Journal of Power Sources 88 (2000) 83–91

JOURNAL OF POWER SOURCES

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Design options for automotive batteries in advanced car electrical systems

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Received 1 August 1999; accepted 1 September 1999

Abstract

The need to reduce fuel consumption, minimize emissions, and improve levels of safety, comfort and reliability is expected to result in a much higher demand for electric power in cars within the next 5 years. Forecasts vary, but a fourfold increase in starting power to 20 kW is possible, particularly if automatic stop/start features are adopted to significantly reduce fuel consumption and exhaust emissions. Increases in the low-rate energy demand are also forecast, but the use of larger alternators may avoid unacceptable high battery weights. It is also suggested from operational models that the battery will be cycled more deeply. In examining possible designs, the beneficial features of valve-regulated lead–acid batteries made with compressed absorbent separators are apparent. Several of their attributes are considered. They offer higher specific power, improved cycling capability and greater vibration resistance, as well as more flexibility in packaging and installation. Optional circuits considered for dual-voltage supplies are separate batteries for engine starting (36 V) and low-power duties (12 V), and a universal battery (36 V) coupled to a d.c.–d.c. converter for a 12-V equipment. Battery designs, which can be made on commercially available equipment with similar manufacturing costs (per W h and per W) to current products, are discussed. The 36-V battery, made with 0.7 mm thick plates, in the dual-battery system weighs 18.5 kg and has a cold-cranking amp (CCA) rating of 790 A at −18°C to 21.6 V (1080 W kg^{-1} at a mean voltage of 25.4 V). The associated, cycleable 12-V battery, provides 1.5 kW h and weighs 24.6 kg. Thus, the combined battery weight is 43.1 kg. The single universal battery, with cycling capability, weighs 45.4 kg, has a CCA rating of 810 A (441 W kg^{-1} at a mean voltage of 24.7 V), and when connected to the d.c. − d.c. converter at 75% efficiency provides a low-power capacity of 1.5 kW h. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Automotive battery; Cranking; Dual-voltage; Lead–acid; Specific energy/power; Valve-regulated

1. Introduction

The pressures placed on the automobile industry to meet ever-increasing environmental demands, reduce fuel consumption and provide new on-board facilities whilst ensuring reliability appears likely to result in major changes in electrical and electronic systems. These changes, some already introduced, include: electrically-heated catalysts; crankshaft starter/alternator arrangements to give improved automatic stop/start features; larger and more efficient alternators, intelligent, smart, digital power switches together with integrated sensors and communication facilities. Associated with these are architectural changes in layout and wire-harnessing. Whilst several of these features are more energy efficient, the overall effect of their introduction will be to increase energy and power demands.

The battery, as one of the heavier and larger components, is a key item in this evolution. It has been estimated [1,2] that if all the prospective changes are introduced, there will be a fourfold increase in both reserve capacity and power requirements (see Fig. 1). Such extensive changes are unlikely within the next 5 years, and when introduced will be in top-of-the-range cars. Nevertheless, a progressive introduction can be anticipated and will require batteries with increased capacity and more power. Without major design modifications or changes of battery type or further compromise within the electrical system, these demands are unlikely to be met without severe weight and application problems. The need to keep the battery weight to acceptable levels also means deeper and more extensive cycling.

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PII: S0378-7753(99)00514-5

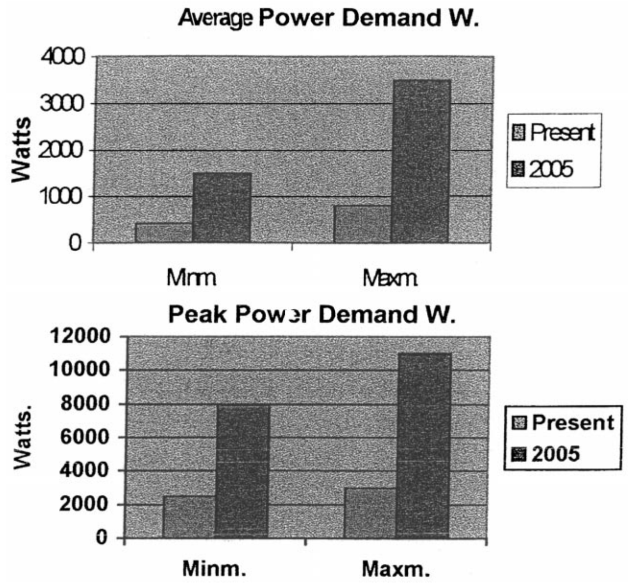


Fig. 1. Trends of electrical system power. Forecast of electrical demand in a luxury car fitted with new electrical functions [2].

