High-power batteries for the new 36/42 V automotive systems

R.F. Nelson[*]

Recombination Technologies LLC, 909 Santa Fe Drive, Denver, CO 80204, USA

Abstract

The new automotive architectures will require high-voltage, high-power batteries that are completely different from existing 12 V flooded lead–acid products. Battery requirements for these applications are reviewed first from the standpoint of the vehicle, and then from an electrochemical/thermal performance perspective. Design and performance characteristics are then critically evaluated for the three major candidates for the new 36/42 V systems, namely: valve-regulated lead–acid (VRLA), nickel–metal-hydride (Ni–MH), and lithium-ion (Li-ion). Design and manufacturing requirements, performance strengths and weaknesses, reliability issues, markets and pricing are then examined for the VRLA battery, which appears to be the leading candidate at this time. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: 36/42 V systems; High-power; Lithium-ion batteries; Nickel–metal-hydride; PowerNet; Valve-regulated lead–acid

1. Introduction

For decades, the venerable 12 V, flooded, lead–acid automotive battery has served well and long in terms of cranking power, life and low cost. Because of these attributes, it has dominated the engine-start market almost completely. Competitive technologies such as nickel–cadmium (Ni–Cd) and, more recently, nickel–metal-hydride (Ni–MH) and lithium-ion (Li-ion) have been excluded largely due to cost, but also because the existing automotive battery performs extremely well and has been able to evolve over the years to keep up with the changing demands of automobile manufacturers. Even the development of the valve-regulated lead–acid (VRLA) battery, in spite of higher performance levels, has not greatly displaced the flooded lead–acid counterpart.

The recent increases in power-demand levels and operational modes in vehicles have, however, resulted in a fundamental shift in the type of battery required. High-wattage batteries are needed to not just start the vehicle, but to restart it often during use, to provide auxiliary power to the heat engine, and to take up regenerative braking energy for the provision of higher levels of fuel efficiency. In addition, because the battery may be positioned in the passenger compartment and may be considerably larger than existing automotive batteries, safety considerations such as acid spillage and gas emissions mitigate against the current product.

In order to provide higher levels of power, a fundamental choice of going for higher voltages and/or higher battery capacities must be made. Below, we shall see that, for a variety of reasons, it makes more sense to adopt a higher system voltage. Moreover, if it is accepted that the guideline of using 12 V multiples (so that a simple option of putting existing 12 V automotive batteries in series could be used to achieve higher voltages), the most logical choice is to use a 36 V system voltage, with a nominal alternator charging voltage of 42 V. Once the 36/42 V option is adopted, the next question is which battery technology to use. This is a complex issue which involves not only cost and performance considerations, but also the status of the new-architecture vehicle developments and the best-guess timetables for candidate battery manufacturing and infrastructure to be in place to service the needs of automobile manufacturers. This presentation will take a brief look at these issues and then concentrate on the high-power battery requirements which are required to satisfy this potentially huge and rapidly developing market.

2. Battery requirements in new vehicles

In existing automobiles, the primary function of the battery is to provide reliably cranking power to start the engine; it also has to support several key-off loads and key-on operations in conjunction with the alternator; typical power requirements are in the 1–2 kW range. In the newer vehicle architectures due to come out in the 2003–2004

[*] Tel.: +1-303-573-7402; fax: +1-303-573-7403.
E-mail address: nelson909santafe@aol.com (R.F. Nelson).

time-frame, referred to as integrated starter-generator (ISG) or integrated starter-alternator (ISA) systems, the battery will be considerably more interactive and will function continuously in several modes during all of the time that the vehicle is operating. The battery operations include the following.

- Initial engine-start down to −30 °C.
- Launch/boost in conjunction with the heat engine roughly twice per km driven.
- Capture of regenerative-braking energy (regen) roughly twice every km driven.
- Continuous partial-state-of-charge (PSoC) operation to accomplish the above functions with high efficiency.
- Restart the engine repeatedly (roughly once per km driven) and rapidly (~0.3 s), and bring the vehicle up to a speed (so-called 'boost') where heat engine efficiency is high (start–stop operation).
- Support 'airport stand' with off-times of up to 31 days, followed by a cold start.
- Provide data to assess state-of-charge (SoC) and state-of-health (SoH) conditions.
- Support key-off loads, which may be substantial (this may be done by a separate 12 V battery in a dual-battery configuration).

To provide such duty, it is likely that a battery power capability of 6–10 kW will be required at temperatures down to −30 °C. In addition, lifetimes of 10 years or 240 000 km have been set. While a representative duty cycle has not been universally accepted, several possibilities have been offered. One algorithm for idle/start–stop (ISS) operation developed by the Japan Storage Battery Company [1] is shown in Fig. 1. This basic algorithm can be made more characteristic of vehicle service by adding regen and boost steps. A more complex algorithm is given in Fig. 2, the so-called new European drive cycle (NEDC) [2]. In this algorithm, it is
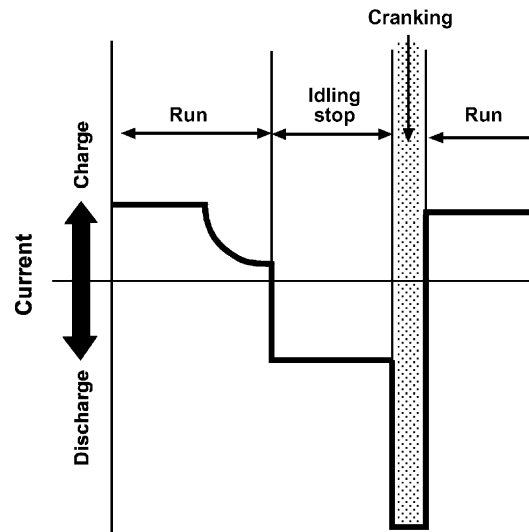

Fig. 1. Simple idle/start–stop (ISS) cycling algorithm for a 36/42 V PowerNet battery.

clear that there is considerable interaction between the battery and heat-engine power outputs, and that the battery is being called upon constantly during vehicle operation in both discharge and charge modes; hence, the need for PSoC operation. The NEDC algorithm is particularly pertinent because it incorporates both urban (0–800 s) and suburban (800–1200 s) drive cycles, with a top speed of 120 km h^{-1} (74 miles h^{-1}) at the end of the cycle; overall, an estimated fuel saving of ~9% is projected compared with normal automotive operation [2].

3. Why go to 36/42 V

It was noted briefly above that simply using a larger capacity 12 V automotive battery was not an acceptable
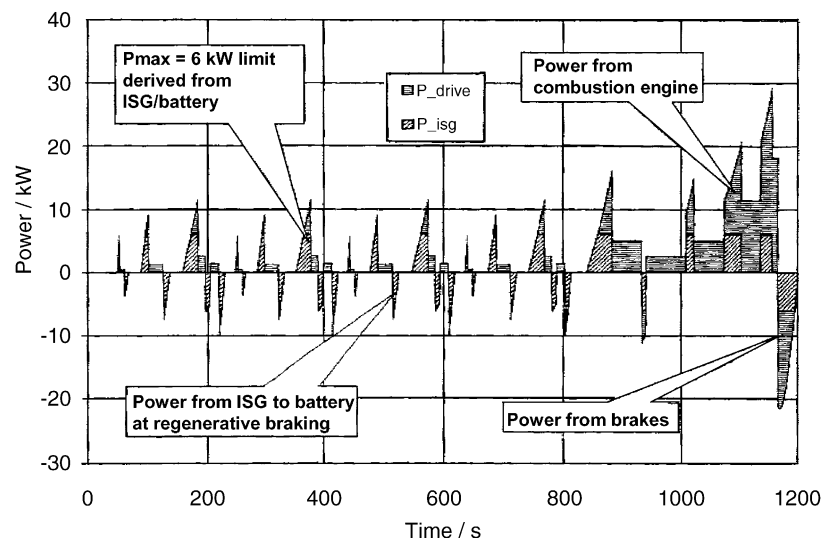

Fig. 2. New European driving cycle (NEDC) with power events which involve heat engine and battery in 36/42 V PowerNet ISG operation.

alternative (although it may be done in some vehicle architectures in the short-term). Moreover, it was considered that multiples of 12 V should be used for design purposes. Given that these constraints are acceptable, why have the automobile manufacturers settled on 36 V?

