Journal of Power Sources, 40 (1992) 63–72

Development status of a sealed bipolar lead/acid battery for high-power battery applications

J. L. Arias, J. J. Rowlette and E. D. Drake
Arias Research Associates, Inc., 13135-C Barton Road, Whittier, CA 90605 (USA)

Abstract

A sealed bipolar lead/acid (SBLA) battery is being developed by Arias Research Associates (ARA) which will offer a number of important advantages in applications requiring high power densities. These applications include electric vehicles (EVs) and hybrid electric vehicles, uninterruptable power supplies (UPS), electrically-heated catalysts (EHCs) for automobiles, utility-power peak-shaving, and others. The advantages of the SBLA over other types of batteries will by significantly higher power density, together with good energy density, high cycle life, high voltage density, low production cost and zero maintenance. In addition, the lead/acid battery represents a technology which is familiar and accepted by Society, is recyclable within the existing infrastructure, and does not raise the safety concerns of many other new batteries (e.g., fire, explosion and toxic gases). This paper briefly reviews the basic design concepts and issues of the SBLA battery technology, various quasi-bipolar approaches and the results of ARA's development work during the past four years. Performance data are given based on both in-house and independent testing of ARA laboratory test batteries. In addition, performance projections and other characteristics are given for three ARA SBLA battery designs, which are compared with other batteries in three example applications: UPS, EHCs, and EVs. The most notable advantages of the SBLA battery are substantial reductions in product size and weight for the UPS, smaller packaging and longer life for the EHC, and higher vehicle performance and lower cost for the EV, compared to both existing and advanced EV batteries.

Introduction

Interest in bipolar lead/acid batteries has historically been because of the inherent high power capability. The first bipolar lead/acid battery was developed and demonstrated by Kapitza in 1923 [1]. Kapitza demonstrated the ability to produce 50 kW/l of power with a bipolar battery, although discharge times were only milliseconds. Later studies by Rowlette [2] have suggested the ability to generate up to 5 kW/kg with bipolar lead/acid batteries having discharge times up to 30 s. Numerous attempts were made during the 1960s to develop bipolar lead/acid batteries for various applications, including hybrid electric vehicles batteries by Westinghouse [3] and Thompson Ramo Wooldridge (TRW) [4], and automobile starter battery by General Motors [5], and a Navy sonar battery by GNB [6]. These batteries, however, all suffered from the disadvantages of flooded construction and/or heavy lead plates and were thus impractical. In 1980, Rowlette combined the lead/acid bipolar battery with the sealed lead/acid

0378-7753/92/$5.00

cell construction developed by Gates [7], and patented the first sealed bipolar lead/ acid (SBLA) battery [8].

Arias Research Associates' (ARA) work on the SBLA battery began in 1988 with a design study [9] of an SBLA battery requiring a long discharge time (4 h). This work suggested the large commercial potential of the battery if reductions in battery weight and cost could be accomplished. In 1989, ARA began the self-funded development of proprietary components and processes, and achieved the increased material utilization efficiencies, which would make the battery attractive for EVs and other commercial applications. In 1990, ARA began development of an SBLA EV battery under the sponsorship of the Los Angeles Department of Water and Power and San Diego Gas and Electric, and later by the California Air Resources Board and the South Coast Air Quality Management District. In 1992, ARA began development of an SBLA battery for electrically-heated catalysts (EHCs), which are used to preheat or accelerate heatup of automobile catalytic convertors in order to reduce 'cold start' exhaust emissions. In 1992, ARA also began preliminary laboratory tests and design studies of small SBLA batteries, for such applications as small uninterruptable power supply (UPS) units.

Battery construction

The sealed bipolar lead/acid battery, as its name suggests, is sealed, using recombinant technology with electrolyte absorbed in a glass mat separator. The ARA SBLA battery utilizes a true bipolar plate construction, with positive and negative active materials on opposite sides of a conductive, acid-resistant plate. The development of a plate material/construction which is lightweight, stiff, inexpensive, resistant to the severe oxidizing environment in the lead/acid battery, and having sufficiently high oxygen and hydrogen overvoltages, has been a historical challenge in the development of a commercially-successful SBLA battery. The proprietary plate material/construction developed by ARA satisfies these requirements, and a patent is pending.

