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Power requirements for batteries in hybrid electric vehicles ☆

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Abstract

The operation of batteries in hybrid electric vehicles (HEVs) involves unusual constraints not seen in other applications. This paper reviews the specifications and operational requirements imposed on batteries due to the projected architectures for HEVs as defined by the DOE/PNGV Program. It also reviews the performance issues involved in battery HEV operation and surveys the strengths and weaknesses of the candidate electrochemical technologies. Finally, battery designs are recommended for the two major projected HEV applications, namely the so-called "fast-response" and "slow-response" systems identified in the DOE/PNGV Programme. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Hybrid electric vehicle; Battery technology survey; Specific power; Duty cycle; Vehicle design; Partial-state-of-charge cycling; Cycle life

1. Introduction

It is fairly common knowledge what constitutes an electric vehicle (EV), but just what is a *hybrid* electric vehicle, or HEV? In the simplest terms, this is a vehicle with two discrete power sources, one generally being the primary and the second the auxiliary. The primary power source is usually a heat engine such as a diesel or turbine, or even a small conventional internal-combustion engine (ICE); conceivably, it could also be a fuel cell. The heat engine is operated as much of the time as possible in its zone of maximum efficiency, some roughly constant power output level, thus minimising harmful gas and particulate emissions. When more power is needed, the auxiliary power source is called upon. This will be some type of energy-storage device, usually a battery (but also possibly a flywheel or supercapacitor), that can furnish and absorb high, short bursts of current. This is a so-called "power-assist" design, where the battery is relatively small and is only used on a demand basis. An alternate configuration involves a roughly equal sharing of power output by the primary and secondary sources, with the latter being used more or less continuously; this is what is called a "dual-mode" hybrid design. In terms of design space, these two configurations lie between a pure heat-engine internal-combustion engine vehicles (ICEV) and a ZEV electric vehicle, as shown in Fig. 1. In both architectures, current is drawn from the auxiliary (battery) power source for acceleration and hill-climbing events, as well as for restarting the engine in city traffic. It also absorbs current during regenerative-braking events, thus capturing this valuable energy that is dissipated and lost in a conventional vehicle. The typical HEV also has an electronic control module that is necessary to coordinate the functioning of the two power sources. The final pieces are sophisticated transmissions and/or electric motors used to drive the vehicle's wheels.

Hybrid-vehicle operation puts unique demands on the battery when it operates as the auxiliary power source. In order to optimise its operating life, the battery must spend minimal time in overcharge and/or overdischarge. HEV batteries, in current designs, have voltages of 100–300 V, or more. As noted above, the battery must be capable of furnishing or absorbing large currents almost instantaneously while operating from a partial-state-of-charge baseline of roughly 50%. As these batteries are large arrays of series-linked (also possibly paralleled) cells or modules, there may be significant thermal issues involved in their operation in a vehicle. Between this and the long-string battery configuration, individual cell balance becomes a major issue. While each of these factors can be

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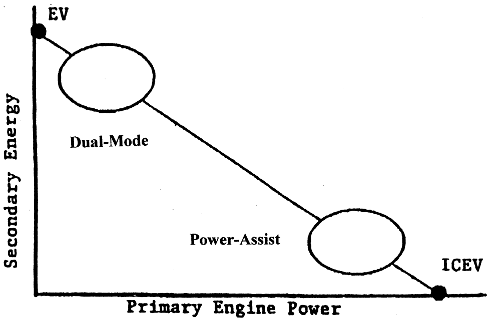


Fig. 1. Hybrid electric vehicle design spaces for power-assist and dual-mode batteries relative to electric vehicles (EV) and internal-combustion engine vehicles (ICEV).

successfully addressed with the appropriate control systems, they must be minimised because it is envisioned that these will be commercial vehicles, with cost being a dominant issue. The above requirements impose a unique duty cycle on the battery, one that is not likely to have been seen in any other commercial application.

This paper will describe the HEV duty cycle in some detail and outline the battery requirements that have been set out by the US Department of Energy (DOE) for use in the Partnership for a New Generation of Vehicle (PNGV) Programme. The various aspects of performance required from the battery will also be reviewed and each of the candidate electrochemical couples will be assessed in light of these requirements. Finally, generic battery guidelines for designs of the two major architectures will be recommended.

2. Discussion

2.1. Batteries in HEVs

2.1.1. The HEV duty cycle

Fig. 2 is a qualitative representation of battery performance demands in a typical HEV duty cycle. The battery is operated at a nominal state-of-charge (SOC) level near 50% so that it can deal with charge/discharge current surges without going into overcharge (above ~ 80% SOC), deep discharge (below ~ 20% SOC) or overdischarge (below 0% SOC). Because these large current spikes will have a great tendency to drive the battery high and low, a realistic operating window for HEV operation is more like 30–70% SOC, as shown. If this is stretched a bit to 25–75%, it is seen that only about half of the battery's rated capacity is being used. Thus, the useful capacity of an HEV battery is only one-half of the normal rated capacity; which means that if "x" kW h is required for HEV operation, a battery with "2x" rated capacity must be sized for the application. The nominal hybrid operating level is chosen based upon the charge-delivery and charge-acceptance characteristics of the electrochemistry and battery type being used in the vehicle. If a battery is stronger on discharge than on charge acceptance, a nominal level somewhat below 50% SOC would be used; conversely, a level above 50% would be chosen if charge acceptance were the stronger property.

The normal HEV operating range for the battery would be about 10% SOC either side of this nominal level, although unusually large current spikes could drive it beyond this in either direction. This depends upon the chemistry employed for the battery and its size, which will be dictated by whether the vehicle design is "fast response" (power-assist, or FR) or "slow response" (dual-mode (pseudo-EV), or SR). Regenerative-braking current surges (charge) tend to be of short duration and will follow the braking pattern of the driver. Discharge events will generally be longer, since they represent acceleration and/or hill-climbing events in the duty cycle. Again, frequency and intensity will depend upon the driver's habits. There are also periods of time, possibly quite long, where the battery is exercised at very low levels or not at all; here, the primary power source (heat engine) is providing everything needed and the vehicle is either cruising or idling. Moreover, in some designs the vehicle does not idle but shuts off in stalled traffic or at lights and then starts up again, thus requiring frequent battery restarts.

The vehicle control system must be able to sense the SOC of the battery and then adjust it if it is getting too close to one of the limit levels. Numerous braking events will drive the battery to a high SOC, necessitating removal of some energy from the battery for vehicle operation or into an external device or source. Conversely, if the vehicle undergoes excessive acceleration events or must climb one or more long hills, the battery may be drained to a low SOC. Here, primary-power-source energy can be used to charge the battery back up to an acceptable SOC level. In order to do any of this, the control system must have a fairly accurate indication of the battery SOC, probably within ~ 5%. This is one of the most difficult and important issues in the operation of an HEV battery and it will be discussed in a later section.

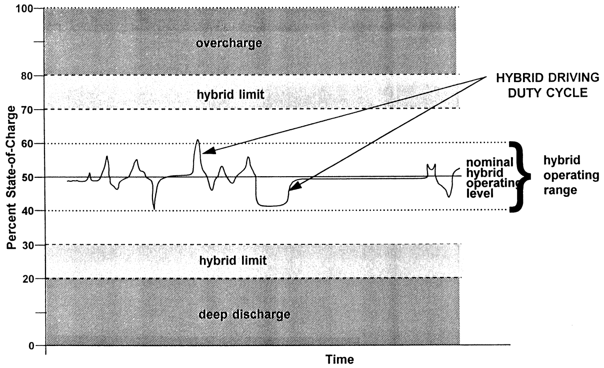


Fig. 2. State-of-charge considerations for battery operation in hybrid electric vehicles.

Table 1
PNGV energy storage system performance goals

Characteristics	Units	Fast response engine minimum values	Slow response engine minimum values
Pulse discharge power (constant for 18 s)	kW	25	65
Peak regenerative pulse power (trapezoidal pulse for 10 s for the specified pulse energy)	kW	30 (for 50 W h pulse)	70 (for 150 W h pulse)
Total available energy (discharge plus regenerative)	kW h	0.3	3
Minimum round-trip efficiency	%	90	95
Cycle life, for specified SOC increments	cycles	200 K for 25 W h 50 K for 100 W h	120 K for 100 W h 20 K for 600 W h
Maximum weight (plus marginal increase per unit of energy > 3 kW h)	kg	40	65 (+10 kg kW h^{-1} over 3 kW h)
Maximum volume (plus marginal increase per unit of energy > 3 kW h)	1	32	40 (+81 kW h^{-1} over 3 kW h)
Operating voltage limits	vdc	300 min 400 max	300 min 400 max
Max allowable self-discharge rate	W h per day	50	50
Operating temperature range	°C	−40 to +52	−40 to +52

As with EV batteries, there is no such thing as a "typical" duty cycle for an HEV battery. Standard test regimes have been developed (vide infra), but these only crudely approximate what happens to the battery in an HEV, as real driving patterns are very irregular. What exists is similar to the FUDS cycle developed in the early days of EV battery development and, as was the case for FUDS, it is likely that the standard HEV cycle will be modified, perhaps repeatedly, in the near future.

2.1.2. DOE / PNGV HEV battery requirements

The US Department of Energy has addressed the anticipated duty cycle for HEV batteries and in 1994 issued a list of battery specifications, given in Table 1, as part of their program entitled "US Hybrid Propulsion Systems Development". Separately, performance goals for the PNGV program have been issued, as shown in Table 2. The PNGV goals are identical to those given in Table 1 for some categories but there are several performance areas addressed by PNGV and not by DOE, and vice-versa. The specifications address both FR and SR architectures and various parameters are listed for "minimum" (current) and, in the case of DOE, "desired" (future) levels. These are for any energy-storage device, not just batteries, and they are very stringent. These are now the existing specifications that must be met for any energy-storage device to be included in the DOE HEV program (which is, in effect, the PNGV program). Following is a brief analysis of how

Table 2
DOE generic energy-storage requirements for hybrid vehicles

Characteristics	Units	Fast-response engine		Slow-response engine	
		Minimum	Desired	Minimum	Desired
Pulse discharge power (constant for 18 s)	kW	25	40	65	80
Peak regenerative pulse power (trapezoidal pulse for 10 s for the specified pulse energy)	kW	30 (for 50-W h pulse)	60 to 110 (for 150-W h pulse)	70 (for 150-W h pulse)	150 (for 150-W h pulse)
Total available energy (discharge plus regenerative)	kW h	0.3	0.5 to 0.75	3	3 to 8
Cycle life, for specified SOC increments	cycles	200 K for 25 W h 50 K for 100 W h	300 K for 35 W h 100 K for 100 W h	120 K for 100 W h 20 K for 600 W h	300 K for 200 W h 100 K for 600 W h
Calendar life	years	10	10	10	10
Maximum weight (plus marginal increase per kW h for $E > 3$ kW h)	kg	40	35	65 (+10 kg kW h^{-1})	50 (+10 kg kW h^{-1})
Maximum volume (plus marginal increase per kW h for $E > 3$ kW h)	1	32	25	40 (+81 kW h^{-1})	40 (+81 kW h^{-1})
Maximum package height	mm	150	150	150	150
Production cost, at 100,000 units per year (plus marginal increase per kW h for $E > 3$ kW h)	US$	300	200	500 (+US$62.50 kW h^{-1})	500 (+US$62.50 kW h^{-1})

batteries in general might fare in meeting these requirements.

2.1.2.1. Power. In terms of charge/discharge performance, the essence of battery operation in HEVs is power delivery and uptake. The pulsed-discharge power and regenerative pulse-power "minimum" specifications are reasonable for the battery sizes requested for both the FR and SR designs. Because the batteries differ in "available capacity" by an order of magnitude, the requirements for the FR battery appear to be considerably more stringent. While technologies such as lead–acid and nickel–cadmium (NiCd) can be expected to meet these standards with commercial products, technologies such as nickel–metal hydride (NiMH), lithium ion (Li-ion) and lithium polymer (Li-polymer) may have to depend upon non-standard products (primarily thin-plate designs) with higher associated costs. The discharge requirements are at lower power levels (25 and 65 kW) but for longer duration (18 s) relative to the charge levels (30 and 70 kW) and time (10 s trapezoidal pulse). Different chemistries will have different efficiencies on charge and discharge and so these requirements may result in operation at different nominal SOC levels near, but not at, 50%. For example, both lead–acid and NiCd have stronger discharge stabilities than for charge and so they are more likely to be operated at a nominal level below 50% SOC. Li-ion and Li-polymer, on the other hand, will have high ohmic voltage drops and sloping discharge curves while their charge-acceptance performance may be somewhat better; thus, they may operate at or above the 50% level.

