The Advanced Lead/Acid Battery Consortium

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Abstract

The Advanced Lead/Acid Battery Consortium, the ALABC, has been organized in order to carry out research to optimize the performance of the lead/acid battery for electric vehicle (EV) applications. A research program has been laid out to develop valve-regulated battery technology for this application, which promises to be substantial due to legislation in the USA and environmental pressures in a number of Europe's largest cities. In order to carry out this program, the Consortium now consists of fourteen of the world's largest lead producers, twelve battery companies world-wide and several industry suppliers. A four-year program with a budget of some US $19.3 million is proposed, with half of that total coming from the ALABC and half proposed to come from various governmental sources from all parts of the world.

Introduction

Legislation in California, initiated in early 1990, has mandated the implementation of zero-emission vehicles (ZEVs) by 1998 to help alleviate air pollution problems in the Los Angeles basin; subsequently, a consortium of New England states has followed suit. In addition, the City of Los Angeles is building a fleet of hybrid EVs and beginning in 1993, a portion of Federal and some state vehicle pools will begin conversion to 'alternative-fuel vehicles', among these possibly being EVs. Similar considerations apply for several of Europe's larger cities. In cities such as Milan, Athens, Madrid and London, pollution levels can become so high in the central areas as to render them dangerous for human life. Through CITELEC (European association of cities interested in the use of electric vehicles) the situation is being evaluated and courses of action are being considered. One solution is to eliminate combustion-type vehicles from the central sectors and bring goods in from peripheral staging areas with electric vans and passenger vehicles. Analogous situations apply in other areas of the world (Mexico City, Tokyo) and no doubt some forms of legislation promoting the use of EVs will result.

To help meet these needs, the Federal Government and the US automotive industry have established the United States Advanced Battery Consortium (USABC) to oversee development efforts and provide funding at a level of US $262 million over the next three years. In order to meet a vehicle production date of 1998, a full-scale battery feasibility demonstration and pilot-scale production capability is to be demonstrated by late 1994. The USABC program is, by design, high-risk, high-cost and, most importantly, long-range. If these undeveloped technologies experience technical roadblocks and/or are not accepted by users for reasons of cost or safety, the USA has no short-term program. In other parts of the world activity is substantial, but no

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comprehensive program exists to develop a second-generation lead/acid product to sustain the growing EV market in its early stages, and possibly beyond.

In June of 1991, ILZRO convened a panel of lead/acid technology experts from around the world to evaluate the position of lead/acid development relative to what would be needed for the first EVs produced for both commercial and consumer applications. The Research Plan that resulted from that meeting served as the technical nucleus for the development of the Advanced Lead/Acid Battery Consortium (ALABC). Further refinement by ILZRO staff members and technical experts from all the Consortium member companies has resulted in a document which clearly demonstrates that with a coordinated research effort over the next four years a lead/acid battery system can be produced that will be adequate to support a fledging EV industry. The research consists of three programs targeted at areas of lead/acid technology needing the most improvement and relating to EV performance areas that are the most critical, namely:

- improvement in specific energy (W h/kg) and battery life
- battery system monitoring and control
- rapid recharge optimization

A systems approach is also emphasized in order to get the most out of even an optimized lead/acid battery system. By targeting the battery as one part of a complete vehicle, in conjunction with significant support technology tailored to enhance the strengths of lead/acid batteries, the road toward formulation of a viable R & D program has begun.

Status of battery development

For the past hundred or so years, those EVs that have been developed for commercial purposes have used flooded lead/acid batteries employing technologies similar to those found in ordinary automotive engine-start and traction batteries. These have served reasonably well and for decades have been successfully implemented in fleet vehicles such as delivery vans and milk wagons in Europe. These applications have largely been relatively short-range, highly-periodic duty cycles with careful maintenance and thus are quite different from what is contemplated for future transportation needs later in this decade. The latter will require batteries and vehicles for commercial and private use with longer range, greater safety, more robust performance and the ability to operate with reduced, irregular maintenance schedules. The lead/acid batteries now in use, though proven feasible on a limited scale and clearly manufacturable, will not do the job in a broader applications sense. They are heavy, have unacceptably short lifetimes, require frequent maintenance, experience excessive gas generation levels and have the potential for acid electrolyte spillage. Still, lead/acid technology must continue to be considered as the primary battery for EVs because of its many inherent advantages, namely:

Low-cost, abundant materials

Lead is relatively inexpensive and availability should not be a problem during this decade when the EV industry is ramping up. When yearly quantities of new lead (all spent batteries will be recycled) exceed roughly 100000 tons, cost and availability may become issues for the domestic US market. Worldwide, lead availability should remain adequate for the foreseeable future.

Technology and manufacturing

Lead/acid batteries have been researched and manufactured for well over hundred years. The technology is proven and well understood, though not perfected. Manufacturing methods are very refined and even production of a new type of lead/acid battery such as a bipolar design will be done on a broad, stable base of production technology and know-how.

