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Results of Advanced Battery Technology Evaluations for Electric Vehicle Applications

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ABSTRACT

Advanced battery technology evaluations are performed under simulated electric-vehicle operating conditions at the Analysis & Diagnostic Laboratory (ADL) of Argonne National Laboratory. The ADL results provide insight into those factors that limit battery performance and life. The ADL facilities include a test laboratory to conduct battery experimental 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. This paper summarizes the performance characterizations and life evaluations conducted during 1991 - 1992 on both single cells and multi-cell modules that encompass eight battery technologies [Na/S, Li/MS (M=metal), Ni/MH, Ni/Cd, Ni/Zn, Ni/Fe, Zn/Br, and Pb-acid]. These evaluations were performed for the Department of Energy, Office of Transportation Technologies, Electric and Hybrid Propulsion Division, and the Electric Power Research Institute. The ADL provides a common basis for battery performance characterization and life evaluations with unbiased application of tests and analyses. The results help identify the most-promising R&D approaches for overcoming battery limitations, and provide battery users, developers, and program managers with a measure of the progress being made in battery R&D programs, a comparison of battery technologies, and basic data for modeling.

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 (1) a versatile computer-operated test laboratory to conduct battery evaluations under simulated application conditions and (2) a post-test analysis laboratory to determine, in a protected atmosphere if needed, component compositional changes and failure mechanisms. The ADL evaluates 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 the 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 electric vehicle (EV) propulsion, utility load-leveling, and standby power applications. The results of evaluations conducted during 1990 and the first quarter of 1991 were reported in August 1991.¹

From January 1991 to May 1992, EV battery evaluations were performed for the DOE Office of Transportation Technologies, Electric and Hybrid Propulsion Division (OTT/EHP), and the EPRI Transportation Program. Performance characterizations and/or life evaluations were conducted on eight battery technologies [Na/S,

Li/MS (M=metal), Ni/MH, Ni/Cd, Ni/Zn, Ni/Fe, Zn/Br, and Pb-acid]. 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. All of the standardized performance 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. Performance characterization includes the measurement of:

1. rated capacity under manufacturer specified operating conditions
2. capacity vs. constant current (CI) and constant power (CP)
3. available peak power vs. depth-of-discharge (DOD) for acceleration capability
4. self-discharge losses vs. stand time
5. sustained hill-climbing capability
6. effect of partial discharge on available 100% DOD capacity
7. projected ranges for various vehicles and driving schedules

Life cycle tests are typically conducted with 80 or 100% capacity discharges using a simulated driving power profile. Life evaluations with 100% DOD cycles are continued until the energy capacity declines to 80% of the initial or rated value, whichever was less. Life evaluations with 80% DOD cycles are continued until the battery can no longer provide the 80% DOD energy before reaching its 100% DOD condition. During the life evaluation, reference cycles are conducted at ~25-cycle intervals to establish a baseline 3-h rate capacity history and at ~50-cycle intervals to determine the effects of age on battery resistance, IR-free voltage, and peak power. 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)

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 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. Table 1 lists the general characteristics of each power profile.

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 2 lists the general specifications and best performance (for the specified test conditions) of each EV battery technology evaluated at the ADL from January 1991 to May 1992. 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 a function 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. Selected 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. Selected results for each technology are discussed below.

SODIUM/SULFUR TECHNOLOGY - Two Na/S systems were evaluated: one was a one-half sized (22-kWh) Na/S EV battery fabricated by ASEA Brown Boveri (ABB), and the other was an 8-V Na/S module from Chloride Silent Power Ltd. (CSPL). The 240-Ah, 90-V battery of ABB was shipped to ANL at operating temperature (310 °C) with thermal and safety management systems in May 1990. It contained 360 cells (30-Ah rating) configured into three series-connected banks. Each bank contained eight parallel-connected strings of 15 series-connected cells. Performance characterization tests were completed, and life testing initiated in October 1990. 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 I^2R heat losses were low, the cooling system was not used during driving profile discharges. The enclosure heat loss at a battery temperature of ~310 °C was 176 W. This heat loss would cause a capacity decline of about 0.8%/h if the battery were used to power its heaters (self-discharge loss). Life testing 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. After 592 cycles, 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 existed in the thermal enclosure wall (below one of the failed cells) that appeared to

be the result of sodium-polysulfide corrosion. Researchers at ABB are conducting a more detailed post-test analysis and will furnish a report of their findings.