In recent years, the automotive industry has established study consortia with manufacturers and suppliers of electric and electronic components and systems to assess the technological options. Under consideration are changes in electrical network architectures, in energy-management systems, and in battery design or configuration that includes the possibility of dual-voltage levels and alternatives to the traditional lead–acid battery.

Traditionally, the choice of battery system or configuration depends on reliability, cost and endurance. Weight and volume further influence decisions. With the proposed changes, whilst the energy and power demands will have to be met, the considerable interaction between components means decisions will be made on the weight, volume, cost and effectiveness of the total system. Although the primary aim of this study is to consider changes in lead–acid battery design and configuration to meet these targets, the threat from alternative electrochemical power sources cannot be ignored.

Prominent amongst the competitive systems under development are lithium-ion batteries and supercapacitors. There have been substantial advances in the performance of rechargeable lithium batteries, but their use is restricted to low-power portable devices, in which they are now widely used. Present designs have relatively poor performance when discharged at high rates and their use in automobiles is likely to be restricted to low-power or reserve duties where their high specific energy is the main attraction. On the other hand, performance improvements and lower costs have been reported recently [3]. There have also been major advances in the development of large double-layer capacitors (‘‘supercapacitors’’) which use high surface-area, carbon powder electrodes [4,5]. These devices have good specific power, but low specific energy. Clearly, the dual combination of these two systems or with a suitable lead − acid battery could be among future options. Whilst such arrangements have yet to be proven, widespread use may be inhibited by high cost, which is partly due to the need for overcharge and undercharge protection in the multi-cell, higher voltage network likely to be used in automobiles.

In this respect, lead–acid batteries may have a significant advantage. As an example, typical ‘factory gate’ costs of European-made, 12-V, automotive batteries are given in Table 1. These show costs of £0.014 per cold-cranking amp (CCA), i.e., approximately £0.2 per watt and £0.092 per min at reserve capacity rates, with the capability of providing several years trouble-free service. The high investment in manufacturing equipment and the continuing low cost of materials (approximately 75% of the total manufacturing cost) have kept prices stable for several years.

Typical energy:power ratios (W h:W) in 12-V lead–acid automotive batteries are of the order of 1:8. This value has evolved to meet present-day duties, but the system is sufficiently flexible for it to be modified as the need changes. This has been demonstrated by the recent development of thin metal foil designs [6,7] which use plates with high surface-area and thin, high porosity, absorbent separators. Such batteries have very high specific power, but relatively low capacities at low rates of discharge.

Of the many significant changes during the evolution of the lead − acid battery, the development of valve-regulated designs (VRLA batteries) has probably had the greatest impact in terms of application and use, most notably in telecommunications, uninterrupted power supplies, and information technology networks. Their introduction in 1981 [8] provided the necessary attributes for their use in distributed power supplies, and in office-compatible equipment; a market which otherwise may have been satisfied by alternative battery systems.

Large-scale manufacture of automotive VRLA batteries began in Australia in 1979, followed by production in USA, South Africa and the UK between 1980 and 1985

Table 1
Ex-factory costs (UK) of 12-V/60-A h automotive batteries (CCA (SAE) = 575 A; Reserve capacity = 90 min)

Total cost[a] (£)	Cost per kW h (£)	Cost per CCA (£)	Cost per reserve capacity minute (£)
8.24	0.011	0.014	0.092

[a] Includes materials at £ 6.10 (lead price on London Metal Exchange = US$ 520 per tonne), labour and factory variable expenses.

[9]. Nevertheless, widespread use decreased, partly due to concern over reliability and higher costs (about 15% more than standard designs). The technical and manufacturing problems encountered at that time are now better understood and recent experiences indicate that reliability is much improved. A further reason for the limited use of automotive VRLA batteries at that time was the adequacy of existing designs to meet the requirements. Carmakers saw no reason to pay a premium price for a VRLA design.

The situation may be different today. The higher power and minimal weight requirement is best achieved with high surface-area, thin-plate designs, but as plates get thinner and lighter, vibration resistance and cycle-life become a matter of concern. Good cycling performance and charge-acceptance is essential if the envisaged stop/start concepts are adopted. In all of these respects, VRLA batteries offer beneficial features and are likely to be the preferred choice in the new electrical systems of automobiles.