2.1.2.2. "Available" energy. The specifications for "total available energy" can be misleading, as this refers to what can be obtained from the batteries *as they operate in HEVs, between ~25% and 75% SOC*. Unlike an EV battery that can have its full capacity withdrawn each cycle, an HEV battery has a capacity draw that ranges only a few percent above and below the nominal operating level which, itself, only moves (ideally) about 10% either side of the battery baseline level of ~50% SOC. Thus, what is "available" is only about one-half of the total battery energy. This means that in looking at weights, volumes, package heights and, particularly, cost, one needs to consider the full battery capacity or energy, not just the "available" value. The FR and SR designs require batteries with "available" energies of 0.3 and 3 kW h, respectively. Thus, the FR battery must have a total energy content of ~0.6 kW h or more and the SR battery a total energy of ~6 kW h, perhaps somehwat less (vide infra). Note that these are only the "minimum" values called for; the "desired" values for the future are higher — at reduced weights, volumes and costs! A further issue here is the rate dependency of energy and capacity. Many batteries have Ah ratings that only apply at low rates of discharge, far below those used in HEV duty. Thus, "available" energy for HEV use may be significantly less than one-half of the low-rate capacity and so actual rated battery capacity for the FR and SR designs may have to be significantly higher than 0.6 and 6 kW h, respectively. The added amount will depend upon the battery chemistry and the design, with thin-plate versions having better retention of low-rate capacity at higher discharge/charge currents typical for HEV use. Again, this factor will make it even more difficult to achieve the non-electrochemical goals for PNGV.

2.1.2.3. Round-trip efficiency. To achieve optimal electrochemical performance and minimise ohmic heating, high round-trip efficiencies are demanded. Even though HEV duty cycles involve relatively high charge and discharge currents, intended operation is within a SOC range where neither deep discharge nor overcharge will impact negatively on efficiencies. Assuming that these are coulombic efficiencies (i.e., A h in/A h out), battery thermal performance will be largely a function of the relative impedance levels for charge and discharge. Thin-plate valve-regulated lead–acid (VRLA) batteries will do best due to their minimal impedances, but NiCd, NiMH and even thin-plate Li-ion will do reasonably well. Li-polymer, particularly at low temperatures (vide infra), will have more difficulty with achieving 90% or 95% efficiency, but it may do so. If this refers to energy efficiency (W h in/W h out), then all technologies except VRLA and, possibly, NiCd will have great difficulty. Between their relatively high impedances and sloping discharge curves due to limited electrolyte diffusion, chemistries such as NiMH, Li-ion and Li-polymer will not likely achieve the round-trip energy efficiencies required at the high current levels used in HEVs.

2.1.2.4. Cycle life. The HEV duty cycle is like no other common application. Shallow cycling of 2–3% either side of a nominal 50% SOC, with high-current spikes either way, should result in very high cycle numbers compared to conventional deep-discharge cycling. Thus, the DOE/PNGV requirements are, on the surface, not unreasonable. However, continuous operation in a partial-state-of-charge may be damaging to a number of the battery chemistries contemplated. VRLA batteries may suffer irreversible capacity decline due to the buildup of hard lead sulfate when operated in extended PSOC operation. NiCd and, to a lesser extent, NiMH batteries may experience the "memory effect" under these conditions. Such a duty cycle is difficult to evaluate for the lithium-based technologies. If the battery is held continuously in the 40–60% SOC range cycling can be very efficient, as coulombic efficiencies are high, with no overcharge and no deep discharge being applied. However, some vehicle control strategies being contemplated require a full recharge periodically, perhaps even daily. This would present a very complicated duty cycle and it is unlikely in this case that technologies such as lead–acid could meet the cycle-life requirements.

One rough example of this type of cycling in the literature is a reference to a simulated HEV duty cycle of a Bolder lead–acid single cell, where it was taken to 50% SOC and then constant-current cycled about 3% either side of that level, yielding about 42,000 cycles before failing [1]. It is interesting to note that the cycle life specification for the SR battery is much less stringent, given that the 100 Wh SOC increment is for a much larger battery (several times the capacity of the FR product), giving a correspondingly smaller depth-of-discharge (DOD) in cycling. Moreover, fewer cycles are required in the "minimum" specifications whereas in projected usage patterns it is likely that the SR battery will be exercised more rigorously than the FR unit in a power-assist mode.

2.1.2.5. Calendar life. Ten years is required in all cases; this will be difficult or impossible for all existing battery chemistries, particularly if one assumes continuous use during this time. This is an ambitious goal, but it is one not likely to be realised.

2.1.2.6. Weight and volume. Unlike EV batteries, weight and volume are not specified stringently for HEVs by DOE/PNGV. For example, assuming that the FR product must supply discharge and charge-acceptance power pulses of 25 and 30 kW for 18 and 10 s, respectively, sustained power levels of 625 and 750 W kg^{-1} are required for a nominal 40 kg battery. Given that the FR product has a full rated capacity of 600 W h and can weigh 40 kg and take up a volume of 32 l, one calculates a specific energy of 15 W h kg^{-1} and an energy density of just under 19 W h l^{-1}. Thus, the power levels demanded are aggressive and dictate the use of thin-plate cell designs with very high plate surface areas for batteries. Fortunately, the energy requirements are very low, to the point where they may be met even by non-electrochemical storage devices such as supercapacitors and flywheels. Clearly, these specifications are written for a "power" battery that can involve inefficient designs in terms of energy content. In fact, the 600 Wh capacity inferred from the "total available energy" specification is quite low and it is likely that a capacity in the range of ~1.5 kW h would be easily achievable, given the weights and volumes available. For applications envisioned where the FR battery would be used extensively in start/stop city traffic situations without the benefit of recharge from the primary power source, this added capacity may be necessary.

The SR product, on the other hand, is required to be energy-intensive, with power demands comparable to those for the FR unit. Using the DOE/PNGV specifications tables, one calculates a required specific energy of 63 W h kg^{-1} and an energy density of 94 W h l^{-1}. These numbers seem easily achievable for technologies such as NiMH and Li-ion, given values published for these technologies for use in portable devices and even in electric vehicles. However, in order to achieve the required power capabilities of ~600–800 W kg^{-1} (at 40–60% SOC), design compromises must be carried out that reduce the "standard" low-rate energy values to levels at or below those called for by DOE/PNGV. Moreover, chemistries such as VRLA and NiCd likely cannot meet the required specific energy level of 63 W h kg^{-1} in *any* design. This may be partially mitigated by the fact that the SR design will have a wider operating window in terms of %SOC than the FR; thus, the full rated capacity may need to be considerably less than twice the available energy.

2.1.2.7. Maximum package height. The specification given for both the FR and SR products — 150 mm, or ~6″ — may not seem that critical, but it adds another dimension of restriction on the device designer, at least for traditional battery technologies in the SR unit. Given that this is specified as an ~350 V/6 kW h unit overall, the battery capacity required for the SR product would be ~17 A h. In order to meet the stringent specific energy/specific power requirements, "head space" must be kept to a minimum relative to the volume of the plate stack. This implies a tall, thin design rather than the relatively short, fat one dictated by the package height. Moreover, it is likely that most of the HEV products utilizing the chemistries available would be in a spiral-wound configuration. For good heat dissipation, a taller, thinner cell/battery envelope may be desirable.

2.1.2.8. Operating voltage limits. For both the FR and SR products, DOE/PNGV specifies an operating range of 300–400 V, which implies an OCV of ~350 V at 50% SOC. This allows for a 50 V swing either way during operation and if one looks at nominal cell voltages for the various battery chemistries it seems to be a reasonable window, one that is necessary for compatibility with the control system electronics. However, it must be kept in mind that the power demands on the battery are relatively high and each chemistry has some relative weakness in terms of discharge and charge acceptance. Furthermore, chemistries such as Li-ion and Li-polymer have steep voltage/SOC slopes (more so at low temperatures), so if the SOC drifts to high or low values the battery may not be able to stay within the 300–400 V limits. Also, individual cells may be at significantly higher or lower voltages than the average and as they weaken from repeated overcharge or deep discharge they will have a disproportionate effect on the overall battery voltage. As will be seen later, all of these factors can interact to result in a relatively small usable SOC range (or total available energy) to provide the power needed by the vehicle.

2.1.2.9. Self-discharge rate. It appears that this specification — a maximum allowable self-discharge rate of 50 W h per day (for both FR and SR products) — was written for devices with very poor open-circuit-voltage stabilities. In fact, it is so generous that batteries meeting this specification would not be practical in many "real world" scenarios. Consider an FR battery with 600 W h of capacity to begin with. When it is operated at its nominal 50% SOC it now has an available capacity of 300 W h before it is flattened. With a self-discharge rate of 50 W h per day it would be dead in 6 days; within a day or two its performance on discharge would be severely compromised. This could be circumvented by starting the vehicle with the primary power source and using it to bring the battery capacity back up to the nominal 50% SOC level, but this would be done under conditions of very poor efficiency (thus, high emissions levels) and may be prohibited in some areas. Chemistries such as lead–acid, NiMH and Li-ion can suffer permanent losses of capacity when fully discharged, particularly at elevated temperatures, so this is a dangerous specification. Clearly, it is not as stringent for the SR battery, as the same daily drain rate in W h is specified for a considerably larger battery.

2.1.2.10. Operating temperature range. The range is the same for both the FR and SR products, namely −40 to +52°C. This will present serious problems for all of the common battery chemistries considered for HEV use. For lead–acid, the upper limit is no problem, but at a 50% SOC level the electrolyte would freeze at low temperatures. This could be circumvented by bringing the battery to a full state of charge after use, but this would have a negative impact on life. For NiCd and NiMH, discharge performance at the lower limit would be poor and at the upper limit the charge acceptance would be minimal. Current versions of Li-ion and Li-polymer batteries will not operate at low temperatures. These problems may be circumvented through the use of sophisticated thermal-management systems, but these would raise the cost of the battery system to unacceptable levels, certainly far beyond those specified by DOE/PNGV (vide infra).

2.1.2.11. Cost. The cost levels given in Table 2 cannot be achieved by any of the battery chemistries, given the specialized nature of products required for HEV duty cycles. One possible exception is lead–acid for the "minimum" FR product, but even this is doubtful. All of the other chemistries cannot meet the required cost levels in currently available products and in most cases they cannot meet them just on the basis of materials costs, manufacturing and packaging aside. Associated charging and thermal-management hardware makes the situation more untenable in practical terms (i.e., total vehicle costs).

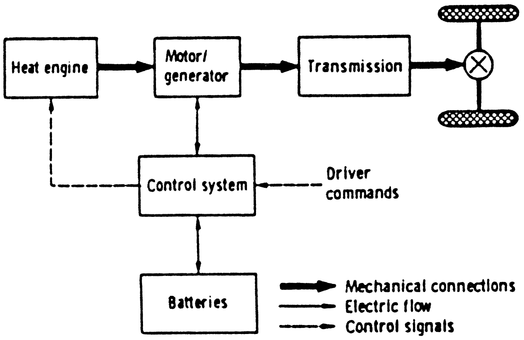
In summary, the DOE/PNGV specifications are unrealistic and inconsistent. Some available batteries can meet some of the specifications but there is no current or near-term battery that can meet all of them. Still, these are good guidelines to drive the technologies forward, but it appears that they are not completely realisitic, particularly the "desired" values. It seems that existing batteries can meet most of the requirements of the FR product, but achieving the objectives set for the SR unit will be very difficult.

2.1.3. Vehicle configurations

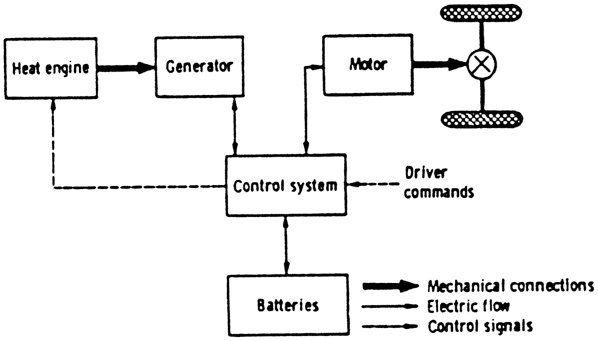
In order to better understand the role of batteries in HEVs, it is useful to have a brief overview of the construction of these vehicles, in general terms. At the simplest level, an HEV is a dual-power source, one primary and the other secondary. Most, if not all, existing prototype HEVs use some form of small heat engine for the primary source (a fuel energy-conversion device such as the traditional internal-combustion engine, ICE), although it could also be a large battery or a fuel cell [2–4]. The secondary power source is some form of energy-storage device that can provide auxiliary power and take up regenerative-braking energy on demand; while normally a rechargeable battery, it could also be a flywheel or supercapacitor. Having such a secondary power source on board allows the vehicle designer to size and operate the primary device(the source of emissions) for optimal efficiency; this, coupled with the ability to capture braking and deceleration energy, makes HEVs potentially very efficient. The PNGV goal is to have "production-feasible" mid-sized passenger vehicles that achieve 100 miles per gallon with conventional fuels by the year 2011.