There are a number of reasons to go to higher voltages, which include the following.

- Each kW of power at 12 V requires 83 A of current; thus, cable size for 10 kW is a considerable problem.
- Using normal 12 V battery cabling, a 12 V/60 Ah (720 Wh) battery with an impedance of ∼12 mΩ will only deliver ∼3.2 kW of power during a 1200 A discharge due to a low system efficiency of ∼35% (because of battery and cable resistances and I^2R ohmic losses). Using the same cabling, a 36 V/20 Ah battery (also nominally 720 Wh) with an impedance of ∼44 mΩ will deliver ∼10 kW of power during a 400 A discharge with a system efficiency of ∼62% [3].
- The cost of semiconductor and solid-state switches drops drastically with increasing system voltage, particularly above ∼30 V [4].
- The voltage must be lower than the safety standard for touch, i.e. 60 V dc, both on open circuit and on charge, including maximum charge and jumper voltage.
- On the other hand, lower voltages are desirable for the battery due to reliability issues: the more cells in series, the lower the reliability.

When all of these factors are taken together, it is clear that 48 V would be too high and 24 V would be too low; 36 V is 'just right'.

4. Required battery capacity and performance

Given that a 36 V battery (42 V charge voltage) has been specified, what rated capacity is needed and what are the most critical performance requirements? As in any application, the smallest battery that will do the job—with a margin of safety—is the obvious choice because the cost is minimal and the performance is acceptable. With a completely new application such as this, however, it is not clear what the minimal capacity would be. Moreover, it is likely to be different for different chemistries (v.i.). The first VRLA batteries developed for 36/42 V use are in the range from 20 Ah (Japan Storage, Yuasa) to 26 Ah (Hoppecke). Nickel–metal-hydride (Ni–MH) batteries, which are also proposed, are in the region of 20 Ah, whereas lithium-ion (Li-ion) products are in the range 10–15 Ah. These numbers are likely to change when all of the performance requirements are taken into account and compared with the weaknesses of each of these chemistries. Most likely, the capacities will be increased somewhat to compensate for inferior performance in one or more areas.

While a standard set of performance requirements has not yet been published by the automotive manufacturers, the following is a fairly representative listing taken from a variety of presentations at various conferences.

- Battery voltage and rated capacity: 36 V/20–60 Ah.
- Required power level (∼10 s): 6–10 kW at PSoC levels between 60 and 80% for both start/boost (discharge at 250–300 A) and regen uptake (charge at 100–200 A).
- Battery will start the vehicle at −30 °C (cranking current up to 500 A).
- Battery will operate up to +50 °C.
- 'Airport stand' requires storage for 30 or 31 days and then engine-start and drive-away capability at temperatures which range from −40 to +50 °C.
- Calendar life of 10 years or 240 000 km driving range.
- Overall operating temperature range from −40 to +85 °C (different manufacturers).
- ∼250 000 Shallow charge–discharge cycles (∼2% depth-of-discharge, DoD) operating in a PSoC range of 50–80%.
- Battery management must determine SoC to within ∼5% at all times.
- The battery diagnostic system must be able to determine imminent failure and assess life remaining.
- Desired cost is in the range of US$ 150–300 (it is clear, however, that Ni–MH and Li-ion batteries will cost considerably more than this).

As with batteries for electric vehicles (EVs) and hybrid electric vehicles (HEVs) in the past 10 years, no chemistry can meet all of these requirements at this time. This is discussed below.

5. Requirements for high-power batteries

While it is clear that a 36/42 V PowerNet battery must have a considerable energy content for continuous operation and good cycling capabilities, it is first and foremost a high-power battery. As such, it should possess many or all of the following features.

- Thin grids, ∼1.0 mm or less, made from high-conductivity grid alloy.
- Thin plates, preferably ∼1.5 mm or less.
- High plate porosities of ∼50–60%, therefore high electrochemical surface-areas.
- Low cell/battery impedance (high plate surface-areas/small inter-plate spacings).
- Conductive additives in both plate active materials to minimize plate polarization during high rate discharge and charge (note, polarization is the departure of the electrode potential from the equilibrium (reversible) value).
- Optimal electrolyte and separator conductivities in the discharge–charge/PSoC operation range of interest.
- Favorable electrolyte distribution/diffusion conditions (small inter-plate spacings, thin paste layers with open, porous structures, large electrolyte amounts in the plates

relative to the separator, liquid electrolyte rather than gel or polymer film).

- High separator compression in the plate stack to facilitate electrolyte diffusion from the separator reservoir into the plate pores, and vice-versa.
- High ratio of surface-area to volume, uniform exposed surface area cell-to-cell, for efficient heat dissipation.
- No 'bottlenecks' for current collection between the plate stack and the external battery terminals.

In summary, a battery optimized for power must have a high plate surface-area per Ah of rated capacity, and it must have a design that results in efficient heat dissipation, since the high currents during discharge and charge, even in PSoC operation where chemical effects are minimal, produce considerable heat just due to I^2R Joule heating.

In this particular application, a balance of energy and power is required for the battery and it must function acceptably in an automotive environment. Thus, in addition to the design features given above, it must have all of the performance characteristics listed in Section 4. Finally, it must be suitable for installation and functioning in an automobile. Thus, performance/design characteristics such as minimal gassing levels, superior vibration resistance and packaging in a standard envelope must be met. The latter is problematic, since automobile manufacturers in Europe, Japan and the USA are requesting different dimensions for 36/42 V PowerNet batteries for their vehicles. It is likely that differences will also exist in connector hardware. Given all of this, global standardization of battery characteristics is not likely. Moreover, there are considerable differences in the capabilities of the three leading candidate electrochemical technologies for this important application. In the following section, these three chemistries will be reviewed and it will become apparent that none of them is suitable in all categories. In fact, each has significant deficiencies that make a clear-cut choice either difficult or impossible. As in most applications, all three types of battery will probably be employed in early models, and it will be a combination of market forces and technical performance that determines the final choice.

6. Candidate technologies for a 36/42 V PowerNet high-power battery

Five years ago, the choice for a suitable 36/42 V Power-Net battery would have been restricted to VRLA; others such as Ni–Cd, Ni–MH and Li-ion would not have been suitable. Even then, Ni–Cd was under severe environmental pressures and both Ni–MH and Li-ion did not have adequate power capabilities to be considered; the latter two chemistries were good candidates for use in small portable devices such as laptop computers and cell phones but they were not then available in larger sizes. Today, Ni–Cd has faded away and Ni–MH and Li-ion have seen tremendous strides

in high-power improvements due to the development of thin-plate designs that sacrifice energy for enhanced power capabilities. Fortunately, these chemistries have specific energies of 80–130 Wh kg^{-1} in thick-plate designs, so energy can be sacrificed for power to a greater degree than in VRLA products. Due to these factors, the three candidates for 36/42 V PowerNet applications must be VRLA, Ni–MH and Li-ion. The following discussion provides a brief review of the strengths and weaknesses of each technology for this type of application.