Whilst VRLA batteries bring the possibility of smaller, lighter, more powerful, and safer batteries, they have a different balance of parameters from traditional designs. For a given cranking capacity, there is less reserve capacity. Alternatively, for a given reserve capacity, there is more cranking capacity. It is a matter of engineering design and economics to decide the optimum balance of parameters. Other beneficial features of VRLA batteries may counter any shortfall in capacity. More importantly, the introduction of new designs of VRLA battery for advanced starting, lighting and ignition duties, either in a high-voltage or dual-battery mode, would be at a time when the architecture of car electrics is changing and the flexibility of packaging and mounting offered by such batteries can be utilized effectively.

2. Attributes of VRLA batteries

2.1. Cold-cranking and reserve capacity relationship

The cold-cranking and reserve capacity (SAE) performances of two, 10-plate automotive batteries made with similar plates are compared in Table 2. One battery is a flooded type, the other an absorbed-electrolyte VRLA design. The highly porous, low tortuosity fibrous separator in the latter battery provides a low impedance, with a 33% increase in the cold-cranking index (A kg^{-1}) and a slightly higher power output due to the higher mean voltage on the CCA test. By contrast, there is a 12% decrease in the reserve capacity index (min kg^{-1}) due to acid limitation.

The ratio of the above two indices can be modified as demonstrated by Nguyen et al. [10] who modelled several separator parameters in starved-electrolyte designs. The 30-s voltage and reserve capacity are shown in Fig. 2(a) and (b), respectively, as a function of the effective porosity of the glass mat for two separator tortuosity factors (T). The effect of porosity on the 30-s voltage is not linear and the influence of tortuosity becomes less important in highly porous structures. As expected, the reserve capacity is proportional to the amount of electrolyte in the separator. The effect of separator thickness on the 30-s voltage and the reserve capacity is given in Fig. 2(c) and (d), respectively. In both cases, the relationship is linear. Therefore, designs can be modified by changing separator dimensions.

2.2. Engine-start capability

Whilst the reserve capacity, or any low-rate discharge, is a measure of the amount of energy which can be taken from a battery under specific conditions, the essential criteria is how much power can be delivered to the starter motor from the energy remaining in the battery. In this respect, it can be argued that it is not the absolute value of capacity that is most important in determining the choice of battery but the balance between reserve and cranking capacity.

In addition to the low internal resistance of compressed VRLA batteries, the very low water loss during service means that such batteries can be designed with electrolyte of higher relative density. The combined effects results in a higher load voltage when the engine is starting. There is also a reduction in heat transfer that can be beneficial in cold conditions, but may require repositioning of the battery in warm environments.

To assess the battery's ability to deliver power in relation to the stored energy, VRLA and flooded batteries were subjected to constant-current discharge, both when fully charged and when discharged at low currents to simulate quiescent 'hotel' loads, or 'deficit' motoring. Discharges for a 10-plate VRLA design and for an equiva-

Table 2
SAE performance of 12-V, 10-plate automotive batteries

Design	Weight (kg)	CCA (A)	A kg^{-1}	W kg^{-1} (@ CCA)	Reserve capacity (min)	Min kg^{-1}
Flooded	12.5	380	30.4	237[a]	75	6.0
VRLA	11.4	460	40.4	323[b]	60	5.3

[a] Mean voltage = 7.8 V.
[b] Mean voltage = 8.0 V.