History of EV development

Lead/acid batteries were used in EVs early in this century. Over the last thirty years they have been studied in EV applications extensively, particularly in the areas of thermal management and capacity/cycle life trade-offs. They have been and are in use in fleet applications in Asia and Europe and while their performance levels are not entirely satisfactory they are acceptable for some uses right now.

Safety

The safety of lead/acid batteries has been demonstrated through millions being in use for decades with minimal safety problems. Those areas of battery design and performance that can result in safety issues (spillable acid, high gassing levels) are largely ameliorated by the valve-regulated lead/acid battery technology proposed for implementation (*vide infra*).

Servicing and recycling infrastructures

Systems to service EV batteries and deal with spent units are largely in place and need only to be augmented. A long history of servicing of deep-cycling batteries for golf carts and marine applications ensures that dealing with lead/acid EV batteries will be a smooth transition. Automotive batteries are now recycled at a level of 95% or more and due to their size and nature it is assured that EV battery systems will be 100% recycled and thus would have no adverse environmental impact. Recycling technologies for lead/acid batteries are well understood and have been in operation for many years.

Performance improvements

Though it has been studied for many years, lead/acid technology still has the potential to be significantly improved. Valve-regulated batteries are an advanced form of lead/acid technology that can carry performance levels of this electrochemical couple to impressive new levels.

The various advanced battery couples now under active development have certain more attractive operating characteristics on paper, but are not even close to commercialization and each has drawbacks at best only comparable to the existing lead/acid technology. Long-term development of one or more of these advanced battery systems is desirable for the establishment of a mature EV industry. However, it is not likely that this can happen for any of the other advanced battery couples mentioned above on a timescale suitable to meet current and future needs. One or more of these battery couples may be commercialized within the next 10 to 15 years, but this does not address the near term, when widespread EV implementation is scheduled to take place. A low-risk, low-cost technology that offers good performance is needed to buy time for perfection of these other systems and promote acceptance of the concept of EVs in the public mind.

For near-term implementation, the most likely candidate for an EV power source is some form of valve-regulated lead/acid battery (VRB) that is designed specifically for EV duties. The VRB is a second-generation form of lead/acid technology derived from the traditional flooded system, but with operating and safety characteristics far superior to its predecessor. The system was first commercialized in small single cells in 1973. Since then, it has been developed in various configurations and sizes by numerous battery companies around the world, both for unique applications and as direct replacements for existing flooded lead/acid and nickel–cadmium batteries. VRB technology fundamentally incorporates flooded lead/acid electrochemistry, but also utilizes the principles of gas recombination to yield products with high-specific energies and power delivery capabilities. Also, they are truly maintenance-free, due to their valve-regulated design and the absence of any free electrolyte. They are spill-proof, can be used in any position (on their side, for example), and will only vent small amounts of dry gases (no acid spray) under all but the most abusive, conditions. VRBs are routinely used as integral electrical components in extremely delicate and expensive medical and telecommunications equipment and are finding rapidly-increasing acceptance in portable devices, telecommunications and computer stand-by applications in proximity to office personnel. This technology has resulted in a transformation of the traditional lead/acid workhorse into a high-tech thoroughbred with advanced performance capabilities that have opened up many new applications previously not accessible to lead/acid batteries. In summary, VRBs are based on a new, advanced technology that has been proven to be widely manufacturable and has the capability to greatly extend the operating characteristics of a lead/acid-based EV.

Although VRB technology has come a long way in its brief lifetime of some 25 years, it will require a broad, coordinated research program among battery manufacturers and research laboratories around the world to yield a system specifically designed and optimized for EV usage. Until now, these products have been largely developed for portable equipment, stand-by power and deep-cycling applications on a limited basis, although gelled-electrolyte versions are now being introduced into battery-powered baggage-handling carts at some airports in Europe.

Formation and objectives of the ALABC

One June 6–7, 1991, a panel of scientists from North America, Europe and Australia met with ILZRO staff to draft a Research Plan for lead/acid development in response to the USABC call for proposals. The plan was developed and submitted to US Department of Energy (DOE) and the USABC. Their stated position was that lead/acid is considered a short-term technology and further development should be carried out by the battery industry, and thus is was rejected. Subsequently, ILZRO called a meeting of interested parties in Washington, DC, on November 7, 1991, for the purpose of forming a separate battery consortium for lead/acid technology. The consensus was favorable and the original Research Plan was modified to reflect what the battery industry members felt could be achieved with an aggressive, effective research program, in contrast to the thrust of the original Plan, which was meant to meet the mid- and long-term goals set by the USABC, as shown in Table 1.

