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AC Delco Systems' advanced valve-regulated lead/acid battery for electric vehicles

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Abstract

AC Delco Systems is committed to providing the battery and associated battery-pack system for the General Motors' electric vehicle, the Impact. This paper provides an overview of the efforts involved in developing the advanced, valve-regulated lead/acid battery and battery-pack system intended for use in this vehicle.

Keywords: Lead/acid batteries; Valve-regulated lead/acid batteries; Electric vehicles

1. Introduction

This paper provides an overview of AC Delco Systems' efforts to develop an advanced, valve-regulated lead/acid battery (VRLAB) and battery-pack system. While the battery will be suitable for a number of electric-vehicle applications, the development work done at AC Delco Systems and the North American Operations (NAO) R&D Center of General Motors is aimed specifically at providing the energy requirements for General Motors' (GM) advanced electric vehicle, the Impact.

2. Battery selection

In 1990, Clean Air legislation was passed in California. This included a mandate for the sales of zero emission vehicles (ZEVs) by volume car producers. Specifically, ZEVs are to account for 2% of the vehicle sales in that State by 1998. This fraction is slated to increase to 10% by the year 2003. Twelve Northeastern States and the District of Columbia may adopt similar legislation. Practically, given the state of technology today, the ZEV requirement can only be satisfied by electric vehicles (EVs). Consequently, all of the major car manufacturers are now heavily involved in development and/or evaluation programs for electric vehicles in order to meet the California mandate. Table 1 contains a list of criteria that are important for the selection of an EV battery system. It was decided early on in GM's electric-vehicle program that an advanced lead/acid battery would be used initially to power the vehicle. While the lead/acid battery has obvious shortcomings with regard to energy density, its low cost and proven track record, both in production and in the field, provided powerful arguments for its use in first-generation electric vehicles.

Table 1
EV battery selection criteria

Energy	Abuse tolerance
Power	Sensitivity to environment
Weight	Cost
Volume	Maintenance
Life	Charge retention
Safety	Voltage
Quality/consistency	Recyclability
Manufacturability	

Having selected the lead/acid system, it was further decided that GM's EV battery would be a VRLAB design using absorptive glass-mat (AGM) separators. Such technology provides significant advantages over conventional flooded-electrolyte designs. These advantages are listed in Table 2. The maintenance-free aspect of these batteries is attractive since it alleviates the need for a cumbersome watering system within the vehicle. In addition, because the acid is completely absorbed within the glass-mat separators, acid cannot spill from the battery during shipping.

The charging potentials used for VRLABs are lower than those typically used for flooded-electrolyte designs

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Table 2
Advantages of VRLABs versus flooded-electrolyte designs

Maintenance-free
Non-spillable
Lower charge potentials
Less gassing
Increased cycle life

since, in the latter, the charging potential is usually chosen such that there is sufficient gassing to mix the electrolyte and thereby prevent acid stratification. Thus, in an EV battery pack which includes many individual cells or batteries connected in series, the use of VRLABs allows a significantly reduced charging potential for the pack. Because of the lower charging potentials, VRLABs generate less gas at both electrodes than flooded designs. Further, due to the oxygen-recombination cycle that is operative in this battery, the amount of gas actually vented from a VRLAB is significantly less than the amount of gas that is generated. Most of the oxygen generated at the positive electrode is reacted to form water at the negative electrode instead of being vented. This decreased volume of vented gas enables the battery to be maintenance-free and helps to prolong cycle life.

The superior cycle life seen for AGM-VRLABs versus comparable flooded-electrolyte designs results from several factors. First, and perhaps foremost, the compression of the AGM design physically retains the active material of the plates against the current collectors. The reduced gas evolution in VRLABs is also a boon in maintaining contact between the active mass and the grid since the active mass is less likely to be dispersed by vigorous bubble formation. In addition, the acid-limited capacity of such designs prevents the very deep discharges that are typically found to be quite detrimental to the cycle life of equivalent flooded-electrolyte counterparts.

3. EV battery design and development

AC Delco Systems' EV Battery is an AGM design that utilizes a reinforced case construction to maintain compression within the battery and to aid in battery-pack construction. A flame-arresting one-way vent system is incorporated into the cover using a patented design. Specialized plate and grid chemistries have been specifically developed for the EV application. A low-profile battery design (enabled by a patented intercell battery-connection manufacturing technique) increases the volumetric energy density of the battery by minimizing the amount of headspace.

The battery is now in its fifth generation of development. The earlier prototypes are shown in Fig. 1. The current design conforms to EV battery standards that have been proposed by SAE and JEVA. Performance characteristics of Generation IV are shown in Table 3.

Marked improvements in cycle life have been achieved by the succeeding design generations. Fig. 2 shows both the initial cycle-life goals and the corresponding performance measured for each design generation. Note that by Generation III, the cycle-life goal at 33% depth-of-discharge (DOD) was surpassed and Generation IV showed even further improvement, achieving 2000 cycles at this depth-of-discharge. Because of this success, cycle testing at 33% DOD is no longer conducted. The cycle-life goal at 50% DOD was also surpassed by Generation III. The Generation V battery has exhibited 1600 cycles at this depth-of-discharge.

