465°C based on performance vs. temperature data. Performance characterization tests were completed, and life tests started in December 1991 after 120 cycles had accrued. Life tests are being conducted with SFUDS discharges to 80% DOD. The cell has completed >125 cycles and retains ~96% of its initial 203-Ah capacity.

ZINC/BROMINE TECHNOLOGY - A 5-kWh, 48-V Zn/Br module (ZBB-5/48) from the Studiengesellschaft fur Energiespeicher und Antriebssysteme, (SEA) (Research Group for Energy Storage and Propulsion Systems, Austria) has completed EV performance and life testing. Life testing with SFUDS simulated driving profile discharges to 100% DOD was started in March 1990 after performance testing (~130 cycles accrued). The module reached end-of-life (>20% loss of initial capacity) after 334 cycles. Early in its life, the module received electrochemical maintenance about every five cycles of operation, during which the module was completely discharged to 0 V for ~4 h to strip all the Zn from its electrodes. Between stripping cycles, module capacity with SFUDS discharges declined at the rate of ~2.5%/cycle. After 300 cycles, this decline in capacity suddenly increased to ~7%/cycle. Electrolyte analyses were conducted to assess the sudden change in module performance. The electrolyte pH level was high and HCl was added at the request of SEA, but there was no change in module performance. Testing was halted when a capacity of <80% of its initial level (126 Ah) was obtained on the first cycle after stripping. The module was returned to SEA for post-test analyses.

NICKEL/METAL HYDRIDE CELLS - Performance and life characterization tests are being conducted on Ni/MH 25-Ah prismatic H-cells and 5-Ah extended C-size cells manufactured by Ovonic Battery Company (Troy, MI). ANL is evaluating the suitability of this technology for EV applications. Previously tested in 1990, C-size, 3.5-Ah cells exhibited good performance characteristics, but the cycle life of four cells (33, 238, 289, and 333 cycles) was less than expected (500 cycles). These early cells exhibited a high self-discharge loss (14 to 38% loss in 24 h and 45 to 70% loss in 7 days). Ovonics subsequently modified component materials and reduced the self-discharge loss to 15 to 20% in 7 days.

Performance and life tests are being conducted on the two 25-Ah Ni/MH cells that represent an intermediate step in an Ovonics program to fabricate and developed large, full-size EV battery cells. The cells were delivered to ANL in June 1991. Performance characterization tests were completed, and life testing started in November 1991. Life tests are being conducted with SFUDS discharges to 80% DOD. Test results show that these H-cells have very low resistance and exceptionally high peak power capability (~200 W/kg at 50% DOD). This peak-power capability is the highest measured at the ADL, and it provides full capacity and maximum vehicle range for all driving profile discharges. The cells have completed about 170 and 80 cycles and retain all of their initial 100% DOD capacity.

NICKEL/CADMIUM TECHNOLOGY - Life tests sponsored by the EPRI are being conducted on a 6-V, 190-Ah Ni/Cd module manufactured by SAFT (Industrial Storage Battery Division), France. The module was received in April 1990 after completing 35 performance characterization cycles at the Idaho National Engineering Laboratory (INEL). Life testing was started at the ADL in June 1990 after 78 cycles of performance testing were accrued. Life evaluation is being conducted with 100% DOD driving profile discharges (J227aC schedule for a Chrysler TEVan). The module has completed more than 700 cycles and retains ~100% of its initial 214-Ah (3-h rate) capacity. The energy obtained with 100% DOD TEVan discharges has declined to ~96% of its initial 1268 Wh.

ADVANCED NICKEL/IRON TECHNOLOGY - Two 6-V advanced Ni/Fe modules (NIF200) manufactured by Eagle-Picher Industries, Inc. (EPI) Joplin, MO, with sintered-powder nickel electrodes were under test in 1991. The NIF200 design provides a capacity of 200 Ah in the same module package as the 170-Ah module developed for the Eaton DSEP program. Due to a change in program direction, testing was halted in January 1991. At that time, one module was under life test using SFUDS discharges to 100% DOD, and the second module was just starting performance characterization. The module on life test had undergone performance characterization in 1990. It had completed 185 cycles and retained ~95% of its initial 198-Ah capacity when testing was halted. It was returned to EPI for additional life tests. The second module had only completed 8 cycles of capacity verification. It was sent to INEL for additional performance characterization testing. Several NIF200 modules remain on test at the ADL for the EPRI Test and Evaluation Program.