6.1. Design parameters

A summary of the design parameters for the three battery chemistries is provided in Table 1. There are considerable differences between these batteries. In fact, the batteries could not be more different! All are built commercially in spiral-wound, flat-wound and flat-plate configurations, with all available as single cells and VRLA as true 18-cell monoblocs. Due to single-cell use and thermal-management requirements, the weights and volumes for Ni–MH and VRLA 36 V products are not significantly different; Li-ion does have an advantage in both weight and volume. Initial offerings of all three technologies are in a capacity range of 20–26 Ah, but it is likely that larger capacities may be required for the shortcomings noted. The low electrical resistance of VRLA is a distinct advantage in minimizing Joule, or ohmic, heating and may obviate the need for thermal-management. Energy/power balances are adequate for all three batteries, but Li-ion clearly has the best values under ambient conditions. Calendar life for VRLA is shorter than for the other two chemistries and may require two or three batteries to reach the target service of 10 years. The others, however, may require two batteries and with the cost differences envisaged this is a distinct advantage for VRLA. Reliability and general suitability for automotive use has not been proven in the field for any of these chemistries, but it is likely that all three will be at least acceptable. The problem areas listed are serious for VRLA but all are being addressed in various research programmes (see below); the major uncertainty is manufacturing reliability in a new type of product with 18 cells connected in series. For both Ni–MH and Li-ion, the main concerns are performance at temperature extremes and cost; these will be elaborated later in this section.

6.2. Performance parameters

Selected performance parameters for the three batteries chemistries are listed in Table 2. These are based on data published in the proceedings of various conferences over the past 2–3 years. In some cases, the data are for recently-developed 36 V PowerNet batteries, while in others the information is more general. Again, there is a significant spread in the values, with each chemistry having strengths and weaknesses. VRLA is deficient in the area of cycle-life

Table 1
Comparison of candidate battery technologies for 36/42 V applications: design parameters

Parameter	VRLA	Ni–MH	Li-ion
Cell configuration	Spiral-wound, flat-wound, flat-plate	Spiral-wound, flat-wound, flat-plate	Spiral-wound, flat-wound, flat-plate
Nominal cell voltage (V)	2.0	1.2	3.0–4.0
Battery envelope	Cyclindrical or prismatic, single cells or monoblocs	Prismatic with single cells, flat-plate or cylindrical	Prismatic with single cells, flat-wound or cylindrical
Weight/volume	Heavy/moderate	Moderate/high	Light/moderate
Projected battery capacity (Ah)	20–26 At present, 40–60 for long cycle-life	20–25 Planned, 40–50 for temperature extremes	20–25 Planned, 40–50 for temperature extremes
Electrical resistance, 36 V/25 Ah battery (mΩ)	~15	~28	~20
Specific energy (Wh kg^{-1})	30–40	50–60	80–100
Specific power (W kg^{-1})	250–400	700–1000	700–1600
Calendar life (years)	4–5	>5	5–10
Projected battery reliability	Good (good enough)	Excellent	Good–excellent (no data)
Target failure mode(s)	Grid corrosion, irreversible sulfation, overcharge/overdischarge, mechanical faults	Oxidation of negative material, venting/dry-out, high impedance	Interface passivation, phase changes, corrosion, electrolyte decomposition, am dissolves
Suitability for automotive applications	Excellent for lead–acid, good for VRLA	Unproven	Unproven
Major problem areas	Weight, cycle-life, charge-acceptance, battery reliability	Cost, performance at temperature extremes	Cost, safety, temperature extremes

Table 2
Comparison of candidate battery technologies for 36/42 V applications: performance parameters

Parameter	VRLA	Ni–MH	Li-ion
Energy/power balance	Good, but low values	Excellent, moderate values	Outstanding, high values
Total energy output over life, shallow discharge (MWh)	0.5–1.0	0.8–1.5	1.5–2.0
ISS cycle-life, present	~150000	300000 or more	>300000
Operating temperature range (°C)	−40 to +60	−20 to +50	0 to +40
Shelf-life/potential damage	>2 Years, hard sulfate forms	6–8 Months Capacity loss	~1 Year capacity loss
PSoC operation	Fair, only good charge-acceptance, cycle-life needs periodic recharge	Excellent, except at temperature extremes	Outstanding, except at temperature extremes
Discharge voltage stability (thin-plat products)	Excellent	Good–excellent	Good–excellent
Discharge power (W kg^{-1})			
100% SoC	600–800	700–1200	700–1600
50% SoC (−10 °C)	~450 (~300)	600–1000 (~300)	600–1000 (~100)
20% SoC	450	~700	800
Charge-acceptance (W kg^{-1})			
20% SoC	450	~700	800
50% SoC (−10 °C)	280 (200)	600 (240)	500 (150)
80% SoC	~100	~400	~400
Useable SoC range (%)	30–70	20–80	10–90
Overall temperature performance	Excellent	Good–poor	Good–poor
Need for thermal-management	Little–none	Extreme	Moderate
Battery monitoring	Yes	Yes	Yes
Charge control	Minimal	Probably none	Extreme need
Safety	Very safe	Moderately safe	Relatively unsafe
Recycling/availability	Yes/profitable	No/will cost	No/will cost
Manufacturing/infrastructure	Good, established	Uncertain	Uncertain
Materials availability	High	Moderate	High
36 V/25 Ah battery cost ($ now)	~150	500–800	700–1000
36 V/25 Ah battery cost with peripherals ($ now)	160–190	800–1200	800–1300

and total energy output, but this could be largely overcome through the use of a larger-capacity battery, perhaps in the 50–60 Ah range. The operating temperature range for VRLA is good, but probably not as wide as some automobile manufacturers would like (although 60 °C on the top end is conservative for some VRLA products). Performance at high and low temperatures for Ni–MH and Li-ion may exclude them from this application if improvements cannot be realized within the next few years. The use of larger capacity batteries, to improve cycle-life, as proposed for VRLA, may not provide the answer, as the deficiencies for these two chemistries are systematic for present products.

Shelf-life is an issue for all three technologies, in different ways. VRLA can suffer from irreversible sulfation and the other two chemistries can have irreversible capacity and cycle-life losses for other reasons, particularly at elevated temperatures. PSoC operation is good for VRLA, but charge-acceptance is inferior and periodic full recharges will probably be required. Both Ni–MH and Li-ion have excellent PSoC characteristics, with the latter being somewhat superior due to a wider usable SoC range.

All three batteries are good-to-excellent in terms of voltage stability and discharge power/charge-acceptance. The values given for VRLA are for typical products and values closer to those cited for Ni–MH and Li-ion may be achievable with thinner-plate VRLA products. Again, a larger VRLA battery would greatly enhance the capabilities of the chemistry for 36 V use.

VRLA is superior to Ni–MH and Li-ion in terms of overall temperature performance and the possible need for thermal-management. All require battery monitoring for SoC and SoH estimation, which has to include predictions of incipient failure (most vehicle architectures include electronic braking and steering). Li-ion requires individual-cell charge control at present and this greatly increases cost and complexity.

Safety is a serious issue for Li-ion in a number of ways and both it and Ni–MH will require costly recycling processes, unlike VRLA. Recycling, manufacturing/infrastructure and overall cost are areas where VRLA is clearly superior to the other technologies and this is likely to remain the case for at least the next several years. The costs given for the batteries with or without system peripherals are estimates that may only be accurate to within ~30%.

Taking all of the values in Tables 1 and 2 into account, there is no clear 'winner' at this time, but it is likely, and this has been stated by Toyota and DaimlerChrysler, that the first vehicles manufactured with 36 V batteries will use VRLA technology. This is not to say that this will not change in the long run, but it will take significant cost reductions and breakthroughs in materials and design for Ni–MH and Li-ion to become more competitive. This is predicated on the assumption that VRLA will perform acceptably in the first vehicles manufactured. If this is not the case, then the other technologies will be much more attractive.

6.3. Nickel–metal-hydride strengths and weaknesses

The development of Ni–MH technology has been rapid and impressive. The fact that it is a serious contender for this important application is a testimonial to the capabilities of the various manufacturers who deal with this chemistry. Overall, it is well-suited for 36/42 V PowerNet applications, particularly in terms of its superior PSoC and cycle-life performance, but it has serious shortcomings in several key areas, as mentioned above. Development work over the past several years for HEV applications has resulted in several products that can be used as 36/42 V PowerNet batteries. The following is a brief analysis of the strengths and weaknesses of this technology.