The 8-V Na/S module from CSPL was under test from June 1990 to March 1992. The module contained 120 cells (10-Ah each) configured into 30 parallel-connected strings of four series-connected cells. This 300-Ah module was of the same design and assembly as those (24 series-connected modules) in the battery system for the ETX-II vehicle (a light-duty van based on the Ford Aerostar). Life testing with SFUDS discharges to 100% DOD was started in October 1990 after completion of the performance characterization tests (~120 cycles accrued). Test results indicate that the performance of this module is similar to that of the ABB battery. However, the CSPL module has a higher internal resistance and, therefore, cannot achieve as high a peak power. End-of-life (<80% of initial 2084-Wh SFUDS discharge energy) occurred at cycle 795, but testing was continued to acquire additional statistics for cell failure analyses. Testing was halted in March 1992 (21 months and 973 cycles at operating temperature) when the SFUDS discharge energy decreased to <75% of its initial level. There was a significant drop in module capacity between 450 and 550 cycles of operation, which reflected the loss of four 4-cell strings (~40-Ah loss). Module resistance increased by ~20%, which also indicated the loss of four strings in the 30-string battery. Due to the increase in module resistance with life, the peak power declined from an initial 94 W/kg to only 68 W/kg at the end of testing (50% DOD). After 973 cycles, the module retained ~79% of its initial 292-Ah capacity (3-h rate) and ~73% of its initial 2084-Wh SFUDS discharge energy (100% DOD). Between cycles 934 and 973, module resistance at end-of-discharge suddenly increased from 7.2 to 7.5 mΩ. This 4% increase in resistance in less than 40 cycles reflects the loss of another 4-cell string. The module was returned to CSPL (England) for post-test analyses. While the module was prepared for shipment, a visual inspection revealed that at least two cells had breached their containers.

LITHIUM/METAL SULFIDE TECHNOLOGY - Two Li/MS cells were delivered to ANL for baseline performance testing under an R&D development contract with SAFT of America, Inc. (Cockeysville, MD). The first cell was placed on test in May 1991. At an operating temperature of 470 °C, a capacity

of 182.5 Ah was obtained at the 3-h rate. This was ~14% below the capacity measured at SAFT using an operating temperature of 485 °C. At the ADL, the operating temperature was raised in 5 °C steps to 485 °C to observe the effect on cell capacity. The results showed that cell capacity, internal resistance, IR-free voltage, and peak power capability were sensitive to temperature. After completing 30 cycles of operation, the cell still retained 98% of its initial capacity, but was removed from test to undergo post-test analysis.

The second cell was placed on test in July 1991. Based on preliminary test results, the cell was operated at a temperature of 465 °C. Because the clamping arrangement used in the test fixture for this cell was modified to allow more compression on the electrode face, this cell performed much better than the first. Performance characterization tests were completed, and life tests started in December 1991 after 120 cycles were accrued. After completing 158 cycles, testing was suspended, and the cell was cooled to ambient temperature for the December holiday shutdown period (two weeks). In January 1992, the cell was heated to 465 °C and testing resumed. A capacity of 198 Ah (239 Wh) was obtained on the first discharge. This was an improvement over that obtained before the holiday shutdown (cycle 155). However, on the second discharge, a capacity of only 174 Ah was obtained, and the cell voltage declined to 0.8 V during a 1-h open-circuit after discharge (OCAD) period (a voltage of >1.2 V is expected). A 120% charge return was applied on the subsequent charge, but the cell voltage never increased to the CV charge level of 1.5 V. The decline in voltage during the (OCAD) period and the inability to reach the CV charge level with 120% charge return indicate a high internal self-discharge rate. A capacity of 174 Ah (208 Wh) was obtained on the last discharge (cycle 163). Testing was suspended at that time, and no further analyses were performed on this cell.