There are several other 'quasi-bipolar' lead/acid batteries which have been developed or are under development, but these lack true bipolar plates. These quasi-bipolar batteries utilize either a 'wrap-around' or a 'side-by-side' plate construction, having both positive and negative materials on grids on the same plate. The comparison of ARA's true bipolar design to these two other approaches is shown in Fig. 1. These quasi-bipolar designs force the current to flow through long paths of small plate/grid cross sections. This significantly increases the electrical resistance to current flow through the plate/grid by 5 to 6 orders of magnitude compared to a true bipolar plate, and thus reduces the power capability of the design. Since plate/grid resistance can account for as much as one-third of the total battery resistance, the peak-power capabilities of these design approaches will be significantly less than a true bipolar design.

The SBLA active materials, sponge lead and lead dioxide, are formed from proprietary ARA materials formulations which imparts high porosity, high materials utilization efficiency and long cycle life. The higher porosity contributes to the higher utilization efficiency and power capability. The higher utilization efficiency enables a substantial reduction in active material weight (and cost) and an increase in battery energy density.

Another historical obstacle to developing a practical SBLA battery has been in achieving a practical, reliable, and low-cost method of sealing the multiplicity of cells.

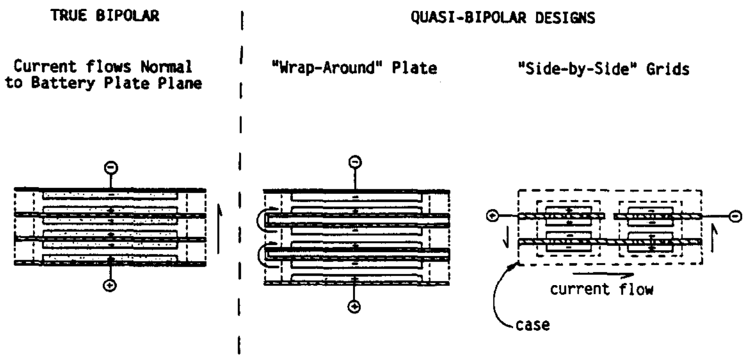

Fig. 1. Basic approaches to sealed bipolar lead/acid batteries (SBLA).

ARA has developed a proprietary method of sealing which provides a reliable seal, rapid battery manufacture, cell venting, and rapid electrolyte filling.

The primary obstacles to developing a commercially-successful SBLA battery in the past have been the bipolar plate construction and sealing method. The proprietary/ patented design features of ARA's SBLA battery appear to have overcome these past difficulties, and should result in a high-performance, reliable and economical battery for extensive commercial applications.

Program status

ARA's SBLA development program has evolved from the initial design studies and computer modeling, through single cell testing, small 12 V battery testing, to fabrication of larger 12 V batteries of sufficient size to start an automobile. The current battery size under development is 12 V/30 A h. ARA's program goal is the development of a 10 kW h EV battery having 750W/kg, 50 W h/kg, and a 3650-cycle life. Power and energy densities approaching ARA's development goals have been demonstrated in current laboratory cells. ARA 12 V laboratory batteries of earlier design have demonstrated 94% and 79% of these goals, respectively, in independent tests conducted at Idaho National Engineering Laboratory (INEL). The INEL tests clearly demonstrate the superior performance capability of SBLA batteries at higher power levels, compared with conventional lead/acid batteries, as shown in Fig. 2. Performance levels of ARA batteries and cells have increased consistently during the past three years, and further increases of 20 to 25% are expected during the next year. Life testing, which is the most time consuming, has been limited and is still in progress. ARA's program goals and results over the past three years are summarized in Table 1.