6.3.1. Ni–MH strengths
Numerical values given in Tables 1 and 2 show that, in several areas, the performance of Ni–MH batteries is good–outstanding. The most striking strength areas are as follows.

6.3.1.1. Power/energy balance. Excellent power with good energy over a wide usable SoC range (20–80%) makes this chemistry ideal for 36/42 V PSoC operation in a moderate temperature range.

6.3.1.2. Charge-acceptance. This is excellent for Ni–MH; at 50% SoC and higher it is ~600 W kg^{-1} at 25 °C, but at −10 °C it drops to ~240 W kg^{-1}, which is still an excellent value.

6.3.1.3. Cycle-life. Several manufacturers have published cycle-life data in PSoC operation at ambient temperature out to 300 000 and the products are still cycling.

6.3.1.4. Total energy output. Due to the long cycle-lives demonstrated, the total output of 0.8–1.5 MWh for shallow cycling at ambient temperatures may be conservative.

6.3.1.5. Calendar life. Estimated to be in excess of 5 years, but this is for continuous use at ambient temperatures. With the temperature extremes encountered in automotive use, however, the life may be considerably less than this. For a 10 years vehicle life, this also means that at least two Ni–MH batteries would be required to reach this target.

6.3.1.6. Reliability. Ni–MH cylindrical cell manufacturing has been refined to a point where product reliability is excellent; this high reliability is likely to be extended to the manufacture of 36/42 V PowerNet batteries.

6.3.2. Ni–MH weaknesses
Careful inspection of the entries in Tables 1 and 2 results in the conclusion that, despite all of the above strength points, there are perhaps more weaknesses in performance and that the cost of these batteries is likely to be prohibitive. The most significant weaknesses for Ni–MH are as follows.

6.3.2.1. Weight/volume. With the high values often quoted for specific energy and specific power, it could be concluded that this would be an area of strength. The energy and power densities are not that impressive for Ni–MH, however, and the need for significant thermal-management hardware increases the weight and volume of a finished 36/42 V battery to the point where these parameters are actually greater than values for comparable 36/42 V VRLA batteries. Thus, a typical 36 V/25 Ah Ni–MH battery may have a weight of ∼30 kg and a volume of at least 15–20 l.

6.3.2.2. Self-discharge rate, shelf-life. The self-discharge rate for Ni–MH is high to begin with, but in thin-plate, high surface-area designs such as those for 36/42 V batteries it will be even higher. Values of ∼1% per day at ambient temperatures are typical, but at higher temperatures such as those experienced in a 31 days 'airport stand' a Ni–MH battery at 60% SoC could lose virtually all of its capacity and might not start the vehicle. High temperature self-discharge to low SoCs can result in permanent loss of power capability

and cycle-life. As self-discharge rate is a parameter that is independent of the rated capacity, use of a larger Ni–MH battery will not help with this deficiency.

6.3.2.3. Low temperature performance. All of the impressive performance characteristics for Ni–MH are quoted at ambient temperatures. Recently, Panasonic/Matsushita published results on their new prismatic Ni–MH module that is being used in the Toyota Prius automobile [5]. Although the performance for this product is superior to most or all other Ni–MH cells, the discharge power capability at −30 °C is only about 10% of the ambient temperature level of 1 kW kg^{-1}. Presumably, charge-acceptance would be similarly reduced. Thus, to provide 6 kW of power for cranking at −30 °C a 60–70 kg Ni–MH battery would be required, at a cost of ∼US$ 2000. The contributions of the various components to the total cell impedance is shown in Fig. 3 [5]. It can be seen that Matsushita has made tremendous improvements in reducing the impedance by creating more efficient cell connections in going from a conventional
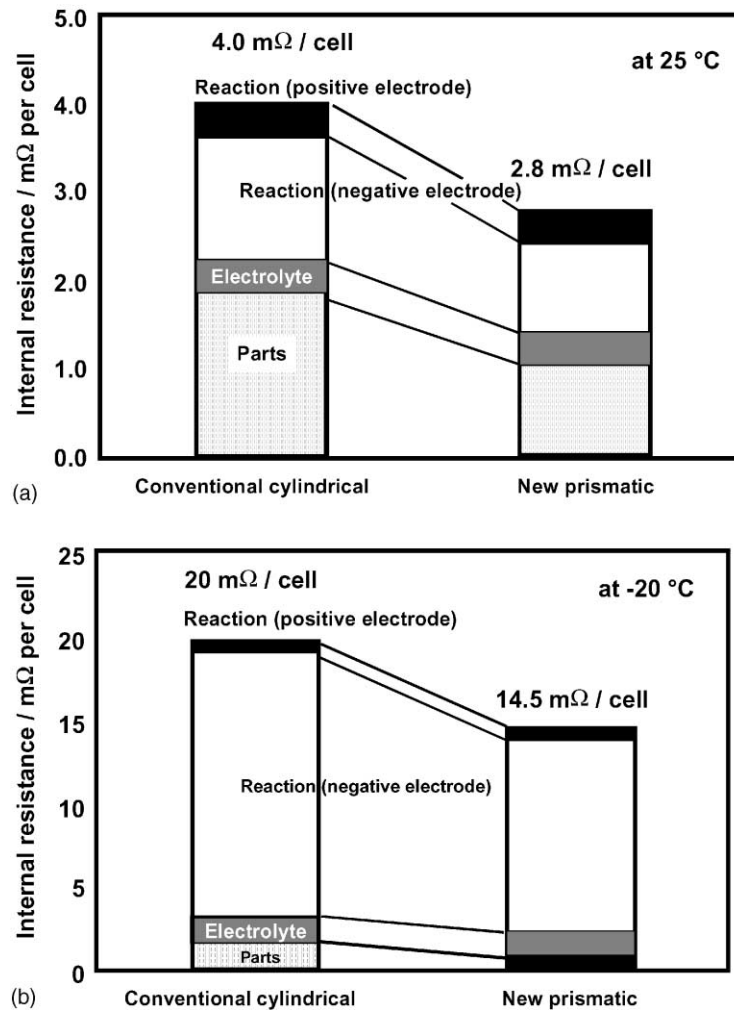

Fig. 3. Contributors to the internal resistance of nickel–metal-hydride cells at (a) 25 °C and (b) −20 °C for Panasonic/Matsushita conventional cylindrical and new prismatic 1.2 V/6.5 Ah cells for 36/42 V batteries.

cylindrical cell to a new prismatic version, but the impedance is still dominated by the negative-plate electrochemistry. At −20 °C, the impedances increase five-fold and here the vast majority of the total is derived from the inefficiency of the negative plate. This is an important defect that will require a materials/design breakthrough to overcome.

6.3.2.4. High temperature charge efficiency. The Matsushita presentation [5] also showed data which indicated that full recharge of their Ni–MH products becomes difficult or impossible at temperatures above ∼50 °C. This is typical for Ni–MH products, but it may not be a critical shortcoming because PSoC operation does not require full recharge and the battery is operating in the range 50–70% SoC most or all of the time.

6.3.2.5. Thermal-management. Both the end-of-charge and discharge processes are exothermic for Ni–MH. This, combined with high Joule heating levels expected in 36/42 V operation from the high currents and high cell impedances, will result in a need for significant thermal-management hardware. It is estimated that for a NEDC cycle with 423 Wh throughput (1.6 kW average power), a Ni–MH cell will experience a temperature rise of 3 °C min^{-1} without cooling [6]. Commercial Ni–MH batteries incorporate liquid-cooling jackets to control temperature adequately. These factors contribute significantly to battery weight, size and cost.