While improvements have also been made in cycle life at deeper depths-of-discharge, the battery has not yet achieved the initial goal for 80% DOD cycling. Note that if this goal of 500, 80% DOD cycles were achieved for a battery pack in an EV with a range of 100 miles, that would be equivalent to having a pack life of 40 000 miles.

Since, in real use, EV batteries may well be fully discharged a number of times during their useful lives, the results of 100% DOD cycling tests are also of interest. Fig. 2 shows the results of such testing for the Generation V design. It is encouraging to note that while the cycle life is reduced under this most severe cycling duty, it is not reduced radically from that achieved at 80% DOD. Also encouraging are the 100% DOD cycling results, shown in Fig. 3, which were obtained with a modified battery design. This battery achieved over 450 cycles before failing to deliver 80% of the rated capacity. This suggests that the new interim goal of 500 cycles at 100% DOD should be readily achievable.

4. Challenges for the EV battery

In addition to achieving the desired cycle life, a number of other challenges must be met if an EV battery is to be successfully produced. Improvements in both the energy and power density of the battery would be warmly received by EV designers. The serviceability of battery modules within a battery pack is also an important design consideration since replacement of a single battery would be much preferred to complete pack replacement in the event of a battery failure.

One of the major issues facing the production of an EV battery is maintaining the uniformity of the batteries produced. In GM's Impact electric vehicle, motive power is supplied by 26, 12 V batteries (156 cells total) in a single series string. In such a system, it is crucial that all of the cells in all of the batteries behave similarly

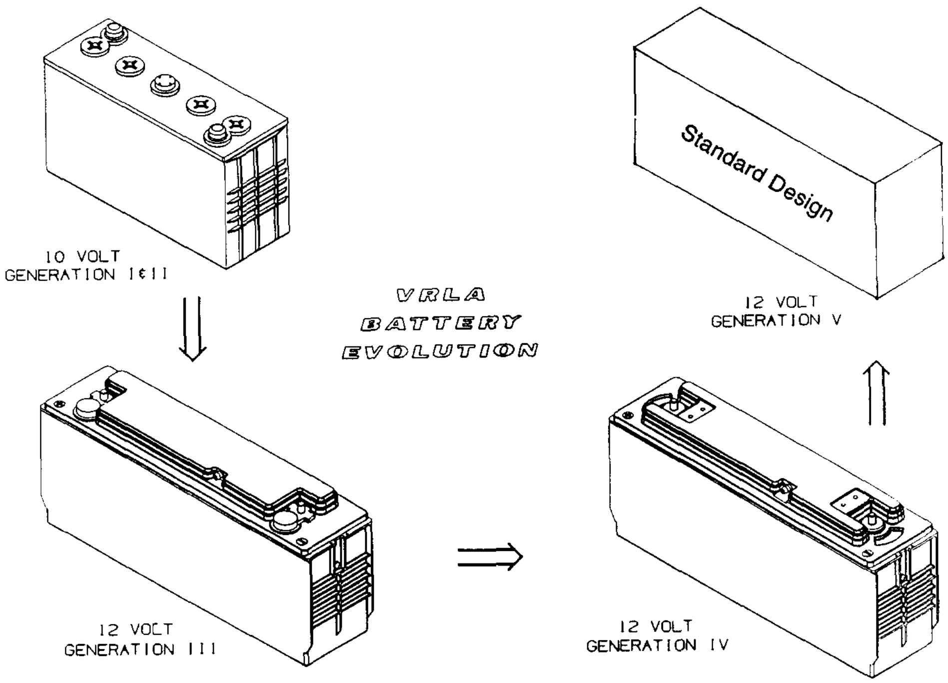

Fig. 1. Several design generations of the AC Delco Systems' EV battery.

Table 3
Characteristics of the Generation IV battery

Nominal voltage (V)	12
Nominal capacity [a] (Ah)	52
Nominal energy [a] (Wh)	614
Battery weight (kg)	17.8
Battery volume (l)	7.43
Specific energy [a] (Wh kg^{-1})	34.5
Energy density [a] (Wh l^{-1})	82.6
Specific power [b] (W kg^{-1})	224
Power density [b] (W l^{-1})	537

[a] 25 A rate at 80 °F.
[b] 400 A rate at 80 °F for 10 s.

since the capacity of the battery pack is limited by the capacity of the weakest cell. To achieve such uniformity will require a tightly controlled manufacturing operation to rival that found in any industry.

On another front, once the batteries have been produced, the way in which they are treated within the vehicle will, to a large extent, determine the long-term performance of the battery pack. Specifically, control methods will be required to prevent battery damage and to recharge the battery pack in an optimal fashion. Towards this goal, the Impact EV will be equipped with sufficient computing power to allow sophisticated control algorithms to be implemented. The development of such algorithms is currently the subject of much work at AC Delco Systems. Various algorithms will be implemented to monitor and control the batteries in the pack for maximum performance and life, and to maintain a record of battery-pack usage and operating conditions for fault diagnosis and service. Specifically, algorithms are needed to:

- provide estimates of state-of-charge and remaining capacity ('gas gauge')
- control the charging process
- limit the regenerative braking energy input
- provide battery-pack diagnostics

Typical inputs for the algorithms include module voltage, current, temperature and time, although others may have to be added to provide accurate measures of state-of-charge and remaining capacity (remaining driving range).