Applications

To demonstrate the commercial benefits of ARA's SBLA technology, three example battery applications were examined: an uninterruptable power supply (UPS), an electrically-heated catalyst (EHC) battery and a battery for electric vehicles (EVs). These examples demonstrate the potential advantages of ARA's SBLA technology and

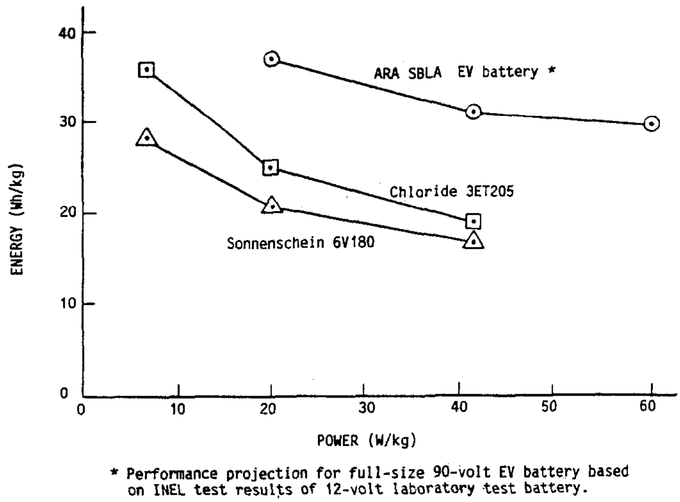

Fig. 2. Energy comparisons at constant power. Chloride Silent Power Ltd. (Worchestershire, UK). Sonnenschein (Büdingen, Germany).

TABLE 1

Summary of ARA SBLA battery development status

	Power (W/kg)[a]	Energy (W h/kg)[b]	Life (cycles)[c]
ARA goals	750	50	3650
Single cell[d]	800	45	>2300[e]
Small battery	665	45	360[f]
Large battery[g]	630	45	*
INEL test results[h]	733	39	*

*Tests not yet conducted.
[a]W/kg for 10 s at 0% DOD (for scale-up to a full-size EV battery).
[b]W h/kg at *C*/2 rate (for scale-up to a full-size EV battery).
[c]Cycles at 50% DOD (3650 cycles = 10 years of average daily use); ARA believes 50% DOD is more representative of average use in most applications.
[d]6 and 12 V batteries with 48 cm^2 electrode areas.
[e]Early JPL tests; no failure at 2300 cycles (testing terminated).
[f]ARA test of early 6 V battery; no performance failure (test terminated due to leakage).
[g]12 V battery with 400 cm^2 electrode areas.
[h]Independent tests conducted at Idaho National Engineering Laboratories (INEL) in May 1992, using earlier design small 12 V batteries (performance shown for scale-up to full-size 10 kW h EV battery).

span the probable range of battery sizes. The examples roughly represent applications for 'small', 'medium' and 'large'-sized batteries. The three example batteries are: (i) a 50 W h, 2.7 kg UPS battery, (ii) a 630 W h, 12 kg EHC battery, and (iii) a 10 kW h, 225 kg EV battery.

These example applications are discussed in detail in the following sections. All SBLA battery characteristics are based on design scale-ups using the performance data obtained from actual ARA laboratory batteries or cells.

Uninterruptable power supply (UPS)

Small UPS systems are widely used to provide backup power for such equipment as personal computers. One of the unusual advantages of the SBLA battery for UPS systems is its higher voltage density, i.e., being able to provide high voltage in a small-size battery. Higher voltage batteries offer two distinct advantages over the conventional low-voltage gel cell batteries currently used in small UPS units: (i) elimination of the power transformer cost and weight, and (ii) reduction in weight due to higher bipolar battery energy and power density.

A very simplified block diagram for a typical UPS is shown in Fig. 3. The line/backup switch can be electromechanical (e.g., a power relay) or semiconductor technology depending on the design. The sensor and power conditioning electronics control the delivery of backup power, battery charging and operation of the backup system status indicators. In a conventional gel cell UPS, the battery typically provides 24 V (E_b), so it is necessary to 'boost' the backup voltage to a level commensurate with the line voltage (E_{line}) and the load voltage (E_{load}) with a power transformer. The power transformer can weigh up to 5 kg for a 200 W, 60 Hz UPS. The gel cell may weigh another 4 kg. Therefore, the minimum weight of a 200 W, 60 Hz UPS would be approximately 10 kg. This added transformer weight contributes to cost, and the transformer can also reduce power-conversion efficiency.