6.3.2.6. Cost. This is the greatest weakness of the technology. As seen in Table 2, a projected cost of US$ 800–1200 is seen for a 36 V/25 Ah Ni–MH battery, but if a larger size is needed for low temperature cranking the cost could be well over US$ 2000. Given that a 10 years vehicle life may require at least one battery replacement, the lifetime battery cost could possibly be US$ 4000 or more.

6.4. Lithium-ion strengths and weaknesses

The development pace for Li-ion has been comparable with, or greater than, that for Ni–MH. High demand for long-run-time batteries in portable devices fuelled the rapid deployment of small Li-ion products. In the past several years, this technology has been considered for EV/HEV and military applications in sizes up to 100 Ah. Thus, it is appropriate to consider it as a candidate for the new 36/42 V PowerNet batteries. As will be seen, it has a number of strengths and weaknesses in common with Ni–MH.

6.4.1. Li-ion strengths
Technically, Li-ion is probably a stronger candidate for use in 36/42 V batteries, but it is not as far along in terms of large-battery manufacturing capability. Still, its strengths are considerable, as follows.

6.4.1.1. Energy/power balance. The balance is comparable with that for Ni–MH, but the absolute values are even greater (60–100 Wh kg^{-1} specific energy, 700–1600 W kg^{-1} specific power) and they are operative over a wider SoC range (10–90%). As with Ni–MH, the drop-off in power capabilities at lower temperatures is extreme.

6.4.1.2. Weight/volume. Because the energy and power values are so great for Li-ion, it has considerable advantages in terms of weight and volume. Thus, a 36 V/25 Ah Li-ion battery is likely to have a weight of ∼10 kg and a volume of ∼6–7 l, given efficient packaging and little in the way of thermal-management peripherals.

6.4.1.3. Cell voltage. On open circuit, Li-ion cells range from 3.6 to 4.0 V; on load, they are typically ∼3.0 V. In either case, it is clear that fewer cells will be required than for VRLA (18) or Ni–MH (30). Thus, Li-ion will have a significant advantage in terms of reliability just due to having a smaller number of cells [12].

6.4.1.4. Discharge power capability. Under ambient conditions, this is excellent. Typically, the discharge specific power may be 1500 W kg^{-1} at 100% SoC and only drop to 1000 W kg^{-1} at 50% SoC and 500 W kg^{-1} at 20% SoC.

6.4.1.5. Charge-acceptance. Regen power is likewise very good at ambient temperatures. It is ∼800 W kg^{-1} at 0–20% SoC (an unrealistic level), 500 W kg^{-1} at 50% SoC, and even 200 W kg^{-1} at 100% SoC. Still, a requirement to absorb 10 kW regen pulses at a nominal SoC of ∼70% would require something like a 25 kg battery.

6.4.1.6. Cycle lifetime. Thus far, testing has shown Li-ion lifetimes in the range of 300 000–400 000 cycles, or more in shallow ISS cycles. At ambient temperatures, lifetimes may be some 50% greater than for Ni–MH and at least double that for VRLA.

6.4.1.7. Total energy output. The value given in Table 2, viz. 1.5–2.0 MWh, is outstanding and may be conservative for this technology.

6.4.1.8. Calendar life. Under ideal conditions, this should be in excess of 5 years; Saft and co-workers quote a lifetime of 10 years or more [7]. Given the vagaries of automotive operating conditions, it is likely that in a 10 years span a 36/42 V Li-ion battery will require at least one replacement.

6.4.1.9. Cost. Unlike Ni–MH, Li-ion promises ultimately to have a fairly low cost, though not on the scale of VRLA. This is difficult to predict, but because of the low materials costs for Li-ion it may have a long-term cost of US$ 300–500 for a 36 V/25 Ah battery with peripherals.

6.4.2. Li-ion weaknesses
As with Ni–MH, Li-ion has serious weaknesses, some of which may be very resistant to resolution. Since it is not

quite as far along in development as Ni–MH, the situation is less clear as to how and if some of the following major weaknesses can be resolved.

6.4.2.1. Self-discharge/shelf-life. This may or may not be a weakness, as Sony and co-workers quote a self-discharge rate of '<10% per month' and Saft and co-workers predict a very slow drop in SoC [7]. It is certain, however, that the very thin plate thickness and resultant high electrochemical surface-areas associated with high-power Li-ion batteries will give rise to relatively high self-discharge rates and, possibly, permanent capacity and life loss.

6.4.2.2. Low temperature performance. As with Ni–MH, this is a serious weakness with Li-ion, perhaps more so. High rate discharge performance is good at 0 °C but there is a roughly 60% loss from ambient [7]. Below 0 °C, there is an even greater drop-off and at −30 °C it would take a very large Li-ion battery to start a vehicle, estimated by Johnson Controls to be 35–40 Ah and weighing ∼20 kg [6]. This may be a conservative estimate. This sharp drop-off in performance is due to the relatively high resistance of the electrolyte (organic solvent + lithium salt) and to reduced diffusion kinetics of the mechanism for intercalation-de-intercalation of lithium. Charge-acceptance is reduced even more at low temperatures, by as much as 70–80% compared with ambient operation.

6.4.2.3. High temperature charging, charge-acceptance. The upper limit for the safe operation of Li-ion cells is 40–50 °C. In this region, there is rapid oxidation of the solvent at the positive. This generates acids which dissolve the passive layer on the negative electrode. At temperatures of ∼80 °C, the cell can rapidly go into thermal runaway which results in cell destruction and, possibly, fires and explosions.

6.4.2.4. Thermal-management. This is not as serious a problem as with Ni–MH, but it is likely that some thermal-management hardware will have to be a part of a Li-ion battery package.

6.4.2.5. Battery monitoring and control. All three of the battery chemistries discussed here will require monitoring in order to track SoC and SoH. Costs for all three will be comparable, but are not likely to be excessive. For Li-ion,

however, precise charge control on an individual-cell basis is required, as lithium plating takes place if any cell in the battery is overcharged. If any cell is undercharged by as little as 100 mV, there is a significant loss of discharge capacity and cycle-life. Such tight charge control adds considerable cost and if a charger failure occurs, it could result in fire or explosion. On the other hand, if a Li-ion battery can operate continuously in a PSoC condition, without requiring a full charge, this may not be a consideration. Still, it is likely that a tight voltage limit will have to be used for safety purposes.

6.4.2.6. Safety. In addition to charge control, there are a number of other serious safety issues for Li-ion, e.g. lithium plating, solvent toxicity and flammability, and the possibility of thermal runaway. Safety issues for Li-ion cells have been carefully reviewed [8] and it is an ongoing active area of development for manufacturers.

6.4.2.7. Cost. It was noted above that ultimate cost is a potential advantage for Li-ion. Present costs, however, are a distinct disadvantage to an even greater degree than for Ni–MH. The cost given in Table 2 for a 36 V/25 Ah battery is US$ 700–1000, but this is only an educated guess, as manufacturing processes have not been set for this type of product. Over the 10 years life of a vehicle, another uncertainty is the calendar life expected for a Li-ion battery in an automotive environment. It has been estimated that this can be as little as 1.2 years under hostile conditions [9], but this is probably overly critical. Still, even if a 36/42 V Li-ion battery requires two replacement events, the cost over the life of the vehicle could be as high as US$ 3000, or more if a large battery is required for low temperature operation as with Ni–MH.