Since the primary and secondary power sources are interactive, an electronic control system is required in order to optimise the performances of both devcies. Other components such as a motor/generator, transmission and one or more electric motors are not common to all HEVs and will depend upon the configuration employed. Because as much as 50% of vehicle power can be lost to air drag and road friction [5], research on aerodynamic designs and low-rolling-resistance tires is also an important consideration.

2.1.3.1. Series/parallel arrangements. How the primary and secondary power sources are arranged can be put into two general categories — series and parallel; common versions of each (there are a variety of different types for each) are shown in simplified block diagram form in Fig. 3. In the parallel configuration, the primary heat-engine shaft provides power directly to the drivetrain; relative to a series HEV this heat engine is large, on the order of 70–80 kW output (for reference, 1 kW = 1.33 hp, or 1 hp = 0.75 kW), but it is small compared to the ICE in a conventional vehicle [6]. A relatively small electric motor (20–40 kW output) is in parallel with the primary power source and will provide additional power for acceleration and hill climbing when the demand exceeds the capability of the heat engine operating in its zone of maximum efficiency. Thus, the drivetrain receives primary mechanical power from the heat engine, but for short periods it can operate on electrical power from the battery/motor(s) alone, such as in city traffic. Alternately, both can provide power concurrently to the transmission and/or electric motor(s).



Parallel Hybrid Configuration



Series Hybrid Configuration

Fig. 3. Block diagrams for parallel and series architecture of hybrid electric vehicles.

Because the battery is relatively small it is worked heavily, but not for a great deal of the time, and needs greater power capabilities than the series battery, particularly when it comes to regenerative-braking (regen) uptake. Interactions between the two power sources are handled through driver commands and the electronic control system.

In a series-configured HEV, the output of the heat engine is converted to electrical energy through a generator which, either separately or jointly with a battery, will power the drivetrain (transmission and/or motors) [6]. Again, interaction of the two power sources is determined by driver commands and an electronic control system, as shown in Fig. 3. In the series system, the two power sources can be sized similarly to the parallel hybrid, but it is more common that the heat engine be smaller and the battery larger; thus, in the 90–120 kW system above, the heat engine and the battery may have power outputs in the range of 45–60 kW each. While the battery is sized considerably larger in a series HEV, it tends to be worked more of the time, albeit at relatively small depths of discharge compared to the battery in a parallel system.

2.1.3.2. Operating strategies. Whether the arrangement is series or parallel, the general operating strategy for an HEV may be represented as follows [7], given for a parallel power-assist (FR in the DOE/PNGV parlance) configuration. Because of low operating efficiencies (and thus high emissions) for the ICE (considered here as a representative heat engine) at low speeds/high torques, the vehicle is initially brought up to some minimum speed by the battery/motor (i.e., an all-electric mode). At a speed of, say, 10–15 km h^{-1}, a clutch control is used to gradually bring in the ICE, adding its torque to that of the electric motor. At higher, steady speeds, the battery is disengaged and the ICE alone is used, operating in its zone of optimal efficiency. If the battery needs to be recharged, a small portion of the engine torque can be used to produce current by the electric motor operating as a generator. If the output of the ICE, operating in this range of optimal efficiency, is not sufficient for passing acceleration and/or hill climbing, the battery will be engaged by the control system to provide the needed power. Because the ICE is sized relatively large, it can normally provide all the cruising power needed on the highway. For downhill driving or coming to a stop or slowdown, the engine may be shut off, the clutch disconnected and a braking torque applied by the electric motor operating as a generator, thus charging the battery and stressing its charge-acceptance capability (vide infra). This would also be the general sequence in stop-and-go city driving, with frequent stops and startups. While shutting off the engine frequently in traffic puts severe pressure on the small power-assist battery, it minimises the time that the ICE would operate at low efficiency, thus keeping emissions low. This makes a point for a higher-capacity FR battery, in the range of 1.5–3.0 kW h.

This is clearly just one mode of operation, but it does give some idea of the operating strategy in an HEV, including the demands put upon the battery. For the above example, it is estimated [7] that a 2.5 kW h battery would be needed, particularly for city driving. This is considerably larger than the 0.6 kW h FR unit capacity implied in the DOE/PNGV HEV specifications (vide supra). Obviously, the greater the capacity of the battery the smaller the impact of the load will be, but cost, volume and weight are confounding factors. Cost is more or less linear with battery output, as are weight and volume. Thus, a heavy, costly battery carries significant penalties in a vehicle and, in the extreme, becomes an EV. Conversely, it is not obvious that minimal battery weight is always the best approach [8]. If the battery is too small, the vehicle has little all-electric driving range, the battery will be severely stressed (and thus will have a shortened lifetime) and would not be effective in regen uptake. Also, the ICE would have to operate for a larger percentage of the driving time, some of this being at very low efficiencies. Thus, a very small battery may result in greater fuel consumption and higher emissions levels relative to the same vehicle architecture with a battery of moderate size. These points are summarized in Fig. 4, showing that, at least in this series HEV, a battery of a moderate size yields optimal fuel efficiency [8], even though the vehicle is

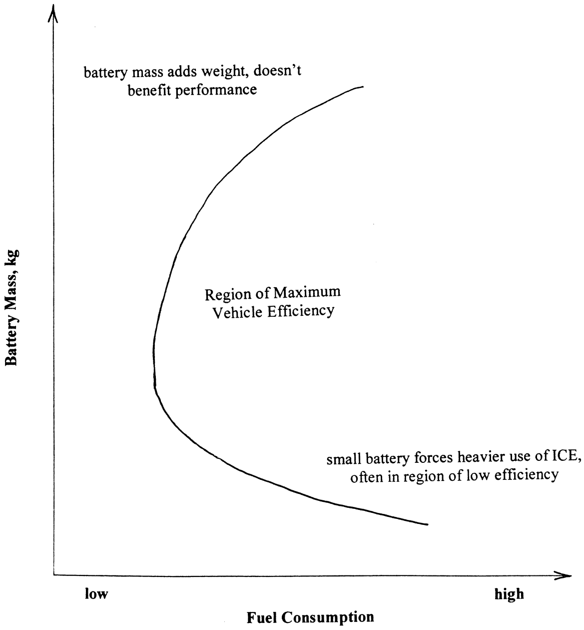


Fig. 4. The influence of battery mass on fuel consumption in a series hybrid electric vehicle.

carrying a greater battery load. The same argument can be made for the above parallel scenario.

The HEV literature contains inconsistent and, sometimes, conflicting views on the relative merits of parallel and series configurations. It appears to be the case that parallel systems are superior in terms of fuel economy and performance [9,10] but inferior in terms of emissions [9]. Cost appears to be greater for the series architecture by a significant amount [11,12], but both are likely to be more expensive than a conventional ICE vehicle, at least in the drivetrains [11]. Higher efficiency in parallel operation apparently comes largely from the primary power source being applied directly to the drivetrain, while in the series configuration there is a longer energy-conversion stream due to the imposition of a generator following the ICE [9,12]. This generator also adds weight and cost, but the series architecture allows for more efficient operation of the ICE because of a more uniform sharing of the loads with the battery. However, this more uniform sharing means the battery, while large, is often used almost continuously and the smaller ICE results in poorer highway performance [9]. One automaker [9] has estimated that the parallel system offers some 10–30% advantage in performance and 5–20% in fuel economy. On the other hand, the larger battery in the series architecture confers several distinct advantages, among these being a longer ZEV range for city driving and a greater capability for capturing regen energy. Clearly, there are many issues to consider and it is likely that the various automakers will choose different vehicle architectures.

2.1.3.3. Dual-mode (SR) and power-assist (FR) operation. In the power-assist (FR) mode, the battery is called upon intermittently to provide power to augment the output of the heat engine and to take up regenerative braking and deceleration energy. It is relatively small in size and capacity and has a design optimised for power. Because it is relatively small and the demands for charge acceptance are greater than for discharge, it is likely to be operated at a state of charge below the nominal 50% level. Thus, all-electric driving range is severely restricted, particularly in start–stop city driving in a passenger vehicle with air conditioning. With a very small battery, this may not be the preferred architecture for city driving. Given all of these considerations, it appears that this battery would ideally be sized in the range of 1.5–3.0 kW h, as noted, primarily for regen uptake and all-electric start–stop city driving. FR is generally, but not always, used in parallel HEVs.

The dual-mode, or SR battery is larger and shares the power load more evenly with the primary power source; generally, it is about 1/5th to 1/3rd the size of a pure EV battery for a correspondingly-sized vehicle. It is most often used in a series configuration, as its large size and capacity would be excessive in a parallel, power-assist vehicle architecture. Being capable of providing substantial power levels, the dual-mode battery allows for the use of a smaller ICE that can be used for more of the driving time in its zone of maximum efficiency, thus accounting for the lower emissions levels for this type of system. The battery is cycled more, but it is relatively large and, thus, the cycling is shallow. A significant advantage is that one has a much larger (several times larger than the FR unit in the DOE/PNGV specifications) battery to capture essentially the same amount of braking and deceleration energies, thus allowing the battery to be operated at a higher nominal SOC, giving it added discharge capacity. This is a good configuration for city driving, allowing extended all-electric operation of some 15–30 miles with no use of the heat engine, if required. However, as noted earlier, having the two power sources in series and needing to convert the ICE output to electrical energy with a generator adds weight, complexity and cost, as well as reducing overall efficiency. In highway driving, the battery might be used continuously or almost so due to the relatively small power output of the ICE, typically 45–60 kW. However, this can be advantageous as it is a way to dissipate the buildup in state of charge from the battery capturing braking and deceleration (downhill) energy.

2.1.4. Thermal issues

Intrinsically tied to vehicle architecture and battery design and performance, thermal management is an issue of great importance in HEVs, perhaps not as significant as in EV systems but important nevertheless. While the battery operates (ideally) in a region of minimal heat generation from overcharge and deep-discharge reaction enthalpies, i^2R heating is significant due to the high-current pulses involved in HEV operation. Different battery chemistries will have varying requirements for thermal management, from minimal for VRLA to extreme for NiMH and Li-ion to critical for Li-polymer. Furthermore, it will be more necessary for the SR battery system due to the larger masses and smaller surface-area-to-volume ratios, designs optimised for energy rather than power (thus, higher impedances in thicker-plate designs) and greater usage patterns relative to the FR battery. As with EV batteries, it is more important to have good thermal uniformity rather than a lower or higher nominal temperature level.

In large arrays such as HEV batteries, uniformity becomes an issue just due to overall heat generation and removal. Problems arise when some portions of the battery are relatively cool and others relatively warm, if not hot; this can lead to significant differences in both discharge and charge-acceptance performance [13] for EV batteries. Fortunately, the HEV application, while unusual in many ways, does not, ideally, impose great thermal stress on a battery system. The battery is normally not used continuously and is ideally operated in a SOC range where it is not likely to experience significant overcharge or overdischarge; this condition is more likely when relatively large FR and SR batteries are used. Thus, ohmic heating is the primary heat-generation source and so the battery chemistry used is important, as reflected by the nominal module impedance.

This is not to say that thermal management is not needed for HEV batteries. A 6 kW h/350 V SR battery will have cells or modules of ~17 A h rated capacity. These are substantial units that, in a large array, will not be able to effectively dissipate even ohmic heating using only radiation and convection — i.e., passive methods. Some active cooling such as forced air or a heat-exchange blanket will be needed, but not to the extreme measures necessary for EV batteries. In addition, the presence of the primary heat engine provides a significant heat source which can be effectively utilised in cold climates to heat not only the battery but the passenger compartment and for chemistries requiring elevated temperatures such as Li-polymer. Cooling and maintaining uniformity are the larger issues.

A small power-assist/FR battery may not need any thermal management, or at least nothing beyond a design utilising air movement for heat removal and distribution. These are low-capacity cells and modules (typically 2–6 A h) with high surface-area-to-volume ratios which facilitate heat transfer out of the modules and the pack. These modules will increase in temperature somewhat as they are cycled, but they may reach steady-state levels that are acceptable from a performance/cycle life standpoint without excessive thermal-management efforts, as shown in Fig. 5 [14]. These two curves are simulations from thermal modeling of cylindrical VRLA single cells during HEV-GSFUDS continuous cycle testing. As can be seen, the cells do reach elevated temperatures, but even the 5 A h cell reaches steady state at ~30°C, easily a manageable temperature. However, this must be considered a “best case” scenario, as larger cells in full 300 V+ packs will doubtless achieve higher temperatures.