ZINC/BROMINE TECHNOLOGY - A 5-kWh, 48-V Zn/Br module (ZBB-5/48) from the Studiengesellschaft für Energiespeicher und Antriebssysteme (SEA) (Research Group for Energy Storage and Propulsion Systems, Austria) underwent EV performance and life testing from November 1989 to June 1991. Performance characterization tests showed that the SEA battery has good specific energy (~79 Wh/kg at 3-h rate), but low power capability (~53 W/kg at 50% DOD). The low power is due to a high internal battery

resistance. The battery also exhibited a high self-discharge loss (~20% loss in 24 h) when its electrolyte pumping motors remain energized. This loss is significantly reduced when pump operation is halted during extended open-circuit times. Life testing with SFUDS discharges to 100% DOD was started in March 1990 after performance testing (~130 cycles accrued). Because of the high module resistance, a peak discharge current limit (150 A) had to be imposed with SFUDS discharges to avoid reaching the discharge cut-off voltage (DCOV) on the first 79 W/kg profile power peak. With a 150 A current limit, a maximum power of ~67 W/kg was obtained at the start of the discharge, and 50 W/kg was attained at the 27-V DCOV. The module reached end-of-life (>20% loss of initial capacity) after 334 cycles, and was returned to SEA for post-test analyses.

NICKEL/METAL HYDRIDE CELLS - Performance and life tests were conducted on Ni/MH cells manufactured by Ovonic Battery Company (Troy, MI) to determine the suitability of this technology for EV applications. Previously tested in 1990, C-size (3.5-Ah rating) cells exhibited good performance characteristics, but the cycle life of four cells (33, 238, 289, and 333 cycles) was less than expected (500 cycles). Two extended C-size cells (~4.5 Ah) were evaluated in mid-1991. The specific energy of these cells was slightly higher than that of the smaller C-cells, but the cycle life was still less than expected. These early cells exhibited a high self-discharge loss (14 to 38% loss in 24 h and 45 to 70% loss in 7 days). Ovonic subsequently modified component materials and reduced the self-discharge loss to 15 to 20% in 7 days.

Performance and life tests were also conducted on two Ni/MH H-cells (25-Ah rating), which represented an intermediate step in an Ovonic program to fabricate and develop large, full-size EV battery cells. The two cells were delivered to ANL in June 1991. Performance characterization tests were completed, and life evaluation started in November 1991. Life tests are being conducted with SFUDS discharges to 80% DOD. Test results show that all of the Ni/MH cells have very low resistance and exceptionally high peak power capability (~200 W/kg at 50% DOD). The peak-power capability of the H-cell is the highest measured at the ADL (between ~35 and 80% DOD). A high peak power provides full capacity and maximal vehicle range for all driving profile discharges. One cell was removed from life test

after 380 cycles due to a sudden decline in capacity (to <70% of its initial 25-Ah capacity). A reduced cell weight indicated that the capacity decline was due to electrolyte loss. Water (13.6 g) was added to the valve-regulated cell, and full capacity (26.5 Ah) was achieved on a subsequent discharge. Thereafter, the capacity declined at a rate of ~0.5 Ah/cycle. Testing was halted when the capacity declined to 13.8 Ah on cycle 399. Cell weight was reduced again (by 6.3 g). This suggests problems with the integrity of the stainless steel case and/or the pressure release vent. A replacement cell (EV35) was furnished by the manufacturer in April 1992. This cell has a 7-h rating of 35 Ah and will undergo performance and life evaluation.

The second H-cell is still under life test with SFUDS discharges to 80% DOD (26.3-Wh discharges and 23-Ah CI/CI charges). This cell has completed >300 cycles and retains ~100% of its initial 28-Ah capacity. The weight of this cell is being periodically measured to identify the onset of any electrolyte losses.

NICKEL/ZINC TECHNOLOGY - Three Ni/Zn cells manufactured by Electrochemica were tested from May 1991 to February 1992. Performance characterization tests were conducted on a 17-Ah cell from May to October 1991. This cell continually exhibited unstable capacity, and its capacity had declined >20% after 170 cycles (end-of-life criterion). Special manufacturer-recommended conditioning cycles were imposed in an attempt to improve cell capacity, but this rejuvenation process was unsuccessful. Testing was halted after the cell had completed 187 cycles, and its capacity had declined to ~40% of its initial 14.6 Ah.