TUBULAR LEAD-ACID TECHNOLOGY - Two advanced, three-cell, lead-acid modules with tubular positive electrodes (3ET205) made by Chloride EV Systems Ltd. (CEVS) England, were acquired and tested in January 1991. This test measured the 3ET205 cycle life with SFUDS discharges (100% DOD) for comparison with that achieved in an EPRI-sponsored test using J227aC/G-Van driving profile discharges to 100% DOD. Both of the new modules underwent an abbreviated performance characterization and one was selected for life testing with SFUDS discharges. After ~150 cycles, this module reached end-of-life (<80% of initial energy). In the EPRI test (1990), the 3ET205 module completed 715 cycles before reaching end-of-life. Post-test analyses revealed that both modules failed due to deterioration of the negative electrodes caused by high levels of antimony and by poor adhesion between the active materials and the grids. The antimony was generated by corrosion of the positive grids and plated onto the negative electrodes during operation. Charging efficiency and effective capacity of the electrodes were consequently reduced. The cells in the module using SFUDS discharges had a greater divergence in post-test findings than those observed in the EPRI module. Hence, cell mismatch may have impaired the evaluation of the SFUDS test.

RECOMBINANT LEAD-ACID TECHNOLOGY - Tests were started in December 1989 for EPRI on two 6-V, valve-regulated lead-acid (VRLA) modules with a gelled electrolyte manufactured by Sonnenschein Battery Co. (Germany).[1] The maintenance-free cells are equipped with pressure-relief valves for venting and use an antimony-free alloy. Both modules completed performance characterization and one underwent life testing with J227aC/G-Van discharges to 100% DOD. After 370 cycles, the simulated driving range had declined to 80% of its initial 58.5 miles. New modules were delivered from Sonnenschein, and one was placed on life test using G-Van discharges. The module was operated to 100% DOD for 122 cycles and then changed to 80% DOD cycling. This module completed 448 cycles before reaching end-of-life (100% DOD limit reached before the 80% DOD discharge completed). At that time, the 3-h rate capacity had only declined by ~9%.

FUTURE EVALUATIONS

In 1991, performance characterization and life evaluations will be continued for DOE/OTT on the Na/S (CSPL) module and Ni/MH (Ovonics) H-cells. Life testing of the Ni/Fe (EPI) and Ni/Cd (SAFT) modules for EPRI will also be continued. New systems to be evaluated at the ADL in 1992 include full-size Ni/MH EV cells from Ovonics, which will undergo performance and life testing with driving profile discharges to 100% DOD. Several Na/S 120-cell modules which will undergo accelerated life testing, are also expected.

ACKNOWLEDGMENT

This work was supported by the Department of Energy, Office of Transportation Systems, Electric and Hybrid Propulsion Division. Data was also provided from tests conducted for the Electric Power Research Institute.

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Table 1. Summary of Test Results from EV Battery Evaluations in the ANL/ADL in 1991

Battery Description			Initial Module		Specific Energy,[a]	Volumetric Density,[a]	Peak Power,[b]	Efficiency a		Life,[c]	Van Range,[f]
Technology	Manufacturer	Model	Weight, kg	Capacity,[a] Ah	Wh/kg	Wh/L	W/kg	Coulombic, %	Energy, %	cycles	mi (km)
Sodium/Sulfur	ABB	B-11	253	238	81	83	152	100	91	592	154 (246)
	CSPL	PB-MK3	29.2	292	79	123	90	100	88	>800	150 (240)
Lithium/ Monosulfide	SAFT, America	Prismatic	2.94	203	66	133	64	95	81	>125[d]	93 (149)
Zinc/Bromine	SEA	ZBB-5/48	81	126	79	56	40	93	75	334	93 (149)
Nickel/Metal Hydride	Ovonics	C-cell	0.081	3.6	54	186	158	92	80	333	97 (155)
	Ovonics	Ext.C-cell	0.093	4.5	57	209	105	90	74	108	-- --
	Ovonics	H-cell	0.628	28.0	55	152	175	90	80	>170[d]	97 (155)
Nickel/Cadmium	SAFT	STM5-200	24.5	217	55	104	175	90	78	>700[e]	102 (163)
Nickel/Iron	Eagle-Picher	NIF200	25	203	51	118	99	74	58	>825[d,e]	87 (139)
Lead-Acid	Sonnenschein	6V160	31.5	184	36	92	68	94	84	370[e]	51 (82)
	CEVS	3ET205	32.8	185	33	78	91	87	68	149	47 (75)

a Determined for 3-h rate CI discharges.
b Determined from driving profile discharge data at 80% DOD.
c Determined with SFUDS discharges to 100% DOD unless otherwise indicated. Ongoing life tests are indicated with the ">" sign.
d Determined with 80% DOD discharges.
e Detemined with J227aC discharges.
f Determined for the IDSEP Van with a 695 kg battery on an SFUDS driving schedule.