6.5. VRLA technology

6.5.1. VRLA and flooded lead–acid technologies

The current automotive battery incorporates lead–acid technology and it is likely that vehicle manufacturers would like to stay with this chemistry. In fact, they would probably prefer to use the same types of flooded lead–acid batteries in use now but this is not feasible for a number of reasons relative to VRLA, as shown in Table 3 [9]. This is just one example, but it is generally accepted that VRLA products will have performance levels some 15–20% greater than comparably-sized, flooded batteries. Several other critical parameters for 36/42 V PowerNet duty such as PSoC operation,

Table 3
Comparison of the performance of VRLA and flooded lead–acid batteries

Parameter	VRLA design	Flooded design
CCA (−18 °C) (A)	460	380
Reserve-capacity (min)	60	75
Consecutive reserve-capacity tests, at 50 cycles (min)	70	20
Charge-acceptance at 20% SoC, 14.5 V/25 °C, current at 30 min (A)	19	16
Charge-acceptance at 20% SoC, 14.8 V/−18 °C, current at 30 min (A)	12	6.5
J240 life cycles, 75 min reserve-capacity	6000–8000	3200

high-power performance and deep-cycle lifetime are not given in Table 3, but these are heavily in favor of VRLA technology. These factors, taken with the clear safety advantage for VRLA in a passenger compartment battery location, can safely exclude flooded lead–acid from this application in favor of VRLA.

6.5.2. Design features for VRLA

There are a wide variety of VRLA battery designs that may be suitable for 36/42 V PowerNet use, but those most qualified are thin-plate (0.6–1.5 mm), prismatic or spiral-wound products. Bipolar batteries are not considered due to their poor energy/power ratios and manufacturing difficulties (seals, substrate conductivity/corrosion characteristics). Likewise, the Bolder-JCI 'Inspira' ultra-thin-plate products are not suitable due to their difficult manufacturing processes and resultant questionable quality issues. Thick-plate products (>1.5 mm) are not considered due to their poor power characteristics and high cell impedances that would result in the necessity for significant thermal-management. Suitable commercial products are the Genesis, SBS (both flat plate) and Cyclon (spiral-wound) products from Hawker Energy Products, spiral-wound SLI batteries (Optima-JCI and Exide Europe), the Delphi/East Penn prismatic EV modules, and a wide variety of early 36 V prismatic products from Japan Storage, Hoppecke, Yuasa, Furukawa, Shin Kobe and Matsushita. While there may be some advantage for spiral-wound designs in superior vibration and power performance, it is likely that thin-plate prismatic batteries will perform acceptably in this application. First, it is useful to consider some of the key design parameters for this type of battery.

6.5.2.1. Weight/volume and nominal rated capacity.
The first 36/42 V PowerNet VRLA batteries developed by Japan Storage, Hoppecke and Yuasa have weights and volumes in the range of 24–28 kg and 9–11 l, respectively, with nominal capacities of 20–26 Ah (total energies of 720–950 Wh). Thus, specific energies are 30–35 Wh kg^{-1} and specific power values are 250–400 W kg^{-1}. Their 10 s power capabilities are 8–9 kW on discharge. For low temperature, PSoC cold-cranking, ambient peak power, battery impedance (which will produce temperatures of 70–80 °C with ISS cycling) and DoD/cycle-life (~2.5%/150 000 ISS cycles), this size of battery is, at best, marginal. Keeping in mind that reliability and long life are absolutely necessary in this application, a battery of between 50 and 60 Ah (weight 60–70 kg, volume 25–30 l) is likely to function better and longer. With a peak-power capability of ~20 kW and an expected cycle-life of ~250 000 cycles (~1% DoD), this size VRLA battery compares well with smaller (but much more expensive) Ni–MH and Li-ion products.

6.5.2.2. Battery envelope and single-cell/monobloc packaging.
In principle, VRLA cells can be flat-plate, spiral-wound or flat-wound. Due to the low vent pressures required and the economies of manufacturing, VRLA products can easily be built in 18-cell monobloc designs, which eliminates significant amounts of weight and reduces greatly the number of connections required (lower impedance, higher reliability). The use of spiral- or flat-wound cells will incur some volume penalties, but in larger capacities they may be more economical to manufacture and they may have better vibration and high-power performance (due largely to higher compression levels in the plate stacks). Because of the greater hoop strength inherent in a cylindrical configuration, spiral-wound monoblocs can also be operated at somewhat higher vent pressures than comparable flat-plate batteries. This will result in higher oxygen-cycle efficiencies and, thus, lower weight losses during use. In addition, the soft grid alloys used in spiral-wound products (lead–tin binary alloys) have superior corrosion properties that may confer greater cycle-lives compared with Pb–Ca–Sn(Ag) alloys used in prismatic designs, all other conditions being equal. It should be noted, however, that these same alloys can be used in flat-plate manufacturing, but great care is required in plate handling to avoid damage and distortion.

6.5.2.3. Other design features.
For VRLA, the nominal cell voltage is 2.0 V. Battery impedance will depend greatly on the basic design. A typical ac impedance (1 kHz) for a 36 V/25 Ah VRLA flat-plate battery with plate thickness of ~1.0 mm would be ~15 mΩ. For a comparable 50 Ah battery, it would be 8–12 mΩ. Calendar life is claimed to be 4–5 years, but this is an estimate given the absence of accurate field data. With a life of 3–4 years, a 10 years vehicle life would require two, possibly three, battery replacements.

Failure modes for VRLA in this application are likely to be grid corrosion of the positive and/or irreversible sulfation of either, or both, plates. Accelerated corrosion is to be expected due to the lower electrolyte relative densities that go with PSoC operation and the likely cell imbalances in an 18-cell string. Poor charge-acceptance and overdischarge will result in sulfation, and prolonged PSoC operation will also promote sulfation. From this, it is clear that VRLA batteries in this application will have to be charged fully at short intervals by means of a variety of mechanisms available.

The major advantage that VRLA has over Ni–MH and Li-ion is that automobile manufacturers are familiar with lead–acid technology and there is a substantial data base on the performance of VRLA products in automotive environments. Nevertheless, there are significant problem areas, primarily PSoC calendar and cycle-life (unproven), charge-acceptance, and long-term reliability. The last-mentioned factor is critical, as most 36/42 V PowerNet architectures use electronic steering and braking that are powered by the battery.

6.5.3. VRLA performance

More detailed performance data for VRLA versus Ni–MH and Li-ion are given in Table 2. General comparisons have

been covered in Section 6.2. Here, performance strengths and weaknesses will be dealt with in somewhat more detail, along with possible solutions.

6.5.3.1. VRLA strengths. As noted previously, VRLA is likely to be the first technology used in 36/42 V PowerNet systems due to a combination of the familiarity of automobile manufacturers with lead–acid, good performance, well-established manufacturing, infrastructure and recycling industries and, not least, comparatively low cost. In terms of performance, VRLA has a number of considerable strengths, as follows.

6.5.3.1.1. Energy/power balance. While the absolute values are inferior to those for Ni–MH and Li-ion, the balance of energy and power for VRLA is good. Discharge power, in particular, is very good and the low specific energy can be compensated through the use of a higher capacity battery. The first batteries from Japan Storage, Hoppecke and Yuasa are marginal in power, at 8–9 kW, particularly at low temperatures (v.i.). It is likely that larger vehicles will require a power capability at ambient of 15–20 kW, which corresponds to a rated capacity of ~50 Ah.

6.5.3.1.2. Operating temperature range. VRLA has the best nominal operating temperature range of the three battery chemistries, in both low and high regions. At the high end, 60 °C is conservative, as charge-acceptance and rechargeability are good even at 65 °C. Prolonged operation at 60 °C, while not good for the battery, can be tolerated, whereas for the other chemistries it is not even possible at this time. The normal operating low temperature can extend to −40 °C, as shown, but this is in the fully-charged state. In PSoC operation, discharge power capacity is only moderate even at −30 °C. At 50% SoC, the freezing point of a typical VRLA electrolyte is about −20 °C. This may call for the use of a high-end nominal electrolyte relative density of 1.320, or more. A second approach would be to operate the VRLA battery at a 60–70% SoC, but this reduces the marginal charge-acceptance performance. Another possible solution would be to recharge the battery fully at the end of use, and then run it back down to 50–70% SoC after the vehicle is started. Again, use of a higher capacity battery will help, as the starting capability of a VRLA battery with 'slushy' electrolyte is excellent due to the large amounts of electrolyte in the plate pores, even at 50–60% SoC.