Performance characterization tests were conducted on two larger cells (60-Ah rating) from August 1991 to February 1992. Testing of the first cell was halted in December 1991 because of excessive heating during an initial charge of 12 A. This occurred after the cell had inadvertently received a CI/CV charge return of 216% during a 50% DOD partial discharge test. The cell could be charged (58.5 Ah) at a reduced rate (4 A for ~14.6 h) without excessive heating, and ~93% of its initial 53.9 Ah capacity was obtained on discharge. Various conditioning cycles were tried in an attempt to improve the charge acceptance of this cell at increased charge rates, but were not successful. After completing 140 cycles, this cell was removed from testing. The second 60-Ah Ni/Zn cell was

tested from December 1991 to February 1992. An abbreviated performance characterization and life test with SFUDS discharges to 80% DOD were conducted. An initial capacity of 52.3 Ah (110.6 Wh) was achieved with ~112% charge return. The cell was operated over the December holiday shutdown, during which its capacity increased slightly and the charge return decreased from ~112 to 105% (fixed 58.5-Ah return). In January 1992, when the charge return was increased from 105 to 110% (manufacturer recommended value), cell capacity increased from ~57 to 70 Ah. Because of this large increase in capacity, the abbreviated performance characterization was repeated. The cell then exhibited a specific energy of 66.7 Wh/kg (3-h rate) and a peak power of 185 W/kg (50% DOD). The highest CP discharge that could be applied without excessive cell heating was 35 W/kg. Life testing with 80% DOD SFUDS discharges (75 Wh) and CI/CV (12 A/1.95 V) charges to 110% return was started in February 1992 (95 cycles accrued). The cell completed only 20 SFUDS cycles, when the 100% DOD termination condition (maximum power capability ≤50 W/kg) was reached before the 80% DOD energy (75 Wh) could be removed (end-of-life). At that time, a 3-h rate capacity of <50 Ah was obtained, and a thermal runaway condition was starting during the CV portion of the CI/CV charges. The cell reached end-of-life on cycle 114 and was removed from test in February 1992 after completing 120 cycles. The cells were returned to Electrochemica.

NICKEL/CADMIUM TECHNOLOGY - Life tests are being conducted on a 6-V Ni/Cd module (190-Ah rating) 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. Life testing was started at the ADL in June 1990 after 78 cycles of performance testing were accrued. Life evaluation is being conducted with J227aC/TEVan discharges to 100% DOD. The module has completed over 900 cycles and retains ~99% of its initial 214-Ah (3-h rate) capacity. The energy obtained with 100% DOD TEVan discharges has only declined to ~95% of its initial 1268 Wh. Variations in module resistance, IR-free voltage, and peak power vs. DOD during the life evaluation were examined. Analyses showed that module resistance has increased by ~21% and IR-free voltage has remained constant to within 0.5%. As a result of

the increased module resistance, the peak power capability was decreased from 190 to 159 W/kg at 50% DOD (~16% decrease) between cycles 46 and 868. This module is still under life test.

ADVANCED NICKEL/IRON TECHNOLOGY -

Life tests are being conducted on several advanced Ni/Fe modules (NIF200) from Eagle-Picher Industries, Inc. The NIF200 design provides a capacity of 200 Ah in the same module package as the 170-Ah module developed for the dual-shaft electric propulsion (DSEP) vehicle developed by Eaton Corp. Performance characterization tests were completed in early 1990, and three NIF200 modules were placed on life tests. Since that time, another five NIF200 modules have been placed on life tests. One module, tested from September 1989 to April 1992, completed 918 cycles with G-Van discharges to 80% DOD before reaching end-of-life.

A charging study was conducted to determine an optimal charge regime for the NIF200.² The study evaluated three charge methods: one-step constant current (CI), two-step constant current (CI/CI), and constant current/constant voltage/constant current (CI/CV/CI). Also investigated were charge returns (overcharge) of 115 and 135%; constant and pulsed charge currents as the final charge structure with CI/CV/CI charging; and a range of overcharge levels to determine the 50% "charge acceptance point" (i.e., 50% of charge current used for electrochemical recharge and 50% used for electrolysis). During these studies, the total outgas volume was measured with each charge regime to indicate charging efficiency. The results of this study showed that charge method and charge current structure had no significant impact on NIF200 module performance. Only the charge return level affected available module capacity and efficiency. At the 50% charge acceptance point, both efficiency and available capacity were maximal. Hence, ANL recommended a CI/CI charge regime (for simplicity) and a charge return of 111% (50% charge acceptance point). A life test has been initiated using the ANL recommended charge regime.