5. The whole package

Instead of merely providing battery modules for GM's Impact EV, AC Delco Systems is committed to providing the entire battery-pack system for the vehicle. The system envisioned must provide the following primary functions:

- manage the energy during charge and discharge
- provide vehicle structure and component retention systems
- provide vehicle voltage and communication interface(s)
- provide an auxiliary power system for vehicle accessories
- provide a thermal management system for batteries

The major components of the battery-pack system are:

- batteries

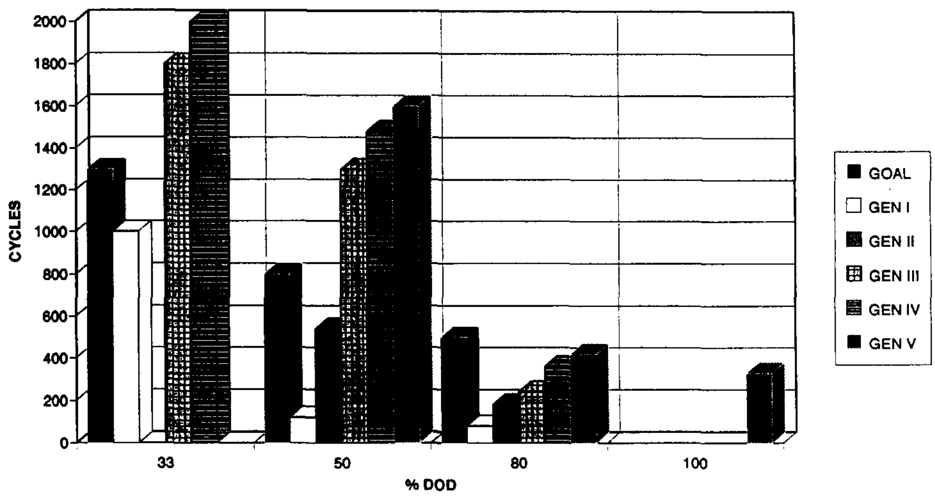

Fig. 2. Cycle life improvements through the design generations of VRLAB. All cycling performed with a 25 A discharge rate.

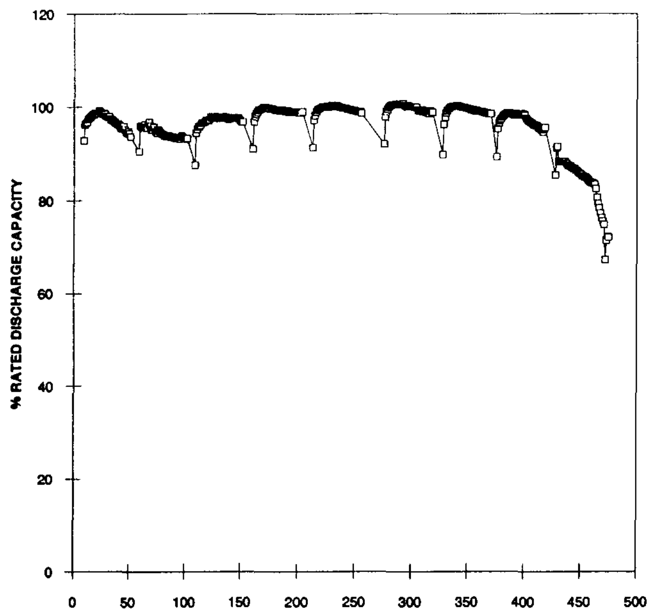

Fig. 3. Cycle life data (100% DOD) from a modified VRLAB design. All cycling performed with a 25 A discharge rate.

- tray and retention system
- manual disconnect system
- automatic disconnect system
- battery interconnects
- voltage/temperature sensing wiring
- thermal system
- output cables
- battery-pack module (computer)

Just as AC Delco Systems is committed to providing a complete EV battery-pack system, so General Motors is committed to developing and producing a complete electric vehicle that will satisfy the driving needs of the public. In an effort to determine how people will use and view the electric vehicle, GM has (along with several utilities) embarked on an EV demonstration and evaluation programme called the EV prEView Drive. In this programme, typical consumers will trade their cars for Impact EVs for periods that range from two to four weeks. Data concerning the drivers' usage patterns and opinions concerning the vehicles will be collected and used to develop further the vehicle and the required infrastructure for EVs. The prEView Drive will utilize 30 Impact EVs in twelve cities across the United States. Over a two-year period, some 1000 drivers will have participated in this programme.

Finally, it should be noted that the Impact is a performance vehicle. Earlier this year (1994), a modified Impact broke the land-speed record for an electric vehicle in its weight class (vehicles weighing over 1000 kg). Over a one-mile course, the Impact averaged slightly over 183 mph. The Impact will be fun to drive!