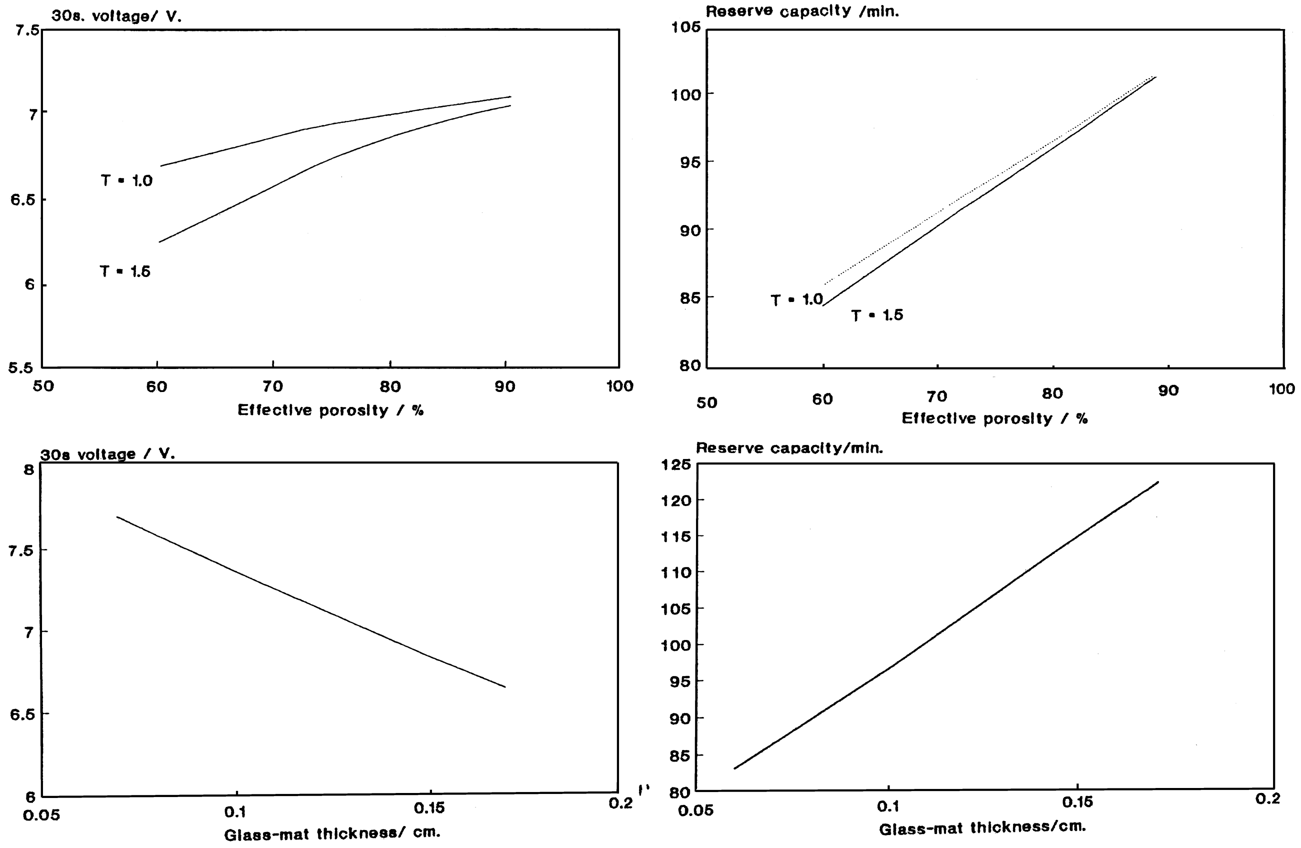


Fig. 2. Influence of separator porosity, saturation, thickness and tortuosity (T) on 30-s cranking voltage and reserve capacity [10].

lent flooded battery made with similar plates are presented in Fig. 3. The higher starting voltage of the VRLA design is maintained until well over half the low-rate capacity has been removed by the prior discharge. Also, the VRLA battery was 1.2 kg lighter.

Constant-current discharges of this type can be criticized in that the output is assessed to a nominal limit. A more realistic test is to drive a typical starter motor. When coupled to a programmable brake and with the torque set to a value or swept from zero to stall, curves for power,

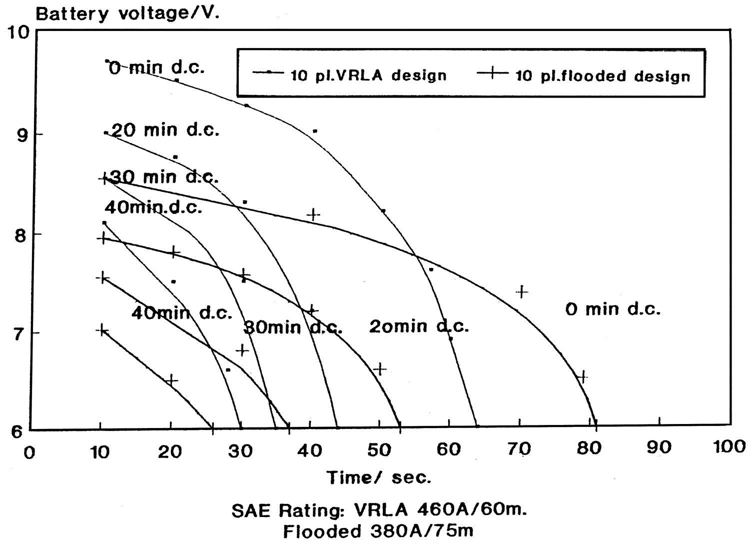
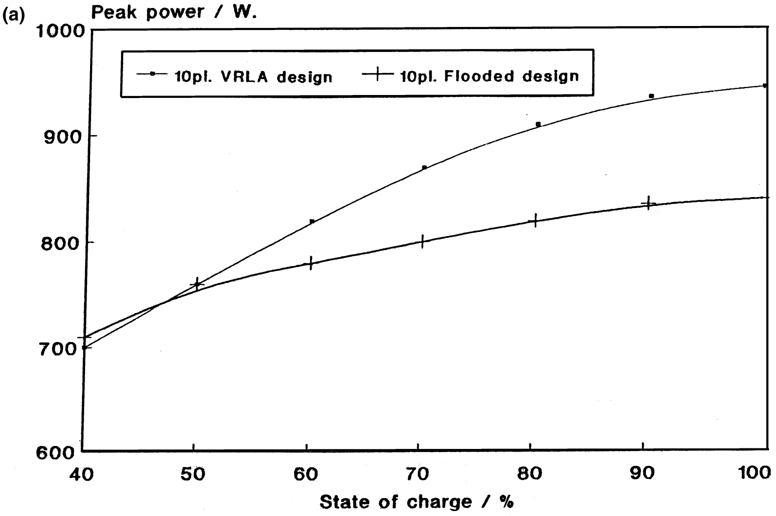