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 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 149 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). The maintenance-free cells are equipped with pressure-relief valves for gas 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 energy obtained on simulated driving profile discharges had declined to 80% of its initial level. 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 condition reached before the 80% DOD energy obtained). At that time, the 3-h rate capacity had only declined by ~9%.

FUTURE EVALUATIONS

In 1992, performance characterization and life evaluations will be continued for DOE/OTT on the Ni/MH (Ovonic) H-cells and EV35 cell. 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 Ovonic, which will undergo

performance and life testing with driving profile discharges. Several Na/S 120-cell modules, which will undergo accelerated life testing, are also expected.

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REFERENCES

1. Performance and Life Evaluation of Advanced Battery Technologies for Electric Vehicle Applications, W. H. DeLuca, et al., SAE 1991 Future Transportation Technology Conf., Portland, OR, August 5-8, 1991, SAE Technical Paper 911634 (1991).
2. Effects of Charge Methods and Pulse Charge Currents on Nickel/Iron Traction Battery Performance, W. H. DeLuca, et al., Proc. of the Seventh Annual Battery Conf. on Applications and Advances, Long Beach, CA, January 21-23, 1992, pp. 92EV-7/VIII-8.

Table 1. Driving Profile Characteristics

	SFUDS	J227aD	J227aC	J227aC
- Driving Schedule	IDSEP	IETV-1	G-Van	TEVan
- Battery Weight, kg	695	488	1180	839
- Avg. Speed, mph	19.0	28.3	15.1	15.9
- Peak Power, W/kg	79	48	36	29
- Avg. Power, W/kg	9.9	12.0	7.3	5.1
- Energy Consumption, Wh/mile	362	207	570	269

Table 2. Performance Summary of EV Battery Technologies Evaluated in the ANL/ADL between January 1991 and May 1992

Battery Description		Initial Module		Specific Energy, ^a Wh/kg	Volumetric Density, ^a Wh/L	Peak Power, ^b W/kg	Efficiency ^a		Life, ^c cycles	Van Range, ^f mi (km)
Technology	Manufacturer	Model	Weight, kg	Capacity, Ah			Coulombic, %	Energy, %		
Sodium/Sulfur	ABB	B-11	253	238	81	83	100	91	592	154 (246)
Lithium/	CSPL	PB-MK3	29.2	292	79	123 ^g	100	88	795	150 (240)
	SAFT of America	Prismatic	2.94	203	66	133 ^g	95	81	163 ^d	93 (149)
Zinc/Bromine	SEA	ZBB-5/48	81	126	79	56	93	75	334	93 (149)
Nickel/Zinc	Electrochemica	R&D Cell	1.69	69	67	142	91	77	114 ^d	108 (173)
Nickel/Metal Hydride	Ovonics	C-cell	0.081	3.6	54	186	92	80	333	97 (155)
	Ovonics	Ext.C-cell	0.093	4.5	57	209	90	74	108	--
	Ovonics	H-cell	0.628	28.0	55	152	90	80	380 ^d	97 (155)
Nickel/Cadmium	SAFT	STM5-200	24.5	214	55	104	90	78	>900 ^e	102 (163)
Nickel/Iron	Eagle-Picher	NIF200	25	203	51	118	74	58	918 ^{d,e}	87 (139)
Lead-Acid	Sonnenschein	6V160	31.5	184	36	92	94	84	370 ^e	51 (82)
	CEVS	3ET205	32.8	185	33	78	87	68	149	47 (75)

^a Determined for 3-h rate C₁ 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 Determined with J227aC discharges.

^f Determined for the IDSEP Van with a 695 kg battery on an SFUDS driving schedule.

^g Based on manufacturer projections of future battery case volume.

Fig. 1. Effect of discharge specific power on available energy of ten advanced battery technologies.

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

Fig. 3. Time (at 45 W/kg) that electric car (IETV-i) could sustain hill climb (7% grade) at 30 mph as a 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.

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