These criteria are reflective of a critical assumption driving the USABC program, namely that in order for EVs to be accepted by the public they will have to possess performance characteristics comparable to present gasoline-powered vehicles. This assumption is not valid for commercial fleet vehicles (which are likely to be the first large-scale market for EVs) and it is questionable even for consumer vehicles. It is

TABLE 1

US Advanced Battery Consortium (USABC): advanced battery technology—primary criteria

	Mid term	Long term
Power density (W/l)	250	600
Specific power (W/kg) (80% DOD/30 s)	150 (200 desired)	400
Energy density (W h/l) (*C*/3 discharge rate)	135	300
Specific energy (W h/kg) (*C*/3 discharge rate)	80* (100* desired)	200
Life (years)	5	10
Cycle life (cycles) (80% DOD)	600	1000
Power and capacity degradation (% of rated specifity)	20	20
Ultimate price (US $/kW h) (10000 units at 40 kW h)	<150	<100
Operating environment (°C)	−30 to 65	−40 to 85
Recharge time (h)	<6	3 to 6
Continuous discharge in 1 h (no failure)	75% (of rated energy capacity)	75% (of rated energy capacity)

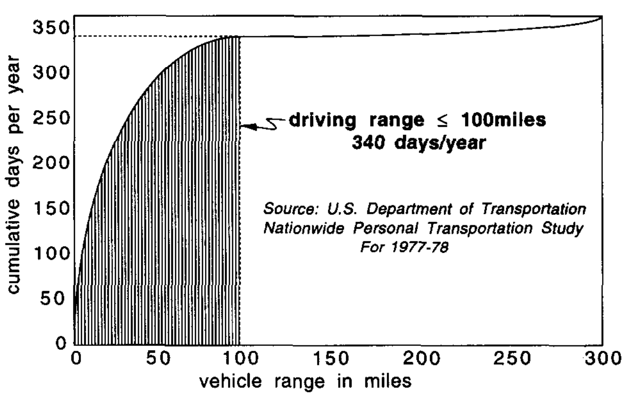

Fig. 1. Typical daily travel characteristics for North American vehicles, statistics of the US Department of Transportation for 1977–1978.

estimated that driving ranges in some of Europe's cities are only in the region of 20 to 50 kilometers per day and even in the USA a vehicle with a driving range of 100 miles would be adequate on most days, as shown in Fig. 1. While the data for this Figure are quite old, it is probably the case that a similar study in large urban areas in North America, taken now, would show an even lower driving range.

Since then, further meetings have been called to crystallize the structure of the organization, broaden the membership base and complete development of the Research

Plan. Regional Technical Committees have been formed and have met several times and a limited amount of research will begin as early as July of 1992.

The ALABC is comprised of lead producers, lead/acid battery companies and associated industries such as charger and equipment manufacturers, separator companies and the like; trade organizations will also be welcomed to join. The sole purpose of the Consortium is to sponsor research and development programs aimed at producing a lead/acid battery system with superior qualities for motive power uses and in high production volumes. However, the technological advances anticipated from the basic research may also be relevant to other lead/acid battery applications. Roughly 50% of the program envisioned has to do with fundamental aspects of lead/acid technology, although the focus is on EV performance.

The research results from this program will be freely available to any organization wishing to utilize them. Discoveries of a significant nature may be patented but licensing will be allowed for nominal sums. This is meant to be an 'open' program which will serve as a technology pool from which battery companies can draw information to aid in their individual EV development efforts. The ALABC will help ensure that appropriate investment will be made to develop the needed technological advances for lead/acid EV batteries, which may not be possible, if attempted by battery companies working on their own in isolation. This mechanism is intended to ensure the participation of battery producers, who will be full partners in the planning and administration of the program.

The core of the ALABC is a partnership among lead producers, battery manufacturers, suppliers to the battery industry and vehicle manufacturers; other participants may include motor manufacturers, controller manufacturers, electric power companies and others. ILZRO staff will be responsible for administrative and research management of the program, in conjunction with personnel from the appropriate member companies.

While the structure of the ALABC is still evolving, the final form will be along the lines shown in Fig. 2. The Steering Committee will be comprised of one representative from each member organization of the ALABC; this Committee, in concert with a smaller executive group, will handle the overall conduct of the Consortium and will exercise final approval of the research program and contractors recommended by the Technical Committee. The latter will be comprised of member representatives from three regional subcommittees, as shown, who will be involved in the organization and monitoring of research programs suited to regional preferences and capabilities. To as great an extent as possible, moneys raised in each region will be invested in research carried out in that part of the world, with exceptions being due to overall Consortium needs or well-qualified researchers being found in another part of the world. The Technical Subcommittees will meet as needed and there will be Consortium technical meetings once or twice a year at sites or events convenient for the majority of the members. The Public Affairs and Marketing Committee and Subcommittees will be responsible for publicizing the Consortium's activities, identifying market opportunities and securing matching government funds, where appropriate. Meetings are approximately on the same timetable as for the Technical Committees. The central focus of the ALABC is research, in the form of projects, and effective project management to ensure that the maximum level of funds go into actual research work, and a minimum for administration.