Fig. 3. Constant-current discharges at 300 A at −18°C after partial discharge at 25 A.



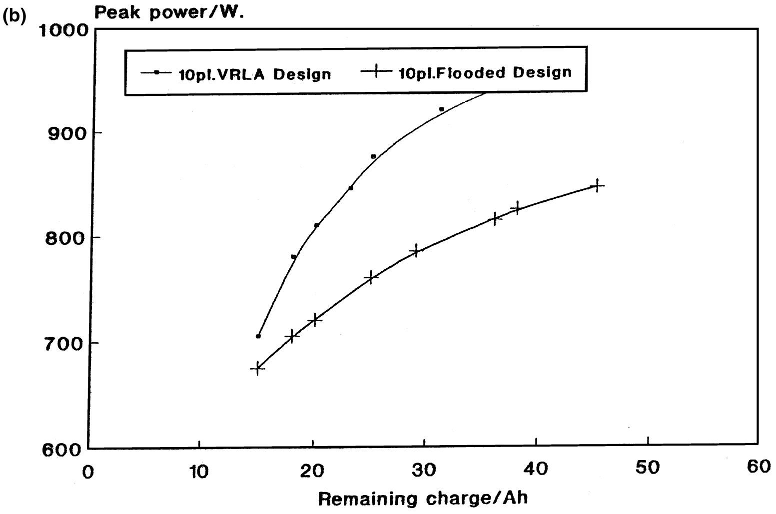


Fig. 4. Starter rig cranking tests at −20°C after discharging at 10, 20, 30, 50 mA for 21 days.

speed, torque and efficiency can be obtained. These curves are a function of both the starter motor and the battery, so either can be standardized or compared. Extensive tests have been performed on a range of batteries and motors.

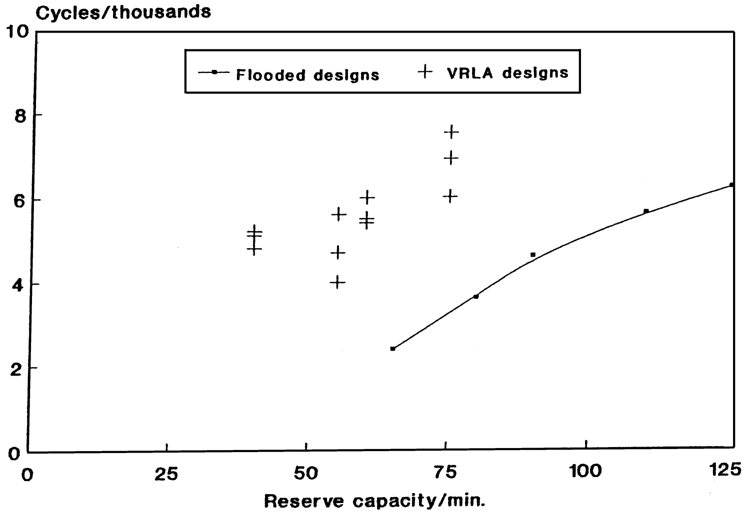


Fig. 5. SAE J240 life cycles on flooded and VRLA automotive batteries.