By using a higher voltage SBLA battery, the power transformer can be eliminated. In addition, the SBLA battery has a higher energy density than the gel cell. This results in a weight savings of 7 kg. Also, the bipolar battery has up to ten times the peak-power capacity of the gel cell, which provides additional design margin for handling non-unity power-factor loads.

The battery can be easily charged over a 12 h period with as little as 5 W of charging power and a very small and inexpensive transformer and high-frequency circuits (100 kHz). Using highly efficient power conversion technology with a volume density of 1.2 W/cm^3, only 6 cm^3 would be needed for the charging circuitry and another 10 cm^3 for the housekeeping electronics. This means that only about 16 cm^3 would be needed to house the support electronics if modern high-speed application-specific integrated circuit (ASIC) technology is used in this UPS design [10].

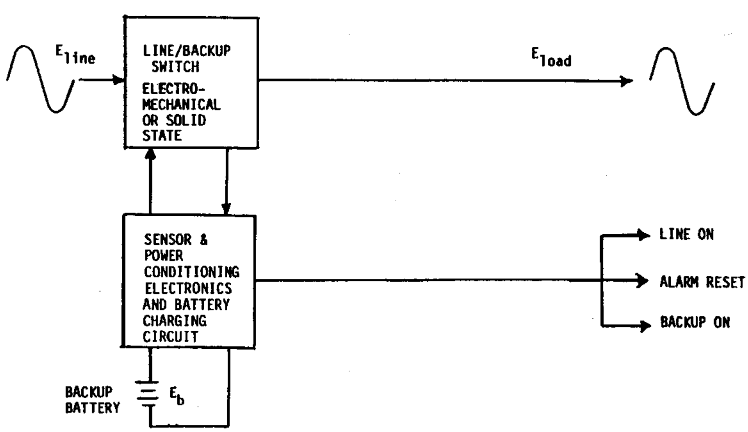

Fig. 3. Simple block diagram of an uninterruptable power supply (UPS).

TABLE 2

Application example for uninterruptable power supplies (UPS)

Characteristics	Battery type	
	Conventional sealed lead/acid	ARA sealed bipolar lead/acid
System rating (W)	200	200
Operating time (s)	900	900
Battery dimensions (mm)	50×150×100	48 dia.×140 long
Battery voltage (V)	6	48
Battery rating (A h/*C*2)	4	0.27
D.c. systems voltage	12	192
Number required	2	4
Total battery weight (kg)	3.8	2.7
Transformer weight (kg)	5.4	0.03
Battery backaging volume (cm^3)	1570	1295
Transformer volume (cm^3)	1050	2.0
Battery cost (US $)	70	82
Transformer cost (US $)	15	3
Total battery and transformer cost (US $)	85	85
Total UPS weight (kg)	10.7	3.5
Total UPS volume (cm^3)	10240	2500

A comparison of a conventional UPS system with a redesigned system based on the SBLA battery is shown in Table 2. It can be seen that the use of the SBLA battery in moderate-size UPS applications offers the potential for substantial reductions in system size and weight as compared to conventional UPS designs. The design can also take advantage of the latest high-speed, high-density ASIC and related power-conversion techniques.

Electrically-heated catalyst (EHC)

It has been shown that electrically-heated catalysts can reduce automobile exhaust emissions by as much as 90% [11]. An EHC, however, requires very high power and up to forty times the energy required to start the engine. This produces unusually high demands on the standard starting-lighting-and-ignition (SLI) battery. Consequently, current fleet test vehicles are demonstrating an EHC battery life of only 6 to 12 months [12] even with two-battery systems (one for engine start and one for powering the EHC). This short battery life is unsatisfactory, and the additional weight is undesirable. ARA's SBLA battery can offer both longer life and lower weight for this application.