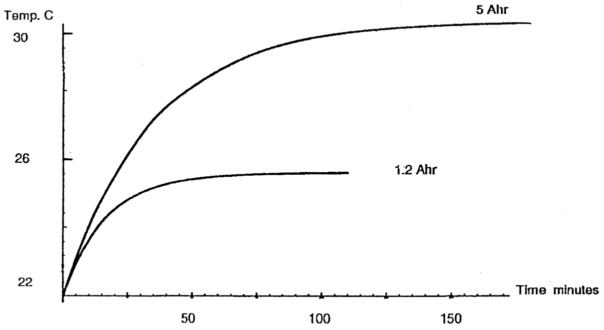


Fig. 5. Simulated temperature profiles for 1.2 A h and 5.0 A h cylindrical VRLA cells resulting from modeling of heat production during HEV-GSFUDS cycling.

As noted earlier, low- and high-temperature operation is difficult or impossible for all of the common battery chemistries considered for use in HEVs. Low-temperature operation is poor in all cases and, for lead–acid, may be impossible due to electrolyte freezing at the 50% SOC level. This can be circumvented through the use of waste heat from the ICE and by fully charging the battery at the end of usage (a realistic operating strategy). Given this, freezing of the electrolyte would not occur except in the most extreme of conditions. High-temperature operation, on the other hand, is very good for lead–acid and is necessary for Li-polymer (~80°C) and, to a lesser extent, Li-ion due to their high solvent/electrolyte resistance values and low ion mobilities. Charge acceptance at elevated temperatures is poor for NiCd and NiMH, making regen and deceleration uptakes inefficient in hot conditions.

2.2. Battery performance issues

As noted earlier, the HEV application puts unique demands on the battery energy-storage device used. Keeping the battery at or near 50% SOC and then demanding high-current events in either direction is unusual. Operation in large strings of up to ~250 cells and, possibly, series–parallel arrays, introduces significant issues relating to cell-to-cell uniformity, reliability of intercell connections and the like. Much of what is in this section is speculative, as most of the performance areas considered have not been tested thoroughly and significant amounts of data do not exist in the literature. Still, this is at the heart of considering the battery’s role in HEV design and performance. Although the tenuous validity of the DOE/PNGV specifications has been highlighted, in some instances these will be used as standards in evaluating performance, as they are the most significant guidelines that exist.

2.2.1. Discharge

Discharge in an HEV application cannot be considered in the traditional sense. Discharge spikes are intermittent and of intense amplitude (as much as 30–40 times the rated capacities), but relatively small in terms of capacity withdrawn from the battery. Thus, the depth of discharge in "cycling" is shallow, typically only ~ 2–3% either side of a nominal SOC level near 50%. Voltage "stiffness" during discharge is important, as exhibited by thin-plate VRLA and NiCd products, particularly for the power-assist (FR) HEV architecture. The power-assist battery will be designed with very thin plates, closely spaced and having relatively large surface areas. Thus, current densities, even during the high-current spikes experienced, are not great so voltages remain fairly stable. The SR battery will be optimised more for energy, so on a relative basis, compared to the FR designs, current densities may be higher. However, these are significantly larger batteries and the loads imposed upon them are not proportional to the greater kW h capacities. In evaluating battery technologies for HEV applications, it is more useful to look at power characteristics rather than the corresponding energy parameters because most of the discharge operations are done at high current levels with small energy drains. Thus, properties such as rated capacities (which are usually taken at very low discharge rates) are less important than the shape of the Ragone plot in the high-power region (i.e., high drain rates) in considering the suitability of a particular battery for HEV use. Beyond that, charge/discharge performance in the region of 50% SOC is of primary importance.

Discharge properties will be discussed in greater detail in the sections on testing and evaluations of different battery technologies.

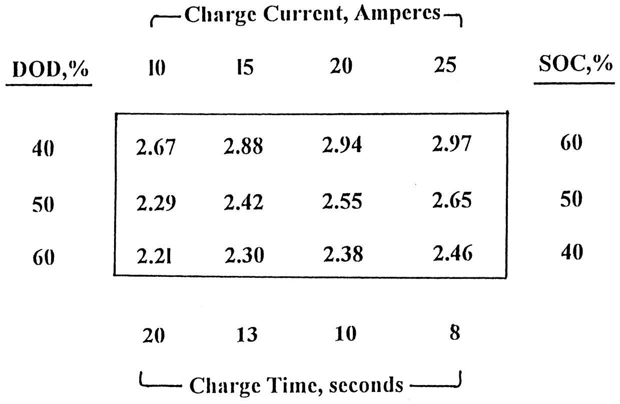
2.2.2. Charge acceptance

Charge acceptance in an HEV duty cycle is, basically, high-current partial recharging. During braking and deceleration events, valuable energy can be recaptured by the battery system through the motor/generator. The primary danger for the battery is that if it is in an elevated SOC and/or the current amplitude input is extremely high and prolonged it can be driven into overcharge, possibly resulting in significant gas venting and heat generation. The ability of a battery to accept charge is dependent upon the chemistry involved, its design (primarily plate surface area per A h of capacity), its size (A h rating) and its state of charge when accepting current. Obviously, thin-plate batteries will be better at charge acceptance than thicker-plate designs, largely because for a given amount of charge the current density will be lower and thus plate polarisation levels will be less. Size is obvious (again relating to current density), but it is worth reiterating that the charge-acceptance requirements on a FR HEV battery are much more stringent than those of an SR product, since either, in the same type of vehicle, will be required to capture roughly the same energy amounts during operation. Thus, fundamentally different designs are required.

Charge-acceptance capability, discharge capacity available and the nominal SOC chosen for a battery are intertwined and interdependent, along with the necessity for the battery to stay within the nominal 300–400 V window required by the control electronics system. Each battery chemistry will have different requirements and performance capabilities relating to these factors and so one cannot specify a universal SOC level for operating all battery chemistries. Table 3 illustrates this point for a small, cylindrical-cell VRLA product which is subjected to a ~ 5% charge input (200 A s for a 1.2 A h cell) from SOC levels between 40% and 60% [1]. Moreover, this is done at different charge currents, with times adjusted so that the charge input is held constant. The values in the center of Table 3 are the cell voltages (nominally ~ 2.05 V at rest) at the end of the charge steps. Without going above ~ 2.4 V/cell (necessary to keep the battery within the 300–400 V window), charge-acceptance power levels of ~ 650 W kg^{-1} are demonstrated (for a bare single cell). As can be seen, this particular product is sensitive to the nominal SOC level chosen, since it shows good performance at 40% SOC but poor voltage regulation at 60% SOC. These data suggest that this product should be operated at a nominal SOC level of 40–45% in order to minimise overcharge and optimise energy capture. The danger in operating at such a low SOC is that relatively little discharge capacity is available. This could be particularly problematic if such a battery, in a small kW h FR package, were put into vehicles that spend much of their time in city driving.

Another factor that can affect the choice of nominal SOC level is the polarisation behaviour on charge and discharge. For VRLA, the slope of the polarisation curve (voltage versus charge or discharge current) is reported to be significantly greater for charge than for discharge [15], as shown in Fig. 6. Thus, for a given current amplitude a battery will be pushed to higher voltages on charge than to

Table 3
End-of-charge voltages for an ~ 5% charge-acceptance step from various states of charge for a 1.2 A h VRLA cell



DOD,%	Charge Current, Amperes				SOC,%
	10	15	20	25	
40	2.67	2.88	2.94	2.97	60
50	2.29	2.42	2.55	2.65	50
60	2.21	2.30	2.38	2.46	40
	20	13	10	8	
	Charge Time, seconds				

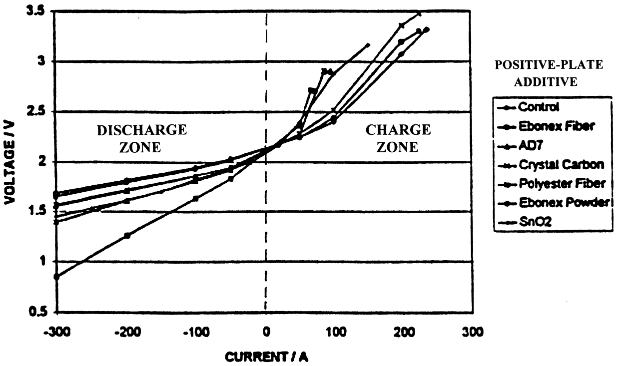


Fig. 6. Charge and discharge polarisations from a nominal 50% state of charge as a function of current level for 12 V/16 A h VRLA batteries with various positive-paste additives.

lower voltages on discharge. This greater inefficiency for the charge process argues for operating lead–acid batteries below a nominal 50% SOC level; other battery chemistries will probably have significantly different charge/discharge characteristics and these must be rigorously defined for evaluation of their suitability for HEV use. For example, the charge–discharge/pulsed-current curve for the Ovonics Ni–MH battery has been shown to be symmetrical, indicating superior charge-acceptance performance to lead–acid [16].

2.2.3. Partial-state-of-charge cycling

As noted in Section 2.1.2.5, the duty cycle for a battery in an HEV is unusual in that it can be crudely characterised as rapid shallow cycling either side of ~ 50% SOC. Literature reports are sparse for cycle-life performance by the different battery chemistries, but it is safe to say that there will likely be significant differences in how well they compare. DOE, through their INEEL facility, have developed standardised cycle tests for FR and SR batteries at a number of energy-extraction levels that represent the cycle-life values called out in the DOE/PNGV Performance Goals given in Tables 1 and 2. However, the charge/discharge profile developed is very simple and it is questionable how accurately it reflects what a battery sees in actual HEV use.

2.2.4. Performance in long strings / matrices

A key issue with HEV batteries, as with EV applications, is the performance of individual cells in long strings and, possibly, series–parallel arrays. Fortunately, the HEV duty is one which seldom requires full charge or complete discharge, so the usual problems with long strings (elevated charge voltages/gassing, cell-to-cell imbalances, overdischarge, etc.) may be minimal. The major problems in HEV batteries are likely to be cell failures, general reliability and current distribution when multiple strings and/or matrices are involved.

As with EV batteries in single, long strings, catastrophic cell failures cannot be tolerated, as one open cell will render the battery useless. More moderate failures will diminish the performance of the battery but, again due to the nature of the hybrid duty cycle, they may not be as critical as in EV batteries where full capacity may be required every cycle. With the duty cycle being shallow PSOC cycling near the mid-capacity level the strain on the battery is minimal. This, of course, is counterbalanced by the fact that many tens of thousands of such cycles are required. The most notable failures will probably be related to the high-power charge/discharge demands put on the battery. Thus, defects such as loss of plate active surface areas, corrosion of materials, electrolyte dryout, intercell connection failures, cell/battery overheating, buildup of passivation layers — conditions that gradually increase the battery's impedance — will be significant. In actual fact, it remains to be seen what the common failure modes will be for HEV batteries, as little is available yet in the open literature.

The paralleling of series strings is a risky and controversial practice, but this will often be done out of necessity in constructing large SR-type batteries where only low-capacity cells or battery modules are available. Inequalities in string impedances can result in uneven current distribution string-to-string which, in the extreme, can lead to thermal runaway if sufficient charging current is available. However, in an HEV battery, unless periodic full recharge is required as part of the vehicle operating strategy, thermal runaway is not likely to be a serious issue. An expensive, but effective way to configure high-voltage HEV batteries is to cross-matrix string-to-string at intervals of anything from individual cells up to every 24 or 48 V, depending upon the size of the battery and the discharge rate [17], using more frequent matrixing the higher the charge/discharge rates experienced in HEV operation. For large arrays requiring high reliability, such as in HEVs, series–parallel matrixing is highly recommended. Thus, a completely failed cell will be isolated and current will continue to flow around it [1]. However, this imposes a greater load on adjacent cells and they are thus likely to fail sooner than they would have otherwise.