Table 3
Vibration tests on VRLA battery (CCA = 400 A; reserve capacity = 70 min)

Vibrate @ 3 G 40 min vertical, 20 – 32 Hz 40 min transverse horizontal, 10 – 17 Hz 40 min longitudinal horizontal, 15 – 30 Hz Sweep rate 0.1 Oct./min	All batteries passed test without damage. Reserve capacity after vibration = 71, 72, 69 min

From this data, the peak power values at −20°C for partially-discharged flooded and VRLA batteries were determined and show (Fig. 4(a,b)) the higher peak power and the improved starting capability of the VRLA design until the state-of-charge is less than 50%.

2.3. Endurance

Various tests are in common use for assessing the durability of automotive batteries, but the most widely used is the SAE J240 test conducted at 40°C and, more recently, at 75°C. This is essentially a shallow cycling test which removes, repeatedly, 4 min of reserve capacity followed by weekly high-rate tests. Thus, the larger the battery in terms of reserve capacity, the shallower the cycle and the higher the number of cycles that can be expected before failure, as is shown in Fig. 5 for a range of conventional flooded batteries with different reserve-capacity ratings. An equivalent group of VRLA designs with, as expected, lower reserve capacities than the flooded designs are shown on the same graph. These designs display improved durability on this test, partly because of a reduction in active-material loss and the maintenance of good material/grid contact due to the nature of the highly compressed design. Compression also improves vibration resistance and deep cycling, as shown in Tables 3 and 4. These are characteristics that become increasingly important with thinner plates and as the total energy demand is increased.

Table 4
Consecutive test of reserve capacity @ 25 A to 10.5 V

Cycles		0	25	50	75	100	125	150
VRLA:	1. 400 A/70 min	60	68	70	60	54	45	40
	2. 400 A/70 min	70	75	70	50	–	–	–
	3. 400 A/70 min	75	78	75	70	65	56	45
	4. 400 A/70 min	75	80	78	72	64	50	40
	5. 400 A/70 min	75	76	70	66	60	55	48
Flooded design:	A	70	74	20	–	–	–	–
	B	80	60	14	–	–	–	–
	C	95	86	74	44	–	–	–
	D	100	90	80	55	–	–	–
	E	110	90	70	40	–	–	–
	F	122	95	84	46	–	–	–

Table 5
Charge-acceptance after 80% discharge of 10-plate batteries

	Flooded design	VRLA design
CCA (−18°C)	380	460
Reserve capacity (min)	75	60
Charge-acceptance:		
80% reserve capacity removed		
recharge @ 14.5 V/25°C		
current @ 10 min	38	40
current @ 30 min	16	19
current @ 60 min	8	6
recharge @ 14.8 V/−18°C		
current @ 30 min	6.5	12
current @ 60 min	14	19

2.4. Charge-acceptance

Under frequent stop/start conditions, the rate of charge-acceptance may be critical in ensuring recovery to near or full charge. Methods of determining this factor vary accordingly to local specifications and may be defined by the carmaker. The results for two European designs tested at 25°C and −18°C after 80% discharges are shown in Table 5. At room temperature, the results are similar for both designs but the rate of charge input to the VRLA design is greater under cold conditions.

3. Design options

Friedrich and Richter [11] recently reviewed the potential changes in electrical/electronic systems for the next generation of cars and assessed the expected higher power

Table 6
Requirements of new electrical systems (Friedrich and Richter [11])

	Present systems	Future systems with additional features	Future systems crankshaft/starter/alternator
Energy content (kW h)	0.4 to 1.2	~ 1.5	~ 1.5
A h (C_{20} /20 rate) @ 12 V	~ 35 to 105	~ 125	~ 125
A h (C_{20} /20 rate) @ 36 V		~ 42	~ 43
Reserve capacity (min) 12 V		180	180
Reserve capacity (min) 36 V		66	66
Total energy throughput (4 years) (kW h)	40 to 120	~ 450	~ 450
Cycles @ 50% DoD	~ 150 to 200	~ 600	~ 600
Starting power (kW)	~ 4	~ 6	~ 20
CCA (SAE) @ 12 V[a]	~ 500	~ 750	~ 2500
CCA (SAE) @ 36 V[b]		~ 235	~ 785

[a] Mean voltage (VRLA design) = 8.0 V.
[b] Mean voltage (thin-plate VRLA design) = 25.4 V.