6.5.3.1.3. Shelf-life/potential damage. The inherent self-discharge rate of the VRLA battery made with pure materials is quite low; the best designs will retain ~50% of their rated capacity after 2 years of self-discharge. Even at 50% SoC a good VRLA product will easily have a usable time of ~6 months. With full recharges every 3–6 months, there is no permanent damage to a VRLA battery. With longer times between charges there may be some build-up of 'hard sulfate', which is difficult to recover. Nevertheless,

recovery can be achieved by using a long, low-level, constant-current recharge. In a test such as the 31 days 'airport stand' the VRLA product will do very well.

6.5.3.1.4. Discharge power and voltage stability. Because of favorable electrolyte-diffusion rates and the short distances involved, discharge power and voltage stability are strong points for thin-plate VRLA products. Even at 50% SoC, discharge plateaux are flat and power capabilities are good at ~300 W kg^{-1}. Thus, a 50 Ah/60 kg battery would have a power capability of ~18 kW at 50% SoC; at −10 °C, it would be capable of delivering 12 kW. Because of the 'stiff' voltage on discharge and the good power capabilities (and the modest charge-acceptance levels), VRLA batteries are likely to be operated at lower SoCs than Ni–MH and Li-ion products, perhaps as low as 40%.

6.5.3.1.5. Thermal-management. The need for active thermal-management will depend on the size and design of the VRLA battery used and the peak-power demands. It has been shown that a 20 Ah battery subjected to continuous ISS cycling will reach steady-state temperatures of 74–77 °C, a dangerous level [1]. On the other hand, a larger battery with a significantly lower impedance may not reach such temperatures when cycled on the same algorithm. Given that some crude active cooling, such as driving air-cooling or a small fan, will be available this will probably provide sufficient thermal-management for VRLA batteries.

6.5.3.1.6. Battery monitoring. This is a difficult area for all of the three battery chemistries, but it should be a point of strength for VRLA, given that several major companies are already working on SoC and SoH algorithms. State-of-charge is likely to be derived from voltage measurements either during 'off' periods (open circuit) or at the end of pulse discharges. State-of-health will be more complex and will likely involve a library of historical data on the battery so that degenerative trends can be seen clearly. A recent study based upon internal resistance mapping is promising [1].

6.5.3.1.7. Manufacturing/infrastructure/recycling/materials availability. Clearly, these are all strengths of VRLA technology, and they are areas where it is well-ahead of Ni–MH and Li-ion. Many types of VRLA batteries are presently in large-scale production and maintenance/servicing is readily available. The recycling business is profitable and all the materials are inexpensive and readily available.

6.5.3.1.8. Cost. This is the strongest area for VRLA, as it allows the use of a large battery to compete with Ni–MH and Li-ion, and still be significantly less expensive. The costing cited in Table 2 for a 36 V/25 Ah battery is aggressive, but it is achievable for a manufacturing process that combines the best features of automotive and VRLA industrial battery technologies. Doubling the capacity to 50 Ah would

probably raise the battery selling price by US$ 30–50, but it would still be at or below US$ 200, while the other battery chemistries are some three–five times more expensive. Given a 3–4 years life for VRLA and greater than 5 years for Ni–MH and Li-ion, three VRLA batteries would be required for a 10 years vehicle life, while two would be needed for the other two batteries. Still, with the costings in Table 2 and use of a 50 Ah VRLA battery, the life cost for VRLA would be US$ 600 (batteries only) and those for Ni–MH and Li-ion would be, at best, US$ 1000 and US$ 1400, respectively.

6.5.3.2. VRLA weaknesses. While VRLA is well-suited to this type of application, the performance demands are sufficiently complex to create some difficulties. Among these are the following.

6.5.3.2.1. Total energy output, cycle-life. In typical PSoC ISS cycling, a 20 Ah battery will experience a DoD of ∼2.5%. For VRLA, this translates to a life of 130 000–150 000 cycles and a total energy output of ∼0.7 MWh. These values are short of what is needed for even a 3 years battery lifetime, but a 50 Ah battery under the same regime would only have ∼1% DoD and should do well in terms of cycle-life and temperature elevation.

6.5.3.2.2. PSoC Operation. This is perceived as the Achilles heel for VRLA, but in actuality it may not be so grim. Given that cycle-life can be achieved with a larger battery, the other areas of concern are charge-acceptance and 'hard' sulfate build-up. The latter is a result of dissolution/precipitation chemistry, which converts many small crystals to fewer, larger ones, also referred to as 'digestion'. This will always take place when lead sulfate crystals are present for a long period of time. It can easily be avoided by fully recharging all or part of the battery on a periodic basis. Methods are available to do this through the vehicle electronic control strategy or by the shuttling of charge within the battery as has been demonstrated for HEVs [10].

6.5.3.2.3. Charge-acceptance. This is an area of performance where many VRLA products are deficient. Over the past several years, however, work has been published by Japan Storage [1] and Nakayama [11] on higher carbon loadings in negative plates that results in much-improved charge-acceptance. With the use of a 50–60 Ah VRLA battery, acceptable charge-acceptance (as high as 18−22 kW at 50% SoC at ambient and ∼12 kW at −10 °C [11]) can be realized under all but the most stringent conditions. As noted previously, performance at −30 °C may be inadequate even for a battery of 50–60 Ah, as the water in the sulfuric acid electrolyte is largely frozen at this temperature in a ∼50% SoC condition.

6.5.3.2.4. Usable state-of-charge range. The SoC range for VRLA, viz. 30–70%, is low relative to Ni–MH and Li-ion.

It is not a serious drawback, however, because the discharge performance is excellent and the use of a larger battery reduces the impact of a limited SoC range. Thus, operating a 50 Ah VRLA battery at a nominal SoC of 40–45% will allow high levels of discharge and charge-acceptance power in spite of this limited nominal 30–70% range.

In summary, from the standpoint of performance, the overall capability of VRLA is good, particularly in a larger size that will allow better energy, power and life characteristics under the stringent conditions that will be required for 36/42 V PowerNet operation.

6.5.4. VRLA manufacturing/reliability issues

At the Fifth ALABC Members and Contractors Meeting [12], John Miller of Ford Motors challenged the lead–acid industry to bring reliability levels up by several orders of magnitude in large EV batteries such as those used in the Ford Ranger EV pickup truck. Miller noted that reliability levels were much higher for comparable Ni–MH batteries, and if the lead–acid industry wanted to be a player in EVs their products would have to be on the same parts per million scale that the automotive industry expects of its major suppliers. While the 36/42 V PowerNet batteries will have many fewer cells than an EV battery, high reliability is even more imperative due to the use of the battery for such critical functions as electronic braking and steering. Little or no data are available in the VRLA literature, but it can be estimated that reliabilities in the parts per million range will be required for these 18-cell series strings. Data published yearly on flooded, automotive 6-cell batteries show failure levels in the parts per thousand, so it is clear that reliability improvement for VRLA 36/42 V products will have to be at a level of about 10^4–10^5, as noted by Miller [12]. This cannot be realized using existing manufacturing approaches. The production of 36/42 V PowerNet batteries will require refinement and diligent application of existing methods and innovative development of new approaches that do not exist in lead–acid manufacturing at present. This will have to be done in several areas, which include the following [13].

6.5.4.1. Alloys and grid preparation. Alloys must have low corrosion rates but must form a good corrosion layer with the positive active material. Nominal grid thickness of 0.5–1.0 mm must be realized with thickness and uniformity tolerances of ±1% or less, whether using casting or wrought technology.

6.5.4.2. Pasting and platemaking. Because of the cycling nature of 36/42 V applications, it is likely that higher paste densities will be required. Moreover, to achieve plate thickness and uniformity levels of ±1% or less, seldom-used techniques such as orifice pasting or totally new approaches (roll coating?) will have to be employed. In order to have uniform plate stack compression and minimal damage on battery assembly, tapered-plate pasting may be required.