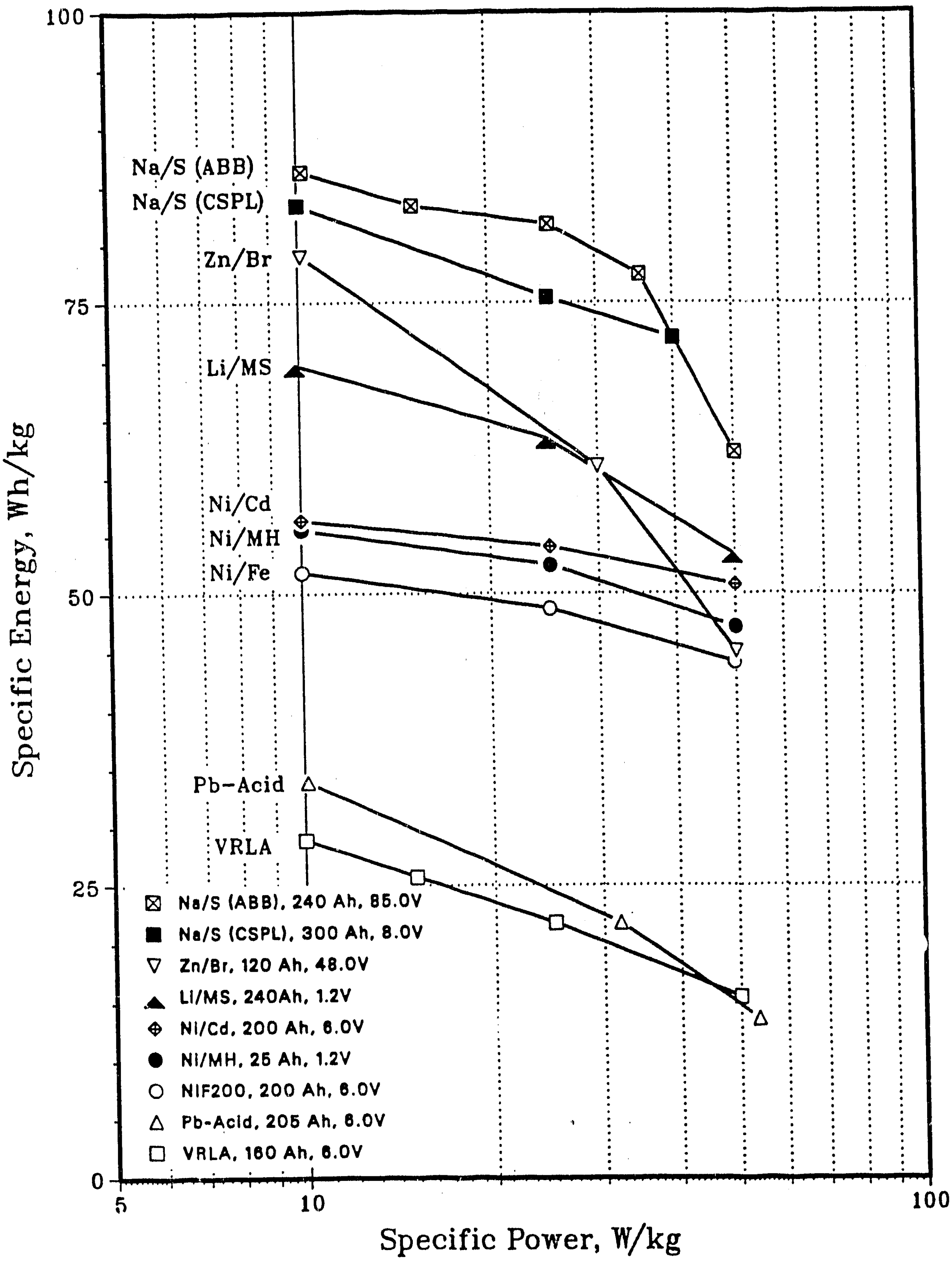

Fig. 1. Effect of discharge specific power on the available energy of the battery technologies evaluated.