The mission of the ALABC is to develop a lead/acid battery system that will capture a significant share of the EV market in the short- to mid-term. Such a battery system, however, is only intended to be a vehicle for technology development and is not meant to be directly commercialized. As mentioned, the research program is seen

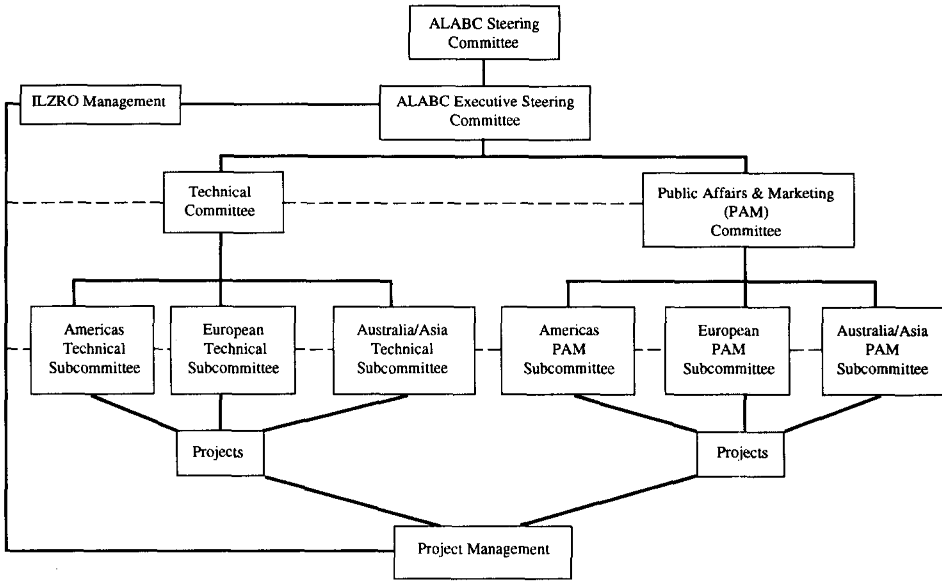

Fig. 2. Advanced Lead/Acid Battery Consortium Committee structure.

as a technology pool to be used by the Consortium member battery companies and others to aid their own individual EV battery development programs.

To accomplish this, the following strategic objectives have been set for the Consortium:

- improve the lead/acid battery through R & D
- maximize research funds spent on R & D in the short term: 4 years ≈US $19.3 million
- optimize research funding from governments and other organizations worldwide
- seek contributions from as many interested parties as possible
- demonstrate the system in one or more vehicles
- increase market share for all participants

This program is meant to be complementary to the objectives and goals of the USABC, and not be in competition with it. It is meant to fill the short-term void left by the USABC program as a result of its focus on high-risk, long-term technology development. In addition, development of a viable lead/acid technology will 'buy time' for the start-up of the EV industry until the more advanced technologies become available.

The lead producers are providing the majority of funding for the ALABC because they realize that better EV batteries will promote market growth and maximize the share for lead/acid. The Consortium has been structured to make it attractive for battery companies to join, as it is evident that their participation in the planning and execution of the research program is essential to its success. For an investment of US $25 000/year they will have access to a research program of some US $3–4 million/year whose results are usable in their own programs, which may not even involve EV development. Suppliers and equipment manufacturers benefit by enjoying extensive interactions with potential customers worldwide and through expanded sales volumes as a result of the growth of the EV market. All the participants benefit from knowing that this program will result in products that will reduce global emission levels of various gaseous pollutants directly attributable to the internal combustion engine.

ALABC research plan

Plan overview and organization

The research is targeted at areas of lead/acid battery technology that require substantial development effort to bring performance levels up to those needed for a viable EV product. This program will be multidisciplinary, and will require worldwide participation to be successful. As an overview to the three programs, which will be discussed in some detail in the following sections, the Plan has three discrete aspects:

- fundamental and applied battery research and development
- systems development for monitoring/control and rapid recharging
- pilot-plant implementation and manufacturing plan for battery module production

As an adjunct to the last item, the battery modules' performance will be demonstrated in existing EV test vehicles. This will involve taking the battery/cell modules developed in the program, building them into a functional EV battery system and mating this with existing platform and shell technologies.

The majority of the research proposed is aimed at improvements in specific energy (which largely translates into driving range) while maintaining or extending service life, power delivery capabilities and designing for effective rapid recharging. Improvements in monitoring and control technology will also be addressed. Power delivery is related to acceleration and hill climbling, while rapid recharging has obvious benefits for fleet applications and could be viewed as a form of range extension for both commercial and consumer vehicles if the necessary infrastructure were in place.