In studying the EHC application, the three-battery systems shown in Fig. 4 were compared: (i) a conventional SLI two-battery system now being used in EHC fleet test cars, (ii) a two-battery system using the SBLA battery to heat the EHC, and (iii) a future hypothetical 48 V system, using only one SBLA battery.

A higher voltage automobile electrical system offers many advantages (smaller wire sizes, solid-state relays, etc.), and are being considered by the auto industry [13]. Again, the higher voltage density of the SBLA battery make packaging of a 48 V

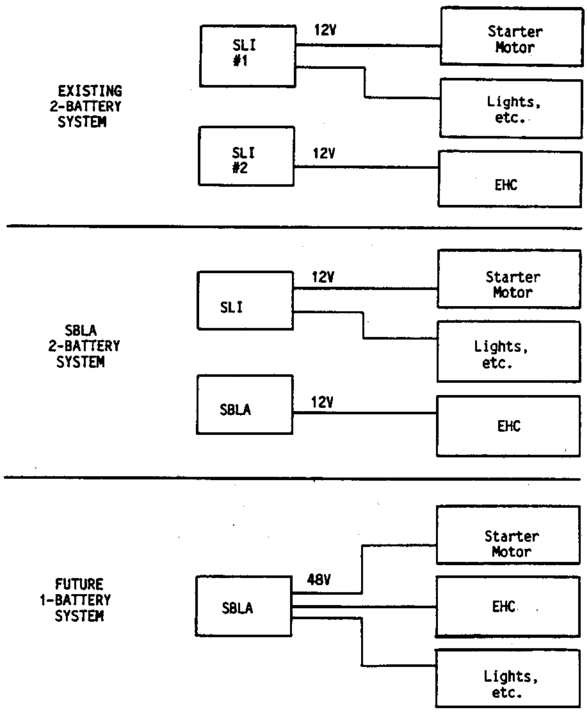

Fig. 4. Comparison of three different battery systems for powering electrically-heated catalysts (EHCs) and other automobile equipment.

system more attractive than with conventional SLI battery construction. The standard SLI battery used in the comparison was the largest available (900 cold-cranking A) from a major SLI supplier, and is the battery now used in EHC fleet tests [12].

The comparison of the three-battery systems is shown in Table 3. The advantages of the SBLA battery are longer life, faster EHC heatup and smaller battery size and weight. In addition, the low-profile envelope of the 12 V SBLA battery would permit it to be located under the car adjacent to the EHC, thereby minimizing electrical cable length and weight. The cost of the SBLA is expected to be approximately the same as a premium-quality SLI battery.

Electric vehicle (EV)

The characteristics of the SBLA battery are ideal for both a hybrid electric vehicle and pure EVs, as has been discussed elsewhere [14–16]. The SBLA battery is compared in Table 4 with a premium sealed lead/acid battery, representing current technology, and a sodium–sulfur battery, representing an 'advanced' technology. The SBLA battery is packaged into 10 kW h modules which fit directly into a number of different EVs, using one, two, or three modules as desired or required. In the example EV, a Ford DSEP-van, three 10 kW h SBLA would be used.

As can be seen in Table 4, the SBLA battery offers significantly higher power which can significantly increase EV top speed, acceleration and hill-climbing ability. The driving range of the EV will be significantly better than conventional lead/acid, and is eventually expected to provide a driving range midway between current lead/

TABLE 3

Application examples of electrically-heated catalysts (EHCs)[a]

Characteristics	Existing 2-battery system	SBLA 2-battery system	Future 1-battery system
Systems voltage (nominal)	12	12	48
SBLA dimensions (mm)		305×305×75	205×230×180
SBLA weight (kg)		13.6	11.8
Total battery weight (kg)	43.6	35.3	11.8
Energy reserve (W h)[b]	630	630	630
Peak power (W)[c]	2640	4600	11700
Heat-up time (s)	10–15	5–10[e]	3–5
Battery life (yr)[d]	0.5–1	>3[f]	7–10[g]