6.5.4.3. Curing and drying. New curing approaches may have to be developed to achieve a more uniform treatment, yet with high throughput. In addition to achieving the desired crystal composition and reduction of free-lead content, initiation of an effective interface corrosion layer will have to be accomplished. In curing and drying, minimal plate carbonation can only be realized with strict control of temperature/humidity conditions in the plant environment, both during and after drying.

6.5.4.4. Lid/box design and assembly. It is likely that much stronger box/lid assemblies will be required so that higher plate stack compressions (50–60 kPa) and vent valve release pressures (55–70 kPa) can be employed, perhaps with a metal sleeve. Lid/box and terminal seals must be effective, and cast-on-strap and through-wall-welds must be performed with much higher reliability than at present. The integrity of lug-top lead and cell-to-cell connections is absolutely critical and, given current manufacturing practices, is likely to be the greatest source of battery failures. Correct assembly checks such as Hipot and polarity reversal (based upon individual-cell impedance measurements) must be conducted.

6.5.4.5. Filling and formation. Uniform electrolyte distribution and the complete absence of hydration shorts must be achieved in the filling process. This will be made more difficult by the use of thin-plate designs and high plate stack compression levels, but it must be achieved. In order to ensure superior cycling performance and long shelf-life, plate formation will have to result in PbO_2 levels in excess of $\sim90\%$. With the use of high-density pastes, this will be difficult to achieve in periods of 24 h or less.

6.5.4.6. High-purity materials. In all of the above, materials of the highest purity must be used. These include: grid materials, oxides (especially), expanders, electrolytes, separators, top lead and plastic parts, that is everything! This will be necessary to provide superior shelf-life, processing and performance in such a critical application.

Some or all of the above will be impossible to attain with existing manufacturing practices and attitudes. Because of the demands of the application and the high costs associated with the competing Ni–MH and Li-ion technologies, the requirements for minimal-cost materials and manufacturing as in the present automotive industry will not exist. It is likely that the automotive manufacturers will tolerate somewhat higher costs in order to achieve the level of performance needed, which is far more complex than for the traditional battery.

7. VRLA 36/42 V PowerNet battery design recommendations

The VRLA products developed by Japan Storage, Hoppecke, Yuasa and others are impressive and, apart from size, may be adequate as first-generation 36/42 V PowerNet batteries. The following are some design recommendations for this type of battery that can be incorporated into these and other products which are under development.

7.1. Grid alloy

Pb–Sn for spiral-wound, Pb–Ca–Sn–Ag–Al for prismatic.

7.2. Grids

Cast or wrought; nominal thickness of 0.5–1.0 mm; $\pm1\%$ or less thickness and uniformity tolerances; high resistance to corrosion and growth should be built in with a solid frame in the grid design.

7.3. Pastes

Wet densities of ~4.5–5.0 g cm^{-3} for the positive; ~5.0 g cm^{-3} or more for the negative; synthetic or high-quality natural lignin and 1–2 wt.% conductive carbon in the negative paste; 10–25 wt.% red lead in the positive-plate oxide.

7.4. Pasted plates

Pasting must be done with minimal calendering and may use separator pasting paper; plate thickness of 0.8–1.5 mm (tapered to match the draft of the box, i.e. slightly thicker at the top); $\pm1\%$ or less thickness and uniformity tolerances; no projecting grid wires or flash that may cause plate-to-plate shorting.

7.5. Separator

All-glass AGM or equivalent in terms of low impedance and high porosity; specific surface-area of 1.8–2.4 m^2 g^{-1}; total amount of separator (pasting paper plus stacked paper) should be 1.5–2.0 g Ah^{-1} of rated capacity.

7.6. Plate stack

Stack compression of 50–60 kPa; separator plate spacing of ~0.5–1.1 mm; sufficient separator overlap to allow for $\sim10\%$ grid growth; top lead is 2 wt.% tin or an equivalent alloy.

7.7. Box/lid configuration

Box and lid made of flame-retardant thermoplastics, e.g. polypropylene, ABS, polycarbonate or ryton; moulded design to accommodate internal vent pressure of at least 55–70 kPa; lid staked to box at positions other than just on the perimeter to avoid bulging.

7.8. Terminals

Terminal posts are either discrete or moulded into the lid; discrete terminals with a seal design that does not allow acid creep to the outside.

These are design parameters that can be fitted into existing small VRLA industrial batteries—and are, in many cases. Simply adopting these design approaches will not ensure success. In fact, the key is more likely to be in processing and the proper application of manufacturing discipline to the building of these batteries. If the VRLA industry takes these and others' recommendations seriously, it is likely that the new generation of automotive batteries will remain lead–acid.

8. Conclusions

The advent of the 36/42 V PowerNet automotive architecture presents a unique challenge to the VRLA industry in maintaining lead–acid dominance in automotive batteries, currently a roughly US$ 10 billion per year market worldwide. The battery required for this developing market is not even remotely similar, however, to the traditional flooded lead–acid automotive battery. The duty cycles involved are complex and not completely suited to VRLA, but when all considerations are taken into account, it is clear that VRLA is superior to the competing chemistries, Ni–MH and Li-ion. Whether these technological and economic advantages can be translated into highly reliable, easily-manufactured products is up to the VRLA manufacturers, some of whom have already begun to manufacture products for Toyota, DaimlerChrysler and other automobile manufacturers. In order to achieve the huge improvements in product reliability demanded by the automotive industry, it is likely that VRLA manufacturing and materials will have to be radically different from what they are today.

References

[1] M. Shiomi, in: Proceedings of the presentation at the 111th BCI Meeting, Las Vegas, NV, USA, 6–9 May 2001.

[2] R. Knorr, H.-M. Graf, in: Proceedings of the 1st Advanced Automotive Battery Conference, Las Vegas, NV, USA 5–8 February 2001, Session 2, Paper 7.

[3] J.M. Miller, R.D. Brost, in: Proceedings of the 1st Advanced Automotive Battery Conference, Las Vegas, NV, USA 5–8 February 2001, Session 2, Paper 6.

[4] T.A. Keim, in: Proceedings of the 1st Advanced Automotive Battery Conference, Las Vegas, NV, USA 5–8 February 2001, Session 1, Paper 1.

[5] S. Yamaguchi, A. Taniguchi, N. Fujioka, K. Kanamaru, M. Ikoma, in: Proceedings of the 1st Advanced Automotive Battery Conference, Las Vegas, NV, USA 5–8 February 2001, Session 4, Paper 17.

[6] J. Zagrodnik, R. Rizzo, J. Symanski, in: Proceedings of the 1st Advanced Automotive Battery Conference, Las Vegas, NV, USA 5–8 February 2001, Session 3, Paper 11.

[7] G. Chagnon, P. Allen, K. Hensely, K. Nechev, S. Oweis, R. Reynolds, A. Romero, T. Sack, M. Saft, in: Proceedings of the 1st Advanced Automotive Battery Conference, Las Vegas, NV, USA 5–8 February 2001, Session 5, Paper 4.

[8] M.W. Juzkow, S.T. Mayer, in: Proceedings of the 12th Annual Battery Conference on Applications and Advances, IEEE, January 1997, pp. 189–193.

[9] K. Peters, J. Power Sources 88 (2000) 83–91.

[10] Southern California Edison, Advanced Lead–acid Battery Consortium, ALABC Project C001.5, Progress Report, June 2001.

[11] Y. Nakayama, in: Proceedings of the 1st Advanced Automotive Battery Conference, Las Vegas, NV, USA 5–8 February 2001, Session 3, Paper 2.

[12] J.M. Miller, in: Proceedings of the keynote presentation at the 5th ALABC Members and Contractors Meeting, Nice, France, April 2000.

[13] R.F. Nelson, Batt. Int. 48 (2001) 51–58.