Several features are necessary in an effective EV battery system; these must be considered in developing a research plan for lead/acid technology or, before that, assessing its suitability for EV applications:

- maintenance-free, safe in handling and operation
- immobilized electrolyte
- low gas emission rate/no toxic gases
- good thermal properties
- automated monitoring and control capability
- efficient and fast rechargeability
- adequate range and acceleration
- high reliability and long life
- servicing infrastructure available or at least feasible
- all materials recyclable
- compatible with existing electric utility systems

Taking all of these factors into account the most promising approach is considered to be valve-regulated lead/acid technology utilizing either tubular- or flat-pasted positive plates and either gelled/granular silica or glass microfiber separators. While flat-plate technologies have dominated US battery designs, it was felt that tubular-plate technology for EV applications should be included due to their use in Europe in vans and milk floats and the field-demonstrated superior lifetimes of 5 years/1500 cycles in such uses.

If the type of battery being developed could be portrayed in terms of its discharge performance (as a 100–200 V unit, cycle after cycle!), it would be as shown in Fig. 3, the upper curve. The 'ideal' EV battery would have a high, flat discharge

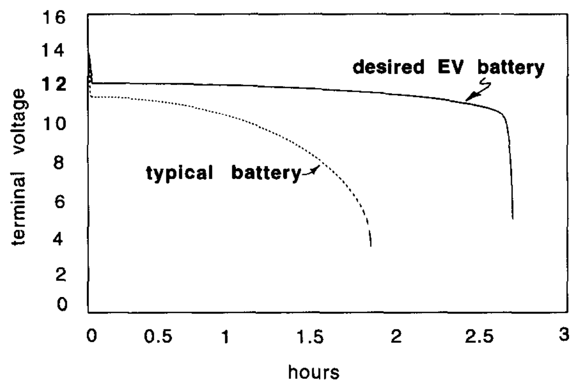

Fig. 3. Discharge curves for 12 V lead/acid batteries at the *C*/2.5 rate of discharge.

plateau with long discharge duration. This ensures constant power delivery over the majority of the discharge duration and a high specific energy value. This curve is for an existing battery, in fact, but not one that is optimized for EV use, and not with adequate specific energy or cycle life for EV use.

Rather than target goals that would provide a vehicle having the same range and performance characteristics as a gasoline-powered internal combustion engine, however desirable, the objectives of the Consortium research effort were set so as to be achievable in light of current capabilities and the development history of lead/acid technology. The following research goals were established:

- improve specific energy to 50 W h/kg at the *C*/3 rate
- achieve 500 SFUDS* cycles/3-year life, with <20% degradation of performance over life
- achieve specific power level of 150 W/kg at 80% depth-of-discharge (DOD)/30 s rate
- develop 100% recharge return in ≤4 hours, 80% recharge return in ≤15 min, 50% in ≤5 min
- develop effective monitoring and control technology
- realize original battery cost of ≤US $150/kW h

These major programs have been broken down into subcategories; for each of these time and cost estimates were assessed and potential research contractors were identified. The overall project plan is available from ILZRO upon request. The research program is summarized in Fig. 4 and some brief comments follow.

PROGRAM I. Optimization of specific energy and service life

Lead is relatively heavy. It has an atomic weight of 207. By contrast, the atomic weights for lithium (7), sodium (23) and sulfur (32) are much lower; even nickel at 59 and zinc at 65 are lighter materials and thus require a smaller mass than lead to furnish the same coulombic output. In small portable batteries this is significant, but it is not a technical barrier. In an EV, however, the obvious need to carry the battery in the vehicle creates a substantial energy drain when a lead/acid battery system is used. This is reflected in the specific energy of a battery couple, or the watt hours provided per kilogram of battery weight (W h/kg). Traditional lead/acid EV batteries

*SFUDS: Simplified Federal Urban Driving Schedule.