Failures aside, the remaining issue is current distribution among parallel strings during charge/discharge events. Even though these are short in duration, they are large in magnitude and current will distribute among strings according to their impedances (all of this is not applicable to a single series-string battery). Fig. 7 shows data on a 4 × 4 (16-cell) test matrix of 1.2 A h VRLA cells subjected to a 300 A discharge (nominally 75 A per string) [18]. Currents are recorded for each of the 16 cells throughout the discharge, as shown, creating a surface going back-to-front that illustrates the fairly uniform distribution of the current load throughout the matrix until ~ 90% DOD, at which point some cells fail and the stronger ones carry the bulk of the load. While this current draw is quite high (corresponding to a 100 kW discharge for a 330 V battery), it is representative of what might be seen by the cells in a FR

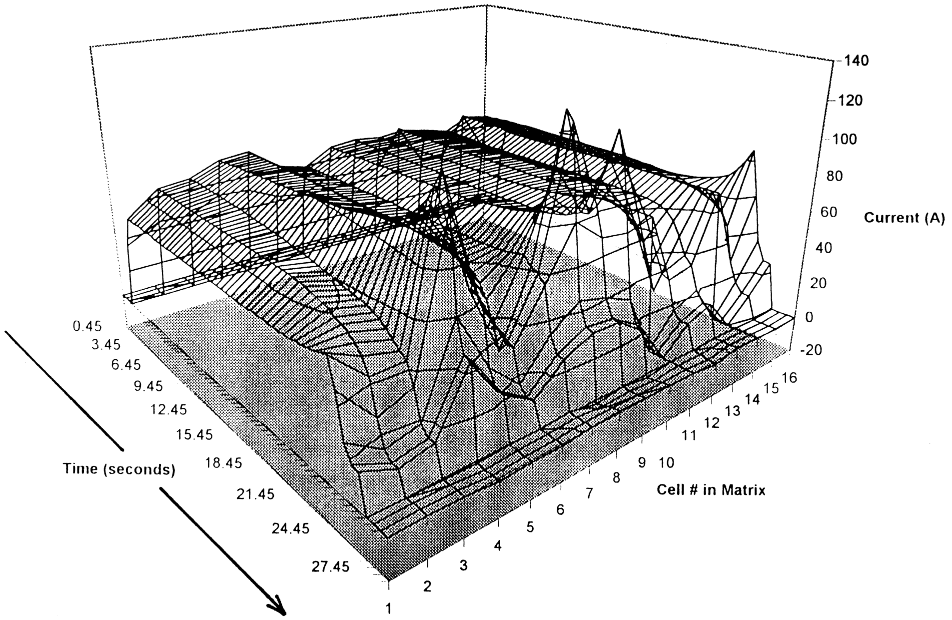


Fig. 7. Surface plot of the discharge current carried by each 1.2 A h cylindrical VRLA cell in a 4 × 4 series–parallel test matrix during a 300 A discharge.

battery in an HEV. As long as the battery is operated in the 30–70% SOC range, the breakdown seen toward the end of discharge in Fig. 7 will not be a factor.

2.2.5. Overcharge / overdischarge

Due to the PSOC nature of the HEV duty cycle, individual cells should not be overcharged or experience overdischarge (cell reversal in the extreme). However, this is only true if the vehicle control system keeps the battery in its prescribed range of SOC and if cell-to-cell imbalances do not occur due to initial mismatching, manufacturing defects or applications abuse such as large temperature variations. Also, the method used to determine SOC must be accurate (see Section 2.2.7). These are rather large "ifs". Overcharge and/or deep- and overdischarge of some cells in very long strings on an occasional basis is alsmost unavoidable, but as a battery ages it becomes more likely. Most chemistries can tolerate moderate amounts of overcharge and overdischarge, particularly the relatively short, infrequent levels likely to be experienced in "normal" HEV operation. Battery management systems are available that can "move" charge and discharge currents between cells and modules during overcharge and deep discharge, but they may be more difficult to use in an HEV battery due to the PSOC operating mode.

2.2.6. Charge / discharge efficiency

Charge/discharge efficiency (also called "round-trip energy efficiency") will vary significantly with battery design and cell electrochemistry. For a given battery it will be optimal in the useful HEV 30–70% SOC range, but it will degrade rapidly for any cells that go into overcharge or overdischarge [19]. It can be defined in terms of either coulombic or energy efficiency. For the former, it is simply charge in and charge out, in units of current and time. Unless a significant amount of charge or discharge current goes into parasitic chemical processes or is dissipated as heat, this factor is always close to unity. It will never be exactly unity because the charge process for most battery chemistries is inherently slightly less efficient than discharge due to the higher energies associated with energy storage. As can be seen in Fig. 8 for a lead–acid battery [20], this can vary with SOC and becomes severe for charging into overcharge. However, in the normal HEV operating window of 30–70% SOC the difference is fairly constant and relatively small. Thus, coulombic efficiencies are close to unity not only for lead–acid but also for the other battery chemistries considered herein.

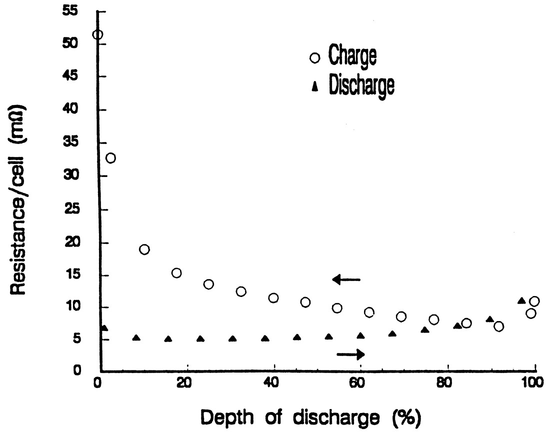


Fig. 8. Calculated resistances on charge and discharge as a function of depth of discharge, taken from pulsed-current measurements. The arrows designate the sequencing of DOD measurements.

More meaningful comparisons can be made when considering the energy (watt-hour, or W h) efficiency, which takes into account voltages as well as currents and thus defines the electrochemical efficiency of a battery more clearly, whether it be a reflection of the basic chemistry or the cell/battery design, or both. The DOE/PNGV definition involving energy efficiency is as follows:

$$\text{Round-trip energy efficiency} = \frac{\text{Watt-hours for discharge}}{\text{Watt-hours for charge}}$$

As can be seen in Table 1, the requirements are for minimum efficiencies of 90% and 95% for the FR and SR units, respectively. Since times and currents (coulombs) are taken as being essentially equal in a "round trip" scenario, the efficiency is dependent largely upon the voltage stability of the battery when it is pulsed with high currents in either direction. In simplest terms, the more stable the voltages during the charge and discharge events (i.e., the less polarisation occurring), the higher the energy efficiency. As noted earlier, due to ohmic [20] and polarisation [19] effects, the charging process is less efficient than discharge, even in the 30–70% window where the vast majority of the current goes into the primary charge/discharge reactions and very little into parasitic processes.

Technically, the round-trip energy efficiency is determined by the battery voltage deflections from open circuit when the battery is given high-power pulses in either direction such as to bring it back, nominally, to its initial state (i.e., coulombs in = coulombs out and initial OCV = final OCV). On discharge, the voltage on load will be less than the nominal OCV; on charge it will be above it. The ratio of the two voltages on load largely determines the efficiency. Efficiencies will be relatively high at low charge/discharge rates and will become lower as the battery is subjected to higher-power pulses. As long as the battery is maintained in the PSOC HEV range ($\sim$ 30–70%) efficiencies will be optimal. Because the relative load demands (hence, current densities) on the SR design are lower than those for the FR unit, the efficiencies for the former are expected to be higher and this is reflected in the values stated in Tables 1 and 2. Thin-plate designs, which also reduce current densities (all other factors being equal), will also have relatively higher round-trip energy efficiencies compared to thicker-plate products.

The most significant factor impacting efficiencies is the battery chemistry. Those chemistries with relatively flat charge/discharge curves will have high efficiencies; those with sloping curves will have lower values. Thus, efficiencies will be good for chemistries such as lead–acid and NiCd, moderate for NiMH and nickel–zinc and relatively poor for the lithium-based technologies. As noted, this can be overcome somewhat for the latter technologies by employing thin-plate designs that will reduce ohmic and polarisation effects.

2.2.7. SOC determinations

It is likely that the most critical aspect of battery management in an HEV is the accurate monitoring and adjustment of state of charge. The strategy adopted for the detection and maintenance of SOC will determine not only how long the battery will last, but also how well the vehicle will operate. Because driving patterns can vary greatly, simply letting the battery depend upon the amount of acceleration/hill climbing (discharge) and braking/deceleration (regen charging) that occurs will quickly take the battery out of the desired 30–70% SOC window of operation. When this happens, energy efficiency quickly deteriorates and continued operation without tight control will result in permanent battery damage due to overcharge and/or overdischarge.

In principle, the simplest way to measure SOC is through OCV values, as OCV is roughly linear with capacity for most battery chemistries. However, SOC determinations in HEVs are likely to be dynamic in nature, with measurements being taken during vehicle operation with current flowing into or out of the battery. When there are periods of operation where the battery is either quiescent (on open circuit) or experiencing low current draws or inputs, it may be possible to use simple voltage measurements to provide battery SOC with accuracy to within a few percent.

An example of this is shown in Fig. 9 [1], both for OCVs and voltages under load. In this case, the load is in the form of 80 A/5 s pulses (representing a "hard" acceleration of ~ 2 kW kg^{-1} for this VRLA cell; the arrow in the figure is where the voltage collapses on load) with intermittent rests of 250–400 s, but it could be any type of reasonable load profile. Load voltages were taken at the end of the discharge pulses and OCVs were at the end of the rest periods, where the voltage rise rate was at or below ~ 2 mV min^{-1}. Throughout most of the SOC range of interest there are roughly linear relationships of the voltages with SOC. If greater accuracy is needed, this can be provided by a curve-fitting exercise and/or through the use of "look-up" tables. Using voltages is the easiest way of determining SOC and it should be quite accurate for chemistries such as Li-ion and Li-polymer, whose voltage/SOC curves have much steeper slopes than those for lead–acid or NiCd. The major problem is that the measurements have to be valid and taking them properly has to fit into the operating strategy of the vehicle.

If it has been determined that the SOC has deviated significantly from its nominal value, say 45%, then the vehicle-control electronics must make an adjustment by either charging or discharging the battery. A small amount of charging could easily be done off of the primary power source through the motor/generator to raise the SOC level in either a series or parallel architecture. For discharging in a series configuration, the control system could just work the battery harder for a short time to bring its SOC down to the desired level; however, this may force the heat

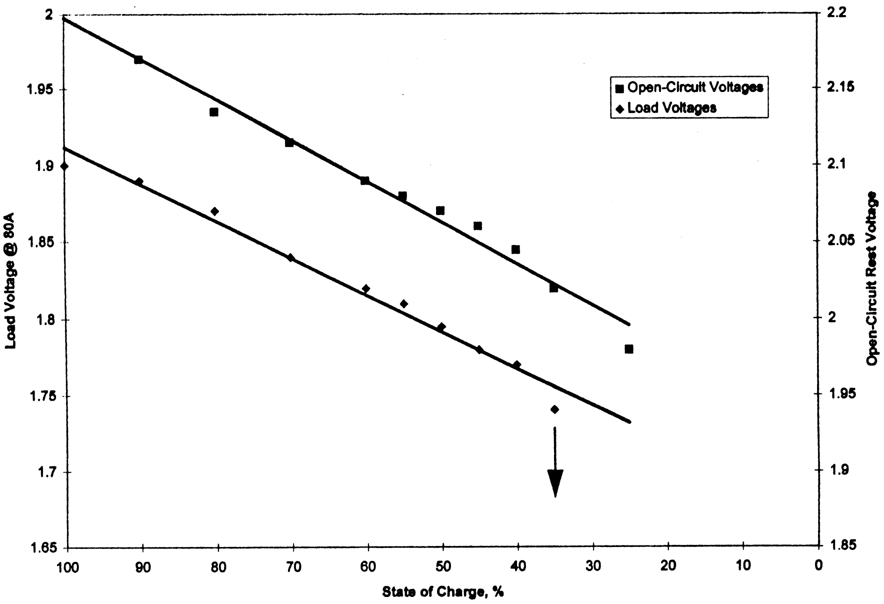


Fig. 9. Voltages on load (diamonds) and open circuit (squares) as a function of state of charge for a 2 V/1.2 A h cylindrical VRLA cell. The arrow signifies voltage collapse.

engine to operate below its power output window of optimal efficiency, thus increasing emissions. In a parallel configuration, the battery would have to be capable of contributing a portion of the power at any time (without accelerating) or the electronics could be designed so it could “dump off” some of its energy to a passive load.

2.2.8. Battery charging

The issue of battery charging is not of the magnitude that it is with EV batteries, but it is still a concern for HEVs and the chemistries envisioned to be utilised. On-board charging during operation can be done by the primary power source as needed to keep the battery from falling too low in SOC. The amount of regulation and filtering required will depend upon the battery chemistry and the charging strategy employed. If small, intermittent charges are employed just to keep the battery within the 30–70% SOC window, then power quality is not a large issue, even for a technology such as Li-ion (and, presumably, Li-polymer), which normally requires very careful voltage regulation. However, if periodic full charges are required then the cost and complexity of the charging system can become a major issue, less so for VRLA and the nickel-based chemistries and more so for Li-ion and Li-polymer.

A real advantage of using the heat engine for on-board charging of VRLA batteries is that significant currents would be available to effect fast charging, which has been shown in the Advanced Lead–Acid Battery Consortium (ALABC) Program to be beneficial in extending driving range and lifetimes for these batteries. Both VRLA and NiCd are advantageous in that, even for full charges, they are capable of accepting high, relatively unregulated charging inputs for full recharges without undue damage.