[a]Assumptions: EHC heat energy = 15 W h/start, starter motor energy = 0.8 W h/start (approximative), 3 starts prior to recharge required, 4.5 starts/day average usage, SLI battery has 900 cold-cranking A and reserve capacity is 135 min at 25 A or 630 W h.
[b]Energy reserve for lighting (one battery only, or 48 V SBLA minus engine start and EHC heat-up energy).
[c]at26.5 °C for 30 s through EHC.
[d]EHC battery life; cell testing now in progress.
[e]SBLA battery can be used with a lower resistance EHC unit.
[f]Near-term demonstration goal.
[g]Long-term goal.

acids and sodium–sulfur. The SBLA also offers a number of advantages over the sodium–sulfur system: (i) lower initial cost, (ii) higher electrical efficiency (the SBLA requires no replacement energy for heat loss), and (iii) most importantly, a practical 'stand time', i.e., the SBLA will not 'freeze up' if left unattended for a few days, as will the sodium–sulfur battery. It should be noted that, although the nominal ($C/2$) rating of the SBLA battery is lower than sodium–sulfur and many other batteries, the SBLA provides a higher than expected range in the SFUDS* driving profile because of its ability to meet the high-power (acceleration) requirement until nearly 100% DOD. Lower-power batteries fail the high power criterion earlier than complete discharge, and deliver only 55 to 89% of their capacity compared to discharge at a lower constant power [17].

Conclusions

ARA's SBLA battery development program has reached the full-size battery demonstration phase for some applications (UPS and EHC) and is progressing toward the goal of a full-size 10 kW h EV battery. The SBLA battery will offer the advantages of improved performance, reduced size, reduced weight, lower cost and longer life in many applications requiring a high-power battery. Independent testing of small SBLA

*SFUDS: Simplified Federal Urban Driving Schedule.

TABLE 4

Application example of an electric vehicle (EV)[a]

Characteristics	Battery type		
	Sonnenschein[b] lead/acid	CSPL[c] sodium–sulfur	ARA sealed bipolar lead/acid
Battery dimensions (mm)	280×180×180	1060×560×150	680×760×280
Battery weight (kg)	18	250	225
Battery voltage (nominal)	12	200	180
Battery capacity (kW h/C2)	12	15.9	10
Vehicle weight[a] (kg)	1700	1700	1700
Number of batteries	40	3	3
Total vehicle weight (kg)	2410	2450	2380
Peak power (kW)[d]	99	68	495
Stand time (weeks)[e]	52	1	52
Annual heat loss (kW h)[f]	0	5940	0
SFUDS range (km)[g]	82	238	111[h]
0–100 km/h time (sec)[i]	>40	>40	6.7
Battery price (US $)[j]	3300	7320	3000
90 km/h range (km)[k]	88	224	138

[a]Ford IDSEP-van, 1.705 kg without batteries.
[b]Sonnenschein (Büdingen, Germany).
[c]Chloride Silent Power Limited (Worchestershire, UK).
[d]15 s, 2/3 open-circuit voltage, 100% state-of-charge.
[e]Time vehicle is left unattended (disconnected from recharge power) until battery cannot deliver 50% of stored energy (time until freeze-up for sodium–sulfur).
[f]Heat loss in one year from high temperature (310 °C) sodium–sulfur battery which must be replaced by electrical energy.
[g]SFUDS range based on 695 kg battery weight (standard INEL SFUDS battery weight); SFUDS range for standard lead/acid and sodium–sulfur from ANL (Argonne National Laboratory) test data, SBLA range from INEL test data.
[h]Based on recent tests at INEL of ARA 12 V laboratory batteries; single cell results are significantly higher on range.
[i]Fastest acceleration time, i.e., with battery at 100% state-of-charge.
[j]OEM price estimate, US $; goals for sodium–sulfur and SBLA.
[k]Assume van energy consumption of 218 W h/km.

batteries demonstrates substantial improvements over existing lead/acid batteries, and ARA testing of small batteries and the latest cells show performance approaching ARA's program goals. Battery cycle life testing is in progress, and has already demonstrated a battery life useful for some applications (e.g., UPS).