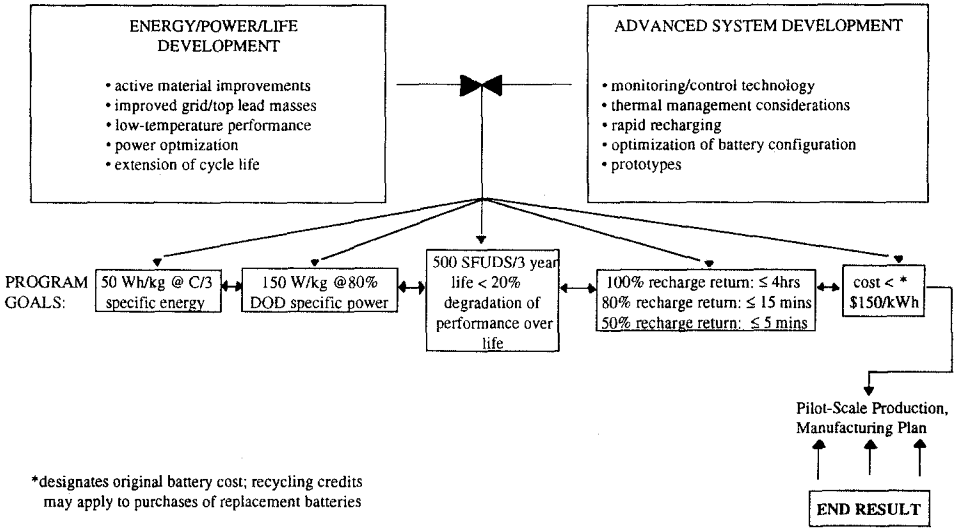

Fig. 4. ALABC four-year research plan and goals.

have had specific energies in the range of 20 to 35 W h/kg at the three-hour drain rate and this has translated into driving ranges of only 60 to 70 miles at best. Most comparisons of the projected performance of EVs using advanced battery technologies with lead/acid have used these numbers and the results have made lead/acid appear to be an inferior technology, by implication in all its forms. VRB products in production or under development for other applications have specific energies of 35–45 W h/kg. This is somewhat at the expense of cycle life compared to flooded lead/acid, but it is clear that such improvements in specific energy are critical to the successful implementation of a lead/acid-based EV technology and thus must be pursued. Low specific energy is clearly the greatest existing shortcoming of lead/acid batteries for EV applications and thus it calls for maximum effort toward improvement. Two approaches will be taken for increasing the battery specific energy, namely, enhanced plate-active material utilization and minimization of material masses not directly associated with the plate charge/discharge processes. It is a prime directive for this work that service life either be maintained or increased; this will be done in part via improved monitoring and control technology. It should be noted that this will be done with special attention to low-temperature performance, an unwritten but real-life requirement of EV batteries, particularly in many northern climates.

Improvements in active material utilization

The usual primary factor limiting the energy output of the lead/acid battery is the utilization level of the positive active material (PAM); in moderate-rate discharge applications such as for EVs, the capacity of the negative plate is well in excess of the positive. However, an optimized EV battery is likely to have almost-balanced positive and negative A h contents and so the negative cannot be ignored. In addition, its efficiency drops off more with lowering temperature than the positive and at high temperatures the lignin fraction of the expander is susceptible to degradation. Therefore, some research must go into achieving the correct paste ratio to maintain performance at low temperatures; at the other extreme, high-temperature expander degradation will also be studied. Plate morphology studies tied into process variations and separator modifications will also be explored to improve low-temperature performance.

In many flooded systems, only about 30% of the PAM is actually involved in providing electrical energy; the other 70%, though theoretically available, is not practically accessible during discharge for a variety of reasons. Valve-regulated technology has raised the utilization level to about 30 to 40%, and some experimental lead/acid EV and bipolar batteries are edging over 50%. However, in order to achieve 50 W h/kg at the *C*/3 discharge rate with long cycle life, further improvements will be needed to raise the PAM utilization level to about 60%. This is considered to be obtainable, and is envisioned as a two-pronged research effort to raise the level of the discharge plateau by increasing the conductivity of the positive active mass and extending the length of the plateau by creating a deeper active porous layer. These combined efforts should raise the positive-plate utilization to about 60%, at which point the performance of the negative plate may be more of a limiting factor. This aspect of the research is seen as taking a full three years and is comprised of three segments:

Generate higher internal usable surface area during discharge via: (i) lower paste density (more reactive leady oxides, improved pasting techniques); (ii) optimized paste composition/morphology (additives and/or crystal growth modifiers—a positive paste expander); (iii) continued consideration of tubular-plate VRB technology in more advanced forms (granular oxides, improved glass mat, gel or granular silica separator); (iv) additives such as perovskites, zeolites, graphitics or glass microspheres to open up the paste structure and provide a stable structural skeleton.

Improve paste conductivity by incorporation of additives in the form of: (i) stable conductive polymers; (ii) tin oxide-coated glass fibers or microspheres; (iii) conducting Magneli phase Ti_nO_{2n-1} or ceramic perovskites.

Negative-plate improvements through studying: (i) optimization of positive:negative paste ratios; (ii) high-temperature degradation of lignin expander components; (iii) low-temperature performance enhancement through plate structure modifications, separator improvements.

Extension of cycle life

In the above research programs it is understood that the enhancement of paste utilization levels must not be at the expense of cycle life (as is traditionally the case), power-delivery capability or other critical performance attributes and it must not add the burden of exceptionally costly or scarce materials. In fact, some of the work in the Section 'Improvements in active material utilization' (see page 10) will be targeted toward extension of cycle life, as mentioned. Service life in an EV application is difficult to predict from data generated for non-EV batteries under different conditions, but published results on VRB cycle/capacity tests are encouraging. Cycle testing will be carried out using the Simplified Federal Urban Driving Schedule (SFUDS), as this regime more accurately reflects what a battery would see in actual driving conditions in contrast to constant-current discharge/recharge cycling typically carried out in laboratory tests.