As noted earlier, most of the candidate HEV battery technologies have potential technical issues related to prolonged PSOC operation, in most cases resulting in a significant loss of subsequent discharge capacity. This may necessitate fairly frequent “top up” charging of the HEV battery, possibly as often as the end of each usage period, particularly if the vehicle is not likely to be operated for some time. Thus, an integral part of the vehicle operation strategy may be full, or almost full, charging of the battery at the end of the day. Depending upon the sophistication of the control electronics, it may be possible to do this (with driver involvement) with the vehicle. Otherwise, “plug-in” overnight charging would be employed. Fast charging in the vehicle would be preferable for VRLA, but most of the other candidate chemistries would probably be better served using slow, low-current charging with a relatively high level of voltage control.

2.2.9. Battery management requirements and handling strategies

Management for an HEV battery will be different from that in an EV in a number of ways. The central issue will be keeping it at the proper SOC, regardless of the usage pattern of the vehicle. This may be more easily accomplished for the SR-type battery due to its greater available capacity for both discharge and regen. However, counterbalancing this is the fact that the SR battery is likely to be in use considerably more of the time than the FR type. Considerable electronic intelligence will be required to characterise the anticipated usage patterns of the vehicle as closely as possible. Simply putting in a few commands based upon occasional measurements of battery parameters or using current integration (A h in/A h out) may lead to disaster. A reference point such as 100% SOC when the vehicle is started up in the morning could be useful not only for locking in on SOC, but it also would give the driver ~50% of the battery's rated capacity for all-electric driving. For a 6 kW h SR battery, this could mean an early-morning all-electric driving range of ~15 miles, assuming a vehicle consumption rate of 200 W h per mile. This added daily all-electric driving range and/or credit for "plug-in" overnight charging would also increase the rated fuel efficiency of the vehicle.

Thus, a typical battery management and handling strategy could be something like the following. The battery has either been brought up to ~100% SOC by in-vehicle or overnight charging. If the battery is not fully charged, the electronic control system records its OCV (which is stabilised) and thus "knows" the SOC from reference to a "look-up" table that incorporates recent performance data. It then informs the driver that "x" miles of all-electric driving range is available and a decision must then be made by either the driver or the control system whether to go all-electric for a period of time to get the battery down to its nominal SOC or operate the vehicle in the normal mode where the driving load demand is shared with the heat engine. After initial startup (which is always done with the battery to minimise emissions), the control system may decide to run the ICE at the low end of its optimal efficiency window so that more power is drawn from the battery. Either way, the battery is taken down to its nominal SOC operating level by the control system having removed a measured amount of capacity, probably by simple coulomb counting. Once the battery is at the nominal SOC, the control system then may interrogate the driver as to the type of driving involved (city, suburban, highway) and it will then decide what strategy to use to monitor and control the battery SOC.

As discussed in the previous section, simple OCV measurements may not be acceptable, as the battery is continuously subjected to small background load currents with additional power events in either direction superimposed. Furthermore, if something like air conditioning is being used in an all-electric zone (city center) this baseline current could be quite high. It may be possible to program the control system with a set of OCV "look-up" tables for each SOC, but a more accurate approach might be to monitor high drive-cycle pulse currents and use these with "look-up" tables to dynamically determine the SOC. Alternately, the vehicle electronics may be configured to apply short, high-current pulses periodically in order to assess the SOC through the measured load voltage. With proper sophistication, the control system could generate a set of response surfaces relating pulse current/time (coulombs), measured voltage and SOC that could be periodically updated as the battery ages. Throughout the drive cycle, SOC "zeroing" could be carried out whenever there is a period of inactivity (errands, stoplights, etc). The OCVs for thin-plate VRLA batteries are reported to stabilise in ~60 s at rest [1], so every time the vehicle is dormant for at least this period of time the OCV/SOC condition can be assessed and, possibly, adjusted by the control system during subsequent use. As noted earlier, if the SOC has drifted out of the 30–70% window, the control system must either activate charging from the ICE/motor-generator or initiate some "dumping off" of energy, perhaps to a dummy load to generate usable waste heat. It is likely that proper operation of the vehicle will require considerable interaction between the control system and the driver; this can no doubt be done with menus displayed on a screen in the cab and a fairly simple set of decision algorithms.

All of the above is done keeping in mind the dual primary requirements of an HEV, namely that the battery be kept near its nominal operating SOC and the primary power source (ICE) be operated as much of the time as possible in its zone of maximum efficiency. Having done this for most of the driving day, the control system and driver must now decide on a "finishing" strategy, primarily whether to bring the battery to a full SOC with the ICE, employ overnight charging or just keep it where it is in a PSOC condition. This may also have been done during the day if, for example, the vehicle was used to drive to work; in this case, ICE charging may have been done to fully charge the battery before the driver went in to work. The obvious danger with this type of scenario is that the driver, in wishing to optimise all-electric operation, may severely shorten the life of the battery due to excessive overcharging.

2.2.10. HEV test protocols and requirements

As part of the DOE/PNGV Programme, the testing of HEV batteries is being addressed by DOE's Idaho National Engineering and Environmental Laboratory, INEEL (formerly INEL) under the direction of Dr. Gary Hunt. Standardised tests have been developed for both FR and SR high-power batteries and other energy-storage devices [21] in order to determine their suitability for meeting the DOE/PNGV requirements given in Tables 1 and 2. The contents of this PNGV Test Manual [22] are discussed here in some detail, as they are likely to become the standards for evaluating the power capabilities of candidate HEV batteries. Following are brief descriptions of some of the more significant tests.

2.2.10.1. Pulse-power characterisation (PPC) profile. The core activity in developing this testing programme was to accurately define a simple charge/discharge cycle that would simulate, at least in a general sense, what the battery might see in HEV operation. While it was acknowledged that energy content is important in an HEV battery (particularly the SR version), the emphasis is on power in order to represent the PNGV demand for specific power levels of ~1 kW kg^{-1} or more. The result is the PPC Test, shown in Fig. 10. The duty cycle for the SR battery involves an 18-s discharge at ~65 kW, followed

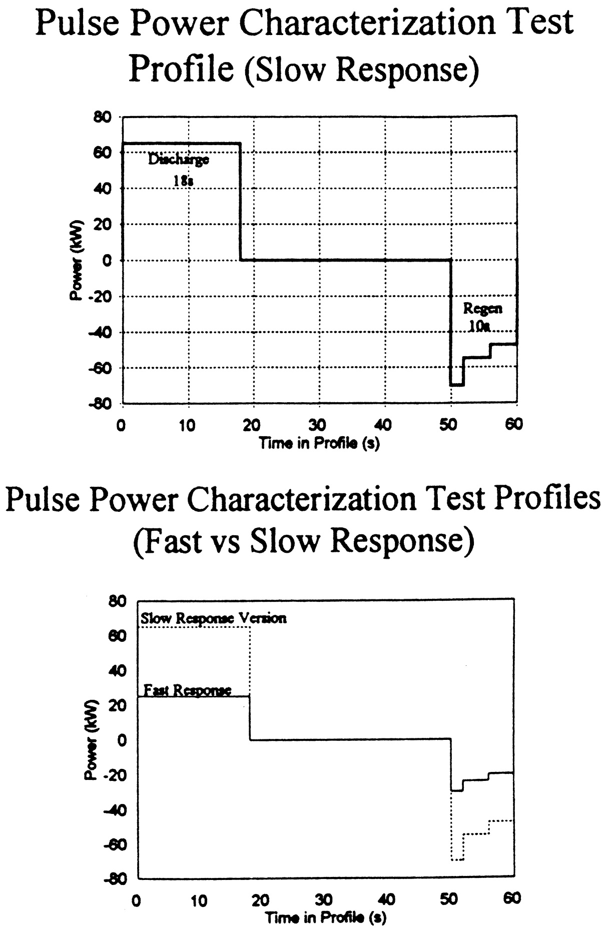


Fig. 10. Pulse-Power Characterisation Test profiles for candidate HEV batteries. Upper curve is for slow response; lower curve is fast vs. slow response.

by a rest period, followed by a 10-s step-wise regen pulse-power event, for a total cycle time of 60 s. These steps represent the charge/discharge power requirements set out by DOE/PNGV. As shown in the lower curves in Fig. 10, the profiles are identical in terms of the times for each step, but the amplitudes of the peak-power pulses are different. Even though the pulse amplitudes are greater for the SR version, because of the large difference in battery capacities the test is considerably more rigorous for the FR battery.

2.2.10.2. Hybrid pulse-power capability/characterisation (HPPC) test. The PPC profile is then run at 10% SOC decremens in order to determine the pulse-power capabilities of a battery as a function of depth of discharge; this test is similar in concept to the USABC 30-s Peak-Power Test for EV batteries. The PPC profile is first run on a fully charged battery. A C-rate discharge is then carried out to remove 10% of the battery's capacity, taking it to 90% SOC. This is followed by a 1-h rest to allow the system to stabilise. The PPC test is then run at this SOC and at successively lower SOC levels until the full range is covered. After each 10% SOC decrement, the battery is fully recharged and then discharged to the next SOC level to be tested. The test protocol is displayed in Fig. 11. Results are interpreted using the PNGV 300–400 V operating window for a full battery (scaling down is done on a proportional basis using module or single-cell voltages, rated capacities and plate surface areas). Only the power delivered within this window is used to define the effective operating SOC range for the battery being tested. Thus, at high SOC values some of the regen power will be omitted and at low SOC values some of the discharge power will not be counted.

The battery is also characterised for charge and discharge pulse resistances/impedances as a function of SOC. Normally, throughout the HEV operating window of 30–70% SOC both impedances are fairly constant and relatively low (see also Fig. 8). Interestingly, the values calculated in this Test Manual are counter to those in Fig. 8 [20], showing discharge resistances being greater than those on charge. These data (open-circuit voltages and resistances) are then used to calculate the power levels observed for the 18-s peak-power discharge step (without falling below the 300 V PNGV minimum voltage) and the first 2-s peak-power regen step (without exceeding the 400 V PNGV upper operating limit). These power data points are then plotted versus SOC (or, conversely, %DOD) and

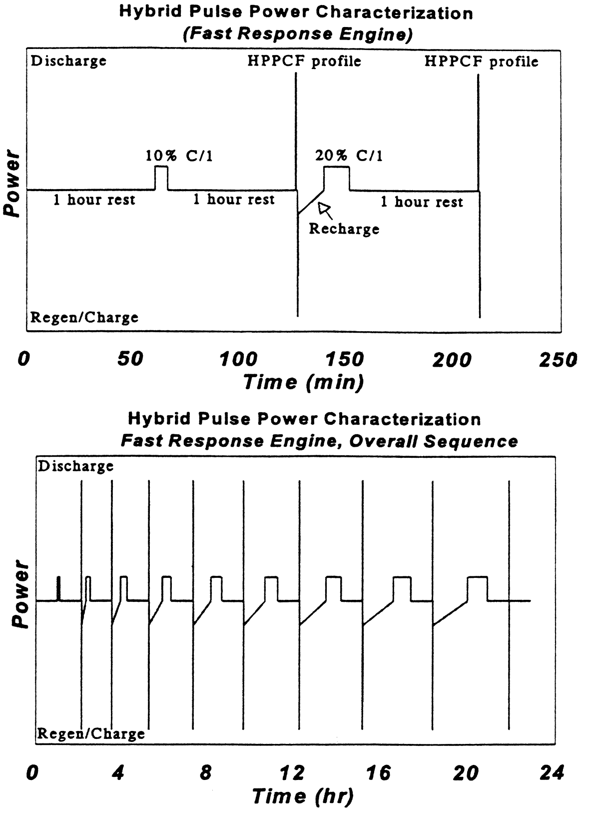


Fig. 11. Hybrid Pulse-Power Characterisation Testing. Upper curve is the beginning of the test sequence; lower curve is the complete test.

the shapes of the two curves define a usable SOC range for the battery where the voltages during the maximum FR pulse discharge (25 kW) and regen (30 kW) steps do not exceed the 300 and 400 V limits, the so-called "sweet spot". This is also the "total available energy" term shown in Tables 1 and 2. This is shown graphically in Fig. 12, taken from a recent presentation by Fritz Kalhammer [23]. For this idealized battery, the "available energy" is, indeed, roughly 50% of the rated capacity. The flatter these two curves (i.e., the more power delivery and uptake are independent of SOC), the greater the usable capacity of the battery. Conversely, for an inefficient battery the "total available energy" may be a small fraction of the rated discharge capacity. In earlier discussions, a value of 50% was used; in fact, this may be unachievable for some battery chemistries, in which case a larger battery will have to be used to be able to support the high-power charge/discharge loads called out in the DOE/PNGV Performance Goals. As a "knock-on" effect, this will require greater weight, volume and cost values for the candidate battery chemistry. This test (Pulse Power Capability ("Sweet Spot") Plot), more than any other, will define the efficiency of a battery, and thus its suitability, for HEV use.