Acknowledgements

ARA's work to develop the SBLA battery for electric vehicle applications is currently being supported by a Consortium consisting of the Los Angeles Department of Water and Power, San Diego Gas and Electric, California Air Resources Board, and the South Coast Air Quality Management District. ARA believes that the successful development of the SBLA battery will be vital to the success of the current EV

commercialization effort, and the support and encouragement of the Consortium Sponsors is gratefully acknowledged. ARA's work to develop the SBLA battery for EHC applications is currently sponsored by the South Coast Air Quality Management District and the California Air Resources Board, and should assist in accelerating the utilization of EHC technology to reduce automobile exhaust emissions in the near term.

References

1 P. L. Kapitza, *Proc. R. Soc. London, 105* (1924) 691–710.
2 J. J. Rowlette, Optimized Design Variable for High Power Batteries, presented *Proc. 22nd Intersoc. Energy Convers. Eng. Conf., Philadelphia,* 1987.
3 D. W. Kasekert, A. O. Isenberg and J. I. Brown, High Power Density Bipolar Lead-Acid Battery for Electric Vehicle Propulsion, *Proc. Intersoc. Energy Convers. Eng. Conf., 1976,* 411–417.
4 Development of High Charge and Discharge Rate Lead-Acid Battery, Thompson Ramo Wooldridge, Inc., *Final Report for Contract No. 68-04-0028,* 1972.
5 D. T. Poe and M. G. Sandber, *US Patent 3 728 158* (1973); D. T. Poe, *US Patent 3 795 543* (1974).
6 R. D. Nelson, *Design and Fabrication of 300 Volt, 3.6 Kilowatt Pile-type Bipolar Lead-Acid Battery for Pulse Duty,* Gould National Batteries, Inc., prepared for Advanced Sonar Development, *US Navy, Report No. 68D-041,* December 1968.
7 McClelland et al., *US Patent 3 862 861.*
8 J. J. Rowlette, *US Patent 4 539 268.*
9 J. L. Arias, J. J. Rowlette and E. D. Drake, *Design Study of The Sealed Bipolar Lead-Acid Battery for Load-Leveling Applications,* Arias Research Associates, Inc., prepared for Southern California Edison Co., May 1989.
10 CH. Kleiner, Private communication and Design Study, CTK Enterprises, April–May 1992.
11 M. J. Heimrich, *Electrically-Heated Catalyst System Conversions on Two Current-Technology Vehicles,* Southwest Research Institute, San Antonio, TX; S. Albu and J. Osborn, California Air Resources Board, El Monte, CA, prepared for US Society of Automotive Engineers (SAE) Int. Congr. and Exposition, Detroit, MI, 1991, Paper No. 910612.
12 W. Whittenberger, CAMET Corporation, March 1992, personal communication.
13 K. Cardinal, SAE Dual/High Voltage Study Committee, February 1991, personal communication.
14 J. J. Rowlette and D. L. Harbaugh, *Matching Electric Vehicle Battery Performance to User Needs,* Arias Research Associates, Inc., prepared for the SAE Int. Congress and Exposition, Detroit, MI, 1992, paper No. 920832.
15 J. J. Rowlette and D. L. Harbaugh, Battery Goals for EV Hybrids, Arias Research Associates, Inc., *7th Annual Battery Conf. Applications and Advances,* January 1992, California State University, Long Beach, CA, paper 92EV–4.
16 *Advanced Vehicle Systems Assessment,* Vol. IV, Part 1, JPL Publication 84–79.
17 A. F. Burke and G. H. Cole, *Application of the GSFUDS to Advanced Batteries and Vehicles,* Idaho National Engineering Laboratory, Idaho Falls, ID, prepared for the *US Department of Energy, 1990, Paper No. EGG-M—90443.*