It is anticipated that cycle life can be extended by the use of single-cell or small-module construction and the implementation of substantial stack compression and separator material that is resistant to electrolyte stratification; optimized positive: negative active material balance will also be explored. While an approach involving the monitoring and control of single cells may be costly in terms of initial investment it may be possible to extend battery life by some 30 to 50% or more by individual cell charging and early detection and replacement of weak cells in the battery system.

Improved grid and top lead masses

A complementary approach to improving specific energy is to reduce the masses of materials within the battery that do not directly provide electrical output. The grids, bus bars and terminals are such materials; they comprise about 30% of the total battery weight and thus it is desirable to eliminate as much of this 'dead weight' as possible. However, this must be done without compromising the battery system's ability to furnish or accept high energy and power levels, without shortening the system lifetime due to complete corrosion of less substantial positive grids or top lead and without causing failure through the effects of vibration. Having said this, the following materials development will be explored:

- development of improved, more corrosion-resistant lead alloys
- cast or expanded composites for grids and top lead
- optimization of paste: grid ratios (fewer, thicker plates) without loss of active material utilization levels
- novel battery designs to minimize top lead and grid amounts

The time scale is such as to have functional units tested and available at the end of a 2.5-year development period.

Program II. Advanced battery systems development

Rapid recharging

In order to have unlimited range and to fit smoothly into typical consumer lifestyles, the ideal EV would have a battery that could be completely recharged in the 2 to 3 min that it takes to fill an existing internal combustion engine (ICE) vehicle's fuel tank. If the battery were a primary type and had to be mechanically replaced this would be a possibility. Development of the infrastructure to support such a technology is complex, however, and any rechargeable battery based wholly or in part on liquid or solid diffusion processes and porous electrodes would not be compatible with this time requirement. Such rapid recharging, though desirable, is not necessary for widespread application of either commercial or private electric vehicles. As a bare minimum, a 6-hour charging period is necessary for overnight 100% charge return and between these two extremes it is safe to assert that the faster the battery can be *safely* recharged the better. As mentioned above, electrochemical systems with good specific energies generally have unacceptably low specific power properties; this not only affects acceleration and hill climbing, but it also severely hinders fast recharging. Among the various candidates for EV batteries, lead/acid and nickel–cadmium, with excellent power characteristics and only moderate specific energies (at present), are the most promising for rapid recharging.

This project is largely one of selecting and combining existing engineering expertise and hardware in the areas of:

- high-wattage charging equipment
- highly-regulated, temperature-compensated chargers
- high-voltage drives and batteries
- thermal management technology to maintain the battery system at a uniform, elevated temperature through efficient heat removal or supply, as well as in cell/battery design to optimize the surface-area-to-volume ratio and make it as uniform as possible, cell-to-cell, within a battery module

Some electrochemical characteristics exist that also must be considered in this program to ensure that battery lifetime is not compromised:

- effect of high recharge rates on plate morphology and cycle life
- minimization of overcharge and attendant heavy gas generation

• development of the most effective cutoff mechanism and hardware (battery voltage/ impedance characteristics, pressure/temperature sensing)
• optimization of battery design for minimal resistance and chemical heat generation, as well as effective heat dissipation

In terms of recharging, the goals of this program are two-fold. The first is to develop a battery system and recharging technology to effectively fully recharge within four hours or less. Considering that EV batteries will not be run to full discharge except in extreme cases, this is not considered to be a technical barrier; such a goal will easily allow for full recharging either overnight, at work or even during extended shopping visits, given that the recharging infrastructure is in place. Such recharging during the day effectively increases the range of most vehicles and facilitates the use of EVs in sprawling urban areas.

The other goal of this program is to develop a charging technology that will allow 'filling up' with at least 80% of the nominal $C/3$ battery discharge capacity within a 15-min time period and/or 50% charge return in 5 min or less. While this will not allow 'at the gas pump' recharging it will improve the versatility of an advanced lead/ acid-based battery technology to take full advantage of situations where 'opportunity charging' is appropriate, particularly in commercial fleet operations (lunch breaks, shift changes, etc.). This offers a powerful means to provide substantial driving range extension for a battery system such as advanced lead/acid with marginal specific energy but excellent specific power. In fact, given this capability, the effective driving range of an advanced lead/acid system with only 'good' specific energy characteristics (50 W h/kg) could far outstrip that of a battery system with superior specific energy but poor recharge performance capabilities. Such an advantage would be applicable to a wide range of commercial and private duty schedules.