2.2.10.3. Life-cycle testing. The PPC profile is also used for life-cycle testing, at different power levels to correspond to the requirements in the DOE/PNGV Specifications (see Tables 1 and 2). In order to satisfy the energy requirements for each life test, power and time levels are adjusted to keep the duty cycle at 60 s; in addition, the cycling is run at a PSOC (e.g., 50%) and in order to keep it "charge neutral" a small recharge step is included at the end of each duty cycle to bring the cell/battery back to the starting point. A reasonable ambient temperature is maintained throughout the test. Typical data are shown in Fig. 13 for several SR battery cycles and a single FR duty step.

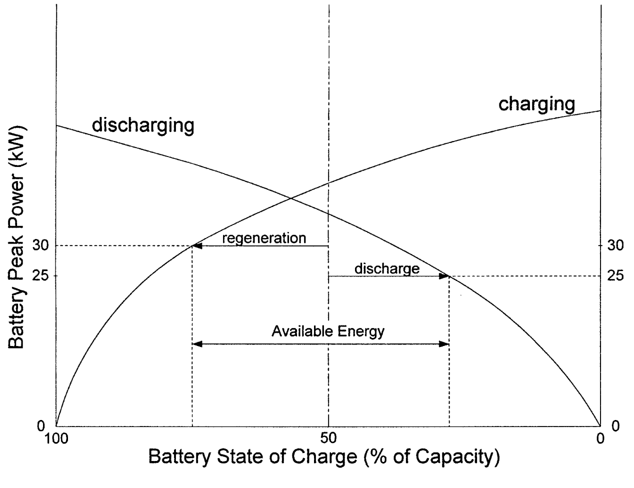


Fig. 12. PNGV "Sweet Spot" plot of battery peak power vs. state of charge. The "Sweet Spot" is the available energy range.

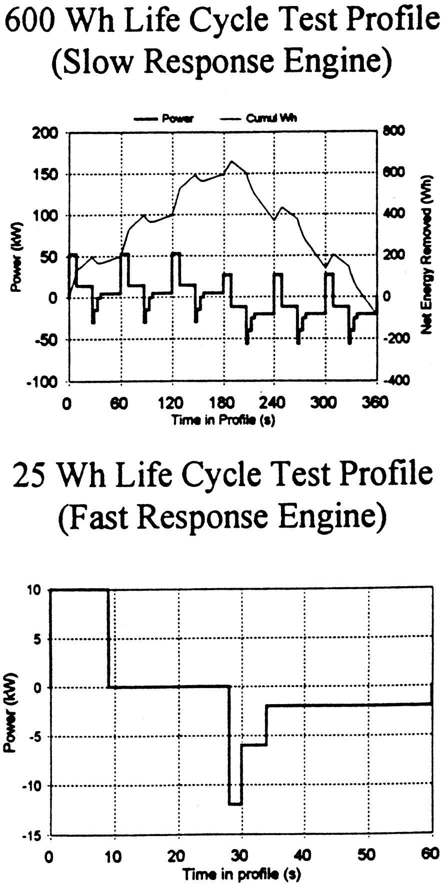


Fig. 13. DOE/PNGV life-cycle testing for candidate HEV batteries. Upper curve shows several slow-response cycles; lower curve shows one fast-response cycle.

Cycling is continued until the cell/battery voltage falls outside of the allowed DOE/PNGV voltage window (scaled to the voltage of the unit being tested). See the INEEL Test Manual [22] for details.

2.2.10.4. Round-trip energy efficiency test. This parameter can be easily determined at any point throughout life-cycle tests by simply comparing the charge and energy removed to those returned during any one of the test profiles. By doing this every, say, 5000 cycles one has a clear picture of how well or poorly the battery is maintaining its round-trip coulombic and/or energy efficiency. In order to use duty cycles where the voltage and temperature of the battery have stabilised, measurements are not done until 1–2 h into testing. Presumably, the battery is considered failed when the efficiency falls below the 90% (FR) or 95% (SR) level given in the PNGV Specifications. However, in a practical sense the battery can continue to operate, albeit at a reduced level of efficiency.

2.2.10.5. Operating set-point stability test. This test is carried out to ensure that voltage stability is maintained by the battery at the chosen SOC throughout life-cycle testing.

The "operating set-point" equates to the nominal HEV operating SOC, usually at or near 50%. Typically, the module being tested is taken to the target SOC and is allowed to stabilise with a 1-h rest period. It is then subjected to something like 100 duty-cycle profiles. Following another 1-h rest, the OCV is measured and compared with the initial value.

2.2.10.6. Self-discharge, or stand loss, test. This test quantifies short-term capacity losses at a 50% SOC as a result of standing on open circuit. The battery is first taken down to 1/2 capacity based upon the value obtained for a full discharge (i.e., 100% capacity). It is then allowed to stand for 48 h to 1 week, at which point another discharge is carried out to determine the remaining capacity. As noted earlier, the specification for self-discharge (50 Wh per day for either a FR or SR battery) appears to be excessive for the FR battery, as it allows the loss of virtually all remaining capacity in less than 1 week. Moreover, it is an unreasonably high self-discharge rate for all of the chemistries in consideration for HEV use.

2.2.10.7. Thermal-performance test. In this test, the PPC profile is carried out over a wide temperature range (unspecified). It is done to characterise the battery performance at various temperatures and thus to define the effective operating range of a battery, with insufficient heat dissipation and poor charge acceptance being the upper limit and insufficient delivery of discharge capacity being the lower limit. It is likely that different temperature windows will be set for the various battery chemistries considered as candidates for HEV use.

2.3. Candidate energy-storage technologies

The focus of this paper is the suitability of batteries for HEV applications. In this section, various candidate battery chemistries will be surveyed. The battery chemistries covered are those that might have the required power:energy balance, cycle life, etc. necessary for effective HEV operation. Several pertinent performance characteristics for each are reviewed, along with other key factors such as safety, environmental concerns, recycling and cost.

2.3.1. VRLA technology

Because of its low cost, good performance and extensive existing manufacturing facilities and infrastructure, including recycling, lead–acid is a technology that must be considered for HEV applications. It is currently available in a wide variety of so-called "sealed" designs, similar to product lines for sealed NiCd. These VRLA cells and batteries are well-suited to HEV applications due to lead–acid's good energy:power balance. While the specific energies for VRLA batteries are typical for lead–acid, ranging from ~ 30 to 40 W h kg^{-1}, specific power levels are very good, from a common value of ~ 150–200 W kg^{-1} for many commercially available products up to values of 3.6 kW kg^{-1} and more for specialty ultrathin-plate Bolder cells [1], the latter at significant specific energy amounts. Moreover, power output remains relatively constant as the SOC varies from 100% to lower values so at 50% SOC specific power levels of 200 W kg^{-1} or more are easily achievable. VRLA can probably meet the "minimum" DOE/PNGV power requirements for either the FR or SR architecture and specialty products can also demonstrate the "desired" levels. In addition, the energy specifications for the FR battery are achievable for VRLA but energy for the SR battery (~ 60 W h kg^{-1}) is a stretch for VRLA. Overall, it appears to be an excellent candidate for the FR battery, and in larger versions than that called out by DOE/PNGV, it can function well in the SR vehicle architecture.

VRLA can meet many of the DOE/PNGV Performance Goals due to its generally good performance and low cost. In the fully charged state, VRLA's high-power, low-temperature charge/discharge capabilities are very good. However, as noted earlier, at a 50% SOC the reduced electrolyte strength makes the battery susceptible to freezing, which would result in a drastic loss of performance. This can be overcome by usage strategies and thermal-management systems, but these will impact on both life and cost. VRLA's ability to operate effectively at elevated temperatures up to the DOE/PNGV limit of 52°C is superior to any of the other battery chemistries being considered. Self-discharge performance is excellent, far exceeding the DOE/PNGV Goal. VRLA battery systems with the required power and energy levels can be provided for hybrid vehicles, particularly larger types such as trucks and buses, but not while meeting the DOE/PNGV Performance Goals for total available energy, weight, volume and package height.

Cycle life for VRLA, as for the other technologies, is largely undefined but selected commercial and developmental products should do well in PSOC cycling, particularly with periodic full charges to control "hard" lead sulphate buildup. Charge acceptance, while not as efficient as for other technologies (vide infra), should be acceptable for HEV use [1,19]. Round-trip energy efficiencies should easily meet the DOE/PNGV Goals, even for relatively thick-plate VRLA products that might be used for SR batteries. The cost targets, both current and projected, should be easily met by VRLA. The calendar life of 10 years is difficult for this technology but may be offset by its low cost. For some HEV batteries (buses, trucks, some passenger vehicles), thermal management may not be necessary because of relatively low impedances and enthalpic heating levels. There are no significant safety or environmental issues, the latter due to the high (> 95%) recycling rate for lead–acid batteries. As noted also, manufacturing and infrastructure facilities are all in place.

In summary, VRLA designs should be excellent for power-assist batteries due to the high power capabilities of lead–acid. It should also be an excellent SR candidate, but not within the constraints of the DOE/PNGV Performance Goals, which it cannot meet. However, in larger sizes than specified, it should function very well and with its low cost and availability of support facilities, periodic servicing and module replacement is less of a problem than for most of the other technologies surveyed.

2.3.2. NiCd technology

Lead–acid and NiCd compete in a wide variety of markets because, in many ways, their performance levels are similar. NiCd is a good candidate technology for HEVs and it is, in fact, being used in a number of hybrid bus development programmes [24]. At this point, it is not considered a candidate technology by DOE for the PNGV programme, but due to its good power:energy ratio and low-temperature performance it is included here.

NiCd batteries typically have specific energies of 40–50 W h kg^{-1} and specific power levels of 150–500 W kg^{-1}. Both flooded and sealed varieties are available, with the sealed NiCd likely to be used in passenger HEVs. These are thin-plate products that are well-suited to operation in large arrays, although with a low 1.2 V cell voltage it requires many cells to make a high-voltage HEV battery. The SAFT bus battery mentioned above [24] has a 100% SOC 15-s specific power rating of 500 W kg^{-1} but, more important, a 50% SOC level of 350 W kg^{-1} (in a 35 W h kg^{-1} specific energy battery, the STX 600). This is adequate power and good, but not excellent, energy; both are short of the DOE requirements but are very serviceable in a hybrid bus. NiCd products have excellent low-temperature/high-rate discharge performance and it may be able to meet the DOE life-cycle goals. It has the best performance at low temperatures of any of the battery chemistries surveyed. Cycle-life values have to be qualified due to the temperature sensitivity shown by NiCds, where lifetimes are roughly halved in going from, for example, 30°C to 40°C. In addition, the discharge and end-of-charge periods are highly exothermic for NiCd so this, combined with the above-mentioned cycle-life issue, makes thermal management imperative for NiCd. Round-trip energy efficiency is poor for NiCds at even moderately elevated temperatures, so many NiCd products may not meet the DOE/PNGV efficiency specifications. Operation in the upper temperature range specified (up to 52°C) would be very difficult for sealed NiCds and for flooded types due to poor charge acceptance and frequent watering requirements, respectively. Because HEV use involves shallow-discharge cycling about some intermediate SOC level, poor performance may result for sealed NiCds due to the "memory effect". Most, if not all, of the NiCd batteries in developmental HEVs are flooded versions that do not suffer from "memory" problems.

Discharge performance in high-power situations would not be as good as for some of the other candidate technologies (vide infra), but the charge acceptance of NiCd in the 30–70% operating window for HEVs should be excellent. Initial cost for NiCd is high (at best ~US$300 kW h^{-1}, probably closer to US$400–500 in most products), but when the excellent cycle-life performance is taken into account, the total life-cycle cost (dollars per kW h per cycle) is likely to be quite good. The overall cost of NiCd is negatively impacted by the cost of recycling, which currently ranges from ~US$0.75 lb^{-1} to break even (perhaps an average of US$0.25–0.40 lb^{-1}), but as recycling of NiCds becomes more common and volumes increase this should improve. An area of uncertainty is the environmental status of cadmium. It is classed as a carcinogen and there is presently a European Union Directive to phase out the use of cadmium in industrial products by the year 2008; however, this may be put off if viable alternatives cannot be developed.

Like lead–acid, NiCd is a mature technology with full-scale manufacturing facilities for a broad range of product types. As noted earlier, it is being used in many hybrid vehicle development programmes world-wide, though most are in larger vehicles such as buses, where low specific energy is not a deterrent to use. It should be suitable as a power-assist (FR) battery, though not up to the DOE/PNGV power Performance Goals. Because of the modest specific energy levels of 35–40 W h kg^{-1} seen in high-power NiCd products, they would not meet the DOE/PNGV Performance Goals for the dual-mode (SR) battery in terms of all-electric driving range. However, from a practical, real-world standpoint NiCd must be considered as a viable candidate for either the FR- or SR-type batteries.