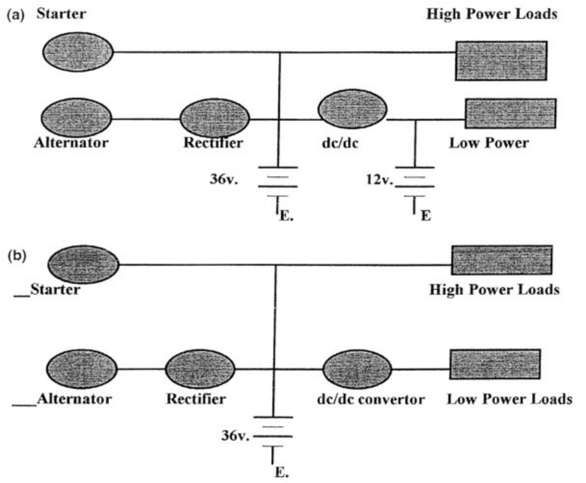


Fig. 6. Circuits for (a) dual-battery and (b) universal battery systems.

and capacity requirements. Whilst higher reserve capacities are likely to be needed to support additional services, larger alternators (up to ∼6 kW) will keep the increase in weight to acceptable levels. If crankshaft starter/alternator arrangements are fitted for automatic and immediate stop/starts, which will significantly reduce fuel consumption and exhaust gases, the high-rate power demand can increase to ∼20 kW. In addition, a threefold increase in the cycling duty is estimated. These additional demands are expressed in Table 6 in terms of two alternative battery voltages and show the energy, power and cycling requirements for 12-V and 36-V batteries.

Various approaches to dual-voltage systems are being considered. Preferred circuitry architecture has yet to be decided, but Fig. 6 shows the following two options.

Option 1: A dual-battery system, consisting of:

a low impedance battery, probably 36 V, for engine starting and other high-power duties;
a higher capacity energy battery, probably 12 V for lighting and other low-power duties.

Option 2: A universal battery, probably 36 V to meet all the electrical requirements of the vehicle, coupled to a d.c.–d.c. converter to supply equipment such as lights which operate more effectively at lower voltage.

The advantageous features of VRLA batteries with compressed separators provides several benefits. Also, for low impedance with high specific power, it is clearly desirable to employ high surface-area, thinner plates. Examples of designs with similar manufacturing costs per W h and per W to present products, and which can be made on commercially available equipment, are given in Tables 7 and 8. Studies of plate-making equipment indicate that

Table 7
Features and performance of dual-battery system (36 V + 12 V)
n.a. = not available.

	36-V battery	12-V battery
Design data:		
Positive plates		
number per cell	8	6
grid size (mm)	118 × 118 × 0.60	144 × 150 × 1.45
plate size (mm)	118 × 118 × 0.70	144 × 150 × 1.95
grid weight (g)	20	102
d.u.p. weight (g)	23	145
Negative plates		
number per cell	8	7
grid size (mm)	118 × 118 × 0.60	144 × 150 × 1.25
plate size (mm)	118 × 118 × 0.70	144 × 150 × 1.50
grid weight (g)	17	65
d.u.p. weight (g)	22	118
Separator thickness	1.0 mm @ 10 kPa 2.0 mm @ 30 kPa	2.6 mm @ 10 kPa 0.75 mm @ 30 kPa
Resistance (Ω cm^{-2})	0.012	n.a.
Battery size (mm)	270 (w) × 180 (h) × 240 (l) (2 × 9)	172 (w) × 220 (h) × 327 (l) (1 × 6)
Weight (kg)	18.5	24.6
Projected performance:		
CCA (A)	790	n.a.
kW @ mean voltage = 25.4 V	20	n.a.
W kg^{-1}	1080	n.a.
capacity @ $C_{20}/20$ rate (A h)	25	125
kW h @ $C_{20}/20$ rate	n.a.	1.5
reserve capacity (min)	35	180
min kg^{-1}	n.a.	7.2

Table 8
Features and performance of universal battery system with d.c. − d.c. converter
n.a. = not available.