Such rapid recharging cannot be accomplished on a substantial scale using existing electrical facilities. Recharging hardware and station designs will have to be developed and the concept of using battery energy storage (load levelling) at such stations will have to be factored in. It is not the goal of this research program to carry this to the demonstration stage, but only to raise the issue and subject it to some scrutiny.

Monitoring and control techniques

Monitoring and control of an EV battery system creates added complexity and expense initially, but as a system function these costs can be more than compensated for in the following ways:
• optimization of charge/overcharge performance
• improved discharge capacity via equalization of state-of-charge of all cells within a battery
• extension of life through efficient thermal management
• early detection (and thus replacement) of weak cells, thus avoiding undue damage to the battery system and resulting in appreciable extension of service life for the system as a whole
• development of an effective 'fuel gauge'.

Such an electronic system is necessary for any type of EV battery chemistry, but for lead/acid it can provide really substantial benefits, as enumerated above.

The system envisioned would utilize individual cells in a single series string with a battery voltage of about 180 V (thus enabling the use of readily-available 210/220 V mains power levels common in many areas of the world) and a nominal cell capacity of about 140 A h; this would yield a roughly 25 kW h/500 kg battery system which would be usable in a small passenger vehicle and provide a driving range of about 100 miles. Each cell will be fitted with sensors and/or have the following cell parameters measured or calculated:

- voltage
- temperature
- resistance or conductance
- internal gas pressure

These data will be collected, along with additional values such as charge current, ambient temperature, etc., to carry out single-cell charging (if necessary), fast battery recharging, discharge voltage monitoring and kickout for individual cells and development of an effective algorithm to accurately indicate the discharge capacity (and thus driving range) remaining.

This phase of the program will clearly involve exhaustive monitoring and control experiments and is intended to be of a pure R & D nature. It will provide fundamental, detailed data on how individual cells function in long strings. This information will then be translated into development of a generic monitoring and control system that will be suitable for use with lead/acid EV battery systems. It is intended largely to demonstrate the principles involved and clearly identify the parameters that require careful monitoring. As a final step, battery performance and life will be tested with and without the monitoring/control system in use.

This program promises to be a powerful tool in extending the service life of the lead/acid system, in facilitating rapid recharging and, ultimately, in lowering the long-range cost of the battery.

Program III. Pilot-plant manufacturing, feasibility testing

The first two Programs of this Research Plan can be broadly considered as precompetitive and, at best, would result in technology and a cell/battery module or modules that could be used as building blocks that virtually any battery company could use in their program. It is largely applied research and it may be that due to the funding available and nature of the ALABC this would be as far as the work would go. Nevertheless, a third Program is deemed desirable, if not necessary, to carry out a detailed technology assessment (of Programs I and II) and implementation of a pilot plant and manufacturing plan for battery production, along with integration of the battery system into a workable vehicle. The last phase may be done in conjunction with power train and vehicle developers and manufacturers, and is necessarily vague at this point. Details of the Program are contained in the ALABC Research Plan and will not be expanded upon here. Again, the full Research Plan is available from ILZRO upon request.

Summary

While traditional lead/acid battery technology is clearly marginal for broad EV markets, the advent of valve-regulated lead/acid batteries (VRBs) over the last 25 years offers considerable promise for the continued use of lead-based batteries in EV applications. Performance levels of VRBs are higher than those of flooded lead/acid batteries; they are maintenance-free; they can be used in any position, and they are safer (due to reduced gassing levels and the absence of any free electrolyte). Thus, VRBs are routinely used in applications requiring proximity to personnel and delicate electronics equipment. Most importantly, VRBs are capable of meeting most of the performance criteria for a viable EV advanced battery technology and thus they clearly merit consideration for development over the next four years. VRBs offers a low-risk, relatively low-cost interim EV technology that can effectively 'buy time' for other advanced battery systems that may require more effort to bring them to a commercially-viable status.

The ALABC research program envisioned to enhance the already considerable performance capabilities of VRBs for EV use is comprised of three major segments:

- improvement in specific energy, power density and service life
- development of an integrated battery system allowing for rapid recharge, good thermal management and automated monitoring and control
- establishment of pilot-plant facilities and integration of mass-manufactured batteries into test vehicles

Over the next four years, a funding level of US $19.3 million is proposed for a multidisciplinary program to be carried out by battery companies and other research facilities around the world. This work will ensure that a viable advanced battery technology is available in the near future to meet the economic, environmental and legislative requirements to implement programs requiring widespread application of EV systems. Lead/acid technology is the primary candidate for near-term EV battery production on a large commercial scale and with even moderate sucess in this research program it promises to offer acceptable performance well into the next century. It can be viewed as being complementary to the USABC long-term advanced battery program in providing a near-term answer and it will also serve as a backup in the event that the successful completion of the long-term program is delayed. Such a program can and will be carried out by the ALABC.