William H. DeLuca
Author Name

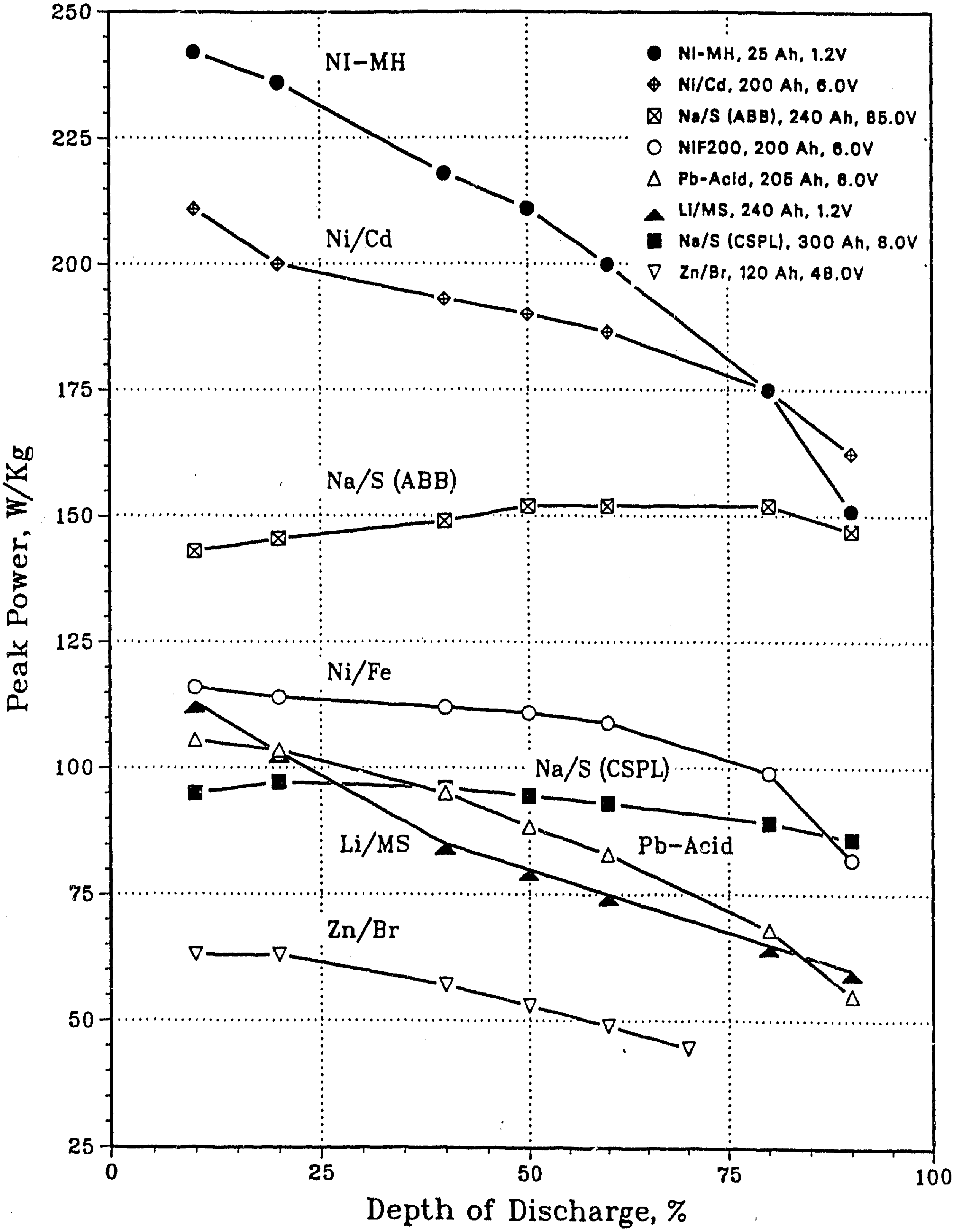

Fig. 2. Derived peak power vs. DOD of the battery technologies evaluated from driving profile discharge (J227aD/IETV1) data.