	36-V battery	12-V battery
Design data:		
Positive plates		
number per cell	8	All dimensions as in 36-V battery
grid size (mm)	123 × 150 × 1.13	
plate size (mm)	123 × 150 × 1.26	
grid weight (g)	60	
d.u.p. weight (g)	74	
Negative plates		
number per cell	7	
grid size (mm)	123 × 150 × 1.00	
plate size (mm)	123 × 150 × 1.10	
grid weight (g)	50	
d.u.p. weight (g)	63	
Separator thickness	1.45 @ 10 kPa 1.08 @ 30 kPa	
Resistance (Ω *cm*$^{-2}$)	0.018	
Battery size (mm)	338 (w) × 190 (h) × 314 (l) (2 × 9)	Dimensions and weight as for 36-V battery
Weight (kg)	45.5	
Projected performance:		With d.c.–d.c. converter @ 75% efficiency
CCA (A)	810	n.a.
kW @ mean voltage = 24.7 V	20	n.a.
W kg^{-1}	441	n.a.
capacity @ $C_{20}/20$ rate (A h)	55	126
kW h @ $C_{20}/20$ rate	n.a.	1.5
reserve capacity (min)	85	180
min kg^{-1}	n.a.	3.96

with relative inexpensive modifications to improve plate handling, production of 0.60-mm grids pasted to 0.70 mm are practicable, and this is the minimum thickness considered. In the longer term, innovative designs such as quasi-bipolar or ultra-thin electrodes may be viable.

The power battery in Table 7 provides 20 kW for the demands of automatic stop/starts but is unlikely to be deeply discharged at any time. It is a 36-V battery that can supply 790 A for 30 s to 21.6 V at −18°C, and with a mean voltage of 25.4 V. The 18-cell battery, made with 0.7-mm thick plates, has a finished weight of 18.5 kg and dimensions, in a 2 × 9 configuration, as shown in Table 7. Connector and top-lead inserts have not been used, but would provide a further weight reduction of approximately 1.0 kg and would increase the high-rate voltage. The estimated specific power of the design in Table 7 is 1080 W kg^{-1}.

Based on the data given in Table 6, the associated 12-V unit is expected to supply 1.5 kW h. It is designed with thicker plates, with higher density positive pastes and compressed separators of sufficient thickness to provide adequate electrolyte without being oversaturated, all of which improve the cycling performance. The battery has dimensions of 172 mm (w) × 220 mm (h) × 327 mm (l), weighs 24.6 kg, and has a capacity of approximately 125 A h ($C_{20}/20$ rate) which is equivalent to 180 min at 25 A to 10.5 V.

The 36-V universal battery (Table 8) is a compromise design with 15 plates per cell that have dimensions similar to more conventional automotive plates and relatively thin separators. The surface area and low impedance of this design provide 20 kW for 30 s at −18°C to 21.6 V with a mean voltage of 24.7 V, but the additional plate numbers and active material provide 1.5 kW h when the voltage is stepped down to 12 V through a d.c.–d.c. converter (75% efficiency). At the same time, the cell connecting straps and posts, etc., must be capable of carrying the heavy starting load with minimal voltage drop and without overheating. This design has dimensions of 338 mm (w) × 190 mm (h) × 314 mm (l) and has a finished weight of 45.5 kg. As mentioned previously, insets in connectors and posts would reduce the weight by about 1.5 kg.

4. Summary and conclusions

Meeting higher energy and power levels with minimal weight, whilst having good cycling capability, presents new challenges to automotive battery design. The beneficial features of VRLA designs in terms of good specific power and power density have been utilized; but in addition to improved cycling capability and vibration resistance, their low gassing characteristics and freedom from dangers of acid spillage means that the batteries can be packaged and mounted in more convenient locations in the car.

The examples provide an indication of the size and weight of batteries in a dual-voltage system, which is required to meet the substantially higher demands, and demonstrate the considerable scope for reduction in size, weight and cost if the battery is required to start the engine only. The designs considered in this exercise have been chosen so that they can be manufactured at good productivity rates in most automotive plants. Further weight reductions are feasible with top-lead inserts and much thinner plates once present manufacturing developments have been proven. As a bulk storage device to provide substantial amounts of energy, however, large and heavy batteries are unavoidable.

To provide 20 kW at SAE cold-cranking rates, the 36-V power battery weighs 18.5 kg when made with 0.6-mm grids pasted to 0.7 mm, the thinnest plates considered. In a dual-battery system, the associated 12-V unit, which must provide 1.5 kW h and several hundred cycles, weighs 24.6 kg to give a combined battery weight of 43.1 kg.

In terms of overall weight, and probably cost, the dual-battery approach is preferable, and also has the benefit of the 36-V power unit never being deeply discharged which, thereby, provides more assured engine starting. There is also considerable potential for the size, weight and cost of this unit to be reduced further with specific power levels much higher than the 1000 W kg^{-1} demonstrated in this example. Decisions on the type and the design of batteries in the new automobile electrical systems will, however, be based on the cost, effectiveness and reliability of the total, fully integrated system.

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