William H. DeLuca
Author Name

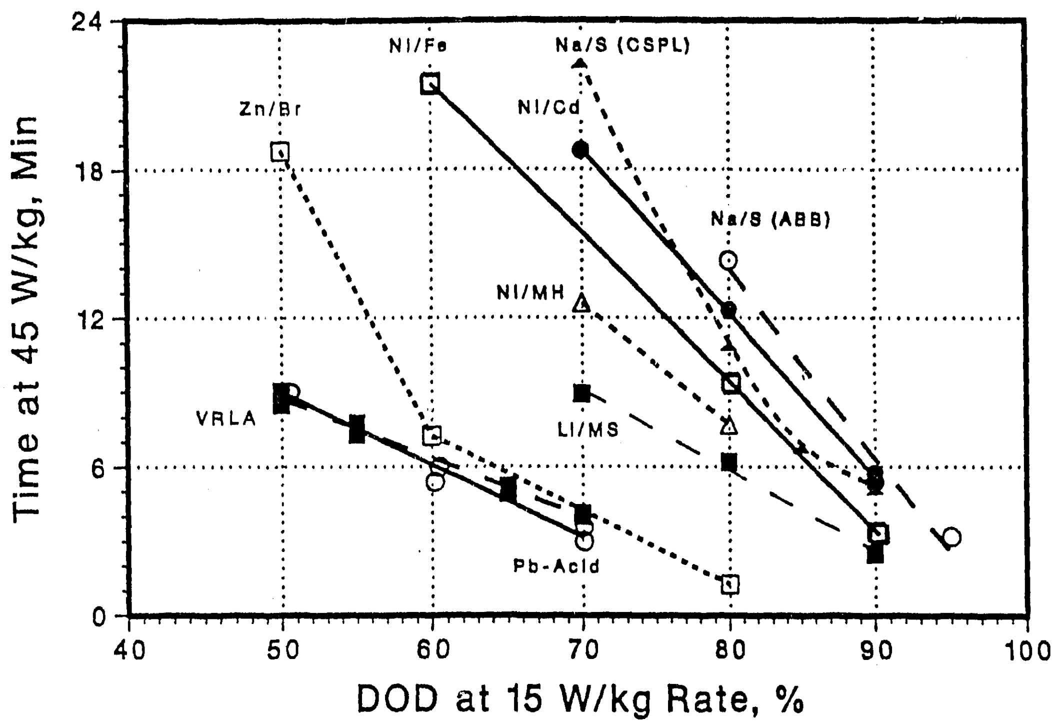

Fig. 3. Time (at 45 W/kg) that electric car (IETV-1) could sustain hill climb (7% grade) at 30 mph as function of DOD (at 15 W/kg rate) for each advanced battery technology evaluated.

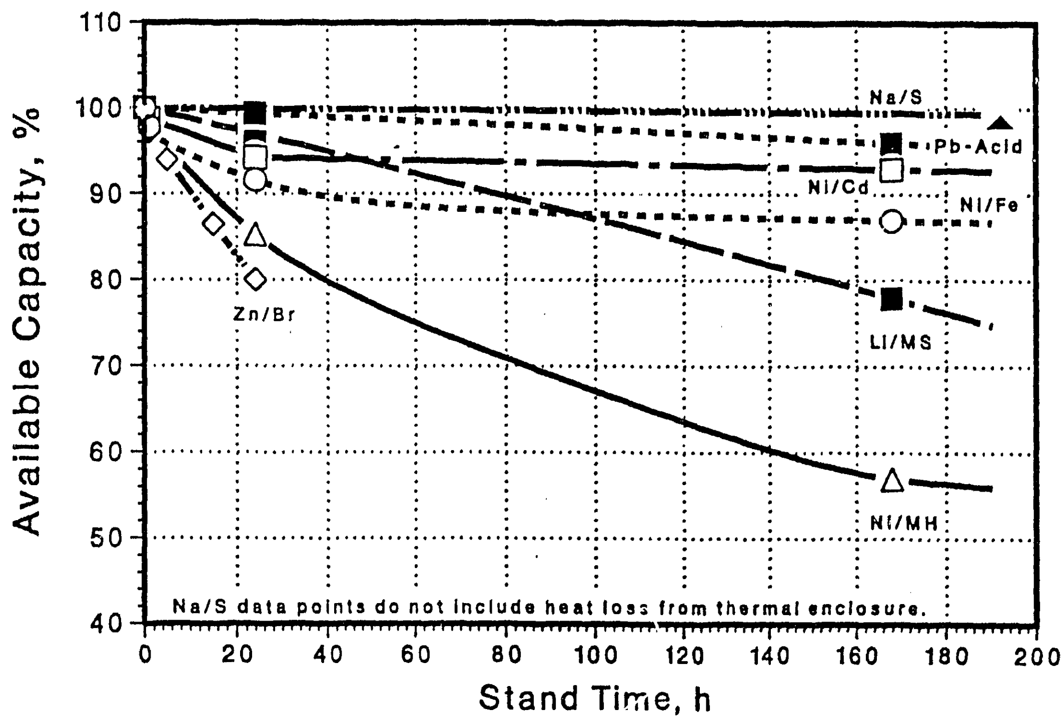

Fig. 4. Available discharge capacity vs. open-circuit stand time after charge for each advanced battery technology evaluated.

William H. DeLuca
Author Name

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