2.3.3. NiMH technology

This technology was developed in the late 1980s/early 1990s as a competitor to NiCd batteries in small portable devices. It offered the promise of being a "drop-in" alternative to NiCd, which was just coming under fire for environmental reasons. It has the same nominal 1.2 cell voltage as NiCd and, as it has developed, can deliver significantly greater specific energy and energy density levels in comparable packages. Thus, NiMH is attractive as an HEV battery, particularly for the SR version. Different developmental products suitable for HEVs have recently been introduced by Varta and Ovonics and they and SAFT are being funded by the DOE/PNGV Programme. Toyota is using a commercially available 6.25 A h cylindrical sealed NiMH D-size cell in its Prius HEV.

Many of the performance factors discussed above for NiCd also apply to NiMH. However, the major area where NiMH excels is in specific energy; typically, the best commercially available sealed NiMH cells for small portable devices (the types that would be used in hybrid passenger vehicles) are in the range of 80–90 W h kg^{-1}. In developing products for HEV use, where power capabilities must be optimised somewhat at the expense of energy, these specific energy values only drop to ~60–70 W h kg^{-1} for the Varta [25] and Ovonics [16,26] developmental high-power batteries. SAFT has now developed a comparable product. Specific-power levels of 500–1000 W kg^{-1}, even at 50% SOC, are quoted and it appears that the charge-acceptance performance of the Ovonics battery is superior to comparable VRLA products [16]. One concern is that the specific energy levels quoted are at low discharge rates and NiMH, more than NiCd, suffers a sharp drop-off in specific energy at high power levels. Moreover, in developing an "ultra-high-power" cell for power-assist HEV operation (presumably by going to extremely thin plates) specific energy drops to ~40 W h kg^{-1} at low power levels of ~30–40 W kg^{-1} and ~22 W h kg^{-1} at ~800 W kg^{-1} (a representative operating level for a power-assist FR battery) [25]. This is still excellent, but not as impressive as it first appears. Because of the significant loss of voltage "stiffness" for NiMH with increasing power levels, these batteries may have difficulty meeting the DOE/PNGV Performance Goal of staying within the 300–400 V window over a significant SOC range during operation.

Performance at temperature extremes is weak for NiMH, as it is for NiCd. The low-temperature performance of the developmental thin-plate NiMH products is better than for commercial products and is comparable to what NiCd can do. At elevated temperatures, NiMH suffers from the same cycle-life losses and lack of rechargeability as with NiCd; operation at the DOE/PNGV upper temperature limit of 52°C is not likely to be impressive. These thin-plate, high-surface-area cells are likely to have very poor self-discharge performance and may not even meet the specification of <50 W h per day. Moreover, NiMH cells reportedly suffer permanent capacity loss if allowed to self-discharge deeply and/or be stored at elevated temperatures, both conditions likely to be experienced in HEV applications. Because both discharge and recharge are highly exothermic and impedances are relatively high, thermal-management measures at least as stringent as those necessary for NiCds may have to be included in NiMH HEV battery packs in order to realise optimal performance levels for this technology.

Environmental limitations are not well defined at this time for NiMH batteries, but it appears that they will be less rigorous than those for NiCd. Recycling technology is not currently available but it should be amenable to development. The biggest single drawback to NiMH is cost. In standard small-cell, sealed commercial products, they cost up to twice as much as NiCd cells. In the developmental HEV products described above the costs are likely on the order of US$2000–3000 kW h^{-1}. It is unlikely that the NiMH battery manufacturers will ever be able to meet the DOE/PNGV cost goals, as these are lower than the current materials costs for these batteries. Apart from the manufacturers themselves, cost estimates for NiMH EV batteries have been set at US$220–500 kW h^{-1}, and that is for future large-scale production [27]. Thin-plate HEV products are likely to be even more expensive. However, products will come down in cost with higher volumes and greater manufacturing experience and the current use in the Toyota Prius will give some indication of NiMH commercial viability.

Overall, this is an attractive candidate for the dual-mode (SR) HEV battery. A bipolar NiMH product [28] has been developed for this purpose. Because this will be a relatively large battery, the energy drain rates will be moderate and it will be able to furnish good power:energy balance and charge acceptance (regen) at these discharge rates. It is not as suitable for the power-assist (FR) architecture unless an oversized battery (2–3 kW h) is used to provide a significant all-electric driving range (this would also be the case for VRLA and NiCd). NiMH appears to be the preferred near-term candidate for DOE/PNGV vehicle development.

2.3.4. Ni–Zn technology

Nickel–zinc is a technology that has been languishing in development for at least the last 20–30 years. This is an alkaline system similar to NiCd and NiMH, using the same nickel cathode but combined with a zinc metal anode. The zinc anode significantly reduces environmental and cost issues, but it introduces a couple of serious technical problems.

The lure of Ni–Zn is that it offers good specific energy (60–80 W h kg^{-1}) and specific power (typically 200–300 W kg^{-1}, but possibly up to 600 in thin-plate designs) with good cycle life and at an optimistic eventual cost of US$70–100 kW h^{-1}. The major technical problems are shape changes and dendrite formation associated with the zinc anode. This has been moderated somewhat by heavily overbuilding the zinc anode and using buffered alkaline electrolytes, and more recently by adding large amounts of calcium and cadmium. Because of these issues, it would be difficult to build a thin-plate Ni–Zn product for HEV applications, particularly power assist. The Ni–Zn discharge curve has a steep slope, particularly at high discharge rates, so it is unlikely that existing Ni–Zn batteries could meet the DOE/PNGV power and voltage-window targets.

2.3.5. Li-ion technology

A few years ago, Li-ion would not have been considered as a candidate battery for HEVs by most technologists. However, its rapid development in small, cylindrical sizes for various portable devices has pushed it ahead in consideration for other uses. These products are rated at up to 125 W h kg^{-1} and estimates on the practical upper limit for specific energy range from 150–180 W h kg^{-1}. More recently, it has been developed in prismatic envelopes with capacities of up to 100 A h and it is being applied to EV and HEV products by Sony/Nissan [29]. The EV module is an 8-cell unit, 28.8 V/100 A h weighing 29 kg and having a specific energy of 100 W h kg^{-1} and a cycle life in excess of 1200 [29]. Other manufacturers have also developed cell sizes up to 100 A h so, from the standpoint of usable batteries realistically being available, Li-ion is viable.

The fundamental attribute that makes Li-ion so attractive for both EV and HEV use is its outstanding specific energy. While the Sony/Nissan EV battery is rated at 100 W h kg^{-1}, because of design compromises necessary to achieve high power delivery levels (primarily going to much thinner plates), the HEV battery is rated at 62 W h kg^{-1} at the C-rate of discharge [29], still an impressive energy content. When this is done, a specific power level of 1000–1200 W kg^{-1} at 50% SOC is also achieved. Thus, power output can be raised significantly at the expense of energy, but with so much energy available the resultant product still has an excellent energy power balance for HEV applications.

These outstanding power and energy figures are counterbalanced by a number of limitations similar in nature to those cited for NiCd and NiMH above. It is not a good high-temperature battery, generally being limited to 45°C or less, above which cycle life decreases drastically. At low temperatures, the charge/discharge performance is poor due to high cell impedance and the low conductivity of the organic solvent/electrolyte system. The high impedance also creates large voltage drops at high discharge currents (although this is less of a problem with the Sony/Nissan thin-plate products) and this, combined with the pronounced slope of the voltage–time curve at high currents, will make it difficult to keep this battery within the DOE/PNGV 300–400 V performance window. Charge-acceptance is good, though [29], so it may be possible to operate the battery at a somewhat elevated SOC (55–60%) in order to minimise the impact of relatively poor high-power discharge performance. The self-discharge rate is lower than for NiCd and NiMH but Li-ion, like NiMH, can suffer irreversible capacity loss if the battery is allowed to discharge too low and/or if it is stored fully charged at elevated temperatures. Also, the thermal characteristics are such that Li-ion will almost certainly require some form of thermal management equipment. Single cells show a temperature rise of $\sim$14°C when subjected to a 180 A ($\sim$8 C rate) discharge lasting for $\sim$400 s. This is an excellent high-rate energy retention, in excess of 80%, but the temperature rise is significant. However, this is a full discharge, which will not be done in HEV usage. Round-trip energy efficiency is better than expected [29], but not good enough to meet the DOE/PNGV Performance Goals except at very low current levels.

The biggest drawbacks to Li-ion are the complexity of charging and safety. Individual cell charge/discharge control is required to ensure that no cell is heavily overcharged or overdischarged. In particular, overcharge is damaging to the cell, as it tends to de-lithiate the cathode and electrolyte and plate excess lithium metal on the anode (an obvious safety factor). The de-lithiated cathode can undergo phase changes that radically affect its ability to intercalate lithium, thus lowering capacity and cycle life. The charge voltage on every cell in the battery must be limited to 4.20 V; going above that initiates the above overcharge scenario. On the other hand, if the charge voltage is even slightly below 4.20 V the cell is undercharged and thus loses discharge capacity. In HEV use, however, where the battery is kept at a partial-state-of-charge where this is not likely to occur, charging may not be so critical. Still, even with a cell voltage of 3.6–4.0, an HEV battery will be comprised of many cells and thus cell-to-cell balance must be excellent to prevent overcharge and overdischarge, particularly as the battery ages and/or temperature and vehicle demand extremes are experienced. It is, thus, likely that the charger will be fairly sophisticated and will add considerable cost to the system.

A greater consideration is safety issues that may arise if and when a charger component fails. Li-ion cells have redundant safety features to deal with high heat and/or pressure and this adds cost to the product. In addition, some of the safety features such as a safety valve and a thermal-breakdown separator are irreversible, i.e., they result in an “open” cell that would shut down an entire HEV battery unless a series–parallel matrix construction were used. The major sources of safety concerns are having a significant amount of lithium metal in one or more cells due to excessive overcharge and flammability of the non-aqueous solvent used. The former can result in thermal runaway, cell rupture and fire. The latter could be a hazard in the event of an accident in terms of toxicity even if researchers accomplish an ongoing objective to develop a fire-retardant Li-ion solvent.

Cost is difficult to estimate at this time. Small commercial Li-ion cells are selling for US$1–2 W h^{-1} and it is felt that even this may be at a loss due to high manufacturing scrap levels. The Sony/Nissan EV and HEV batteries are probably in the range of US$3000–4000 kW h^{-1} when chargers, thermal management and packaging costs are factored in. This type of battery will likely never meet the DOE/PNGV cost goals, but it is likely to be heavily funded for HEV development due to its attractive energy and power values.

In addition to Sony, Varta, SAFT and Polystor are being funded by the DOE/PNGV HEV programme to develop Li-ion technology. SAFT has demonstrated a specific power of 1200 W kg^{-1} with 45 W h kg^{-1} at the single-cell level [30] and Varta has reported similar figures for products developed for HEV use [25]. As research efforts in this area are intense, better performance values have no doubt been achieved as of this writing.

2.3.6. Li-polymer technology

A potential improvement on the Li-ion cell is one where the non-aqueous organic carbonate/lithium salt liquid electrolyte is replaced by one that is in the form of a gel or polymer (a so-called "solid polymer electrolyte", or SPE) [31]. This would reduce the tendency for the liquid solvent of a Li-ion cell to undergo the slow decomposition it experiences by reacting with the highly oxidising lithium metal oxide cathodes; it would also reduce manufacturing complexity (and, presumably, cost) by allowing the use of commonly available roll-to-roll technology. It should also, in principle, overcome the relatively high impedances of Li-ion products by going to very thin plates and separators with huge active surface areas, thus also achieving superior high-rate power capabilities. These high surface areas also reduce the safety issues of lithium-foil anodes by lowering current densities on charge, which normally lead to lithium dendrites. The plates and separator are, indeed, very thin; the 3 M/Hydro-Quebec Li-polymer design [32] shows a total plate stack thickness of only 100 μm. Apart from the dangers inherent in having lithium–metal foil anodes (this can be circumvented by designing a lithium-ion polymer cell), the SPE has even poorer conductivity than the Li-ion organic carbonate/electrolytes by at least two orders of magnitude and so the gains in going to ultra-high active surfaces is partially lost. Moreover, the SPE film does not really bond to either electrode, so there are significant interfacial effects. Because of this, many of these products have to be operated at elevated temperatures (80°C or more) in order to realise good power delivery at high currents.

The promise of a low manufacturing cost makes the Li-polymer system attractive for HEV use, but the technical limitations are likely to result in performance well short of that of Li-ion for the near term; moreover, designs using lithium metal will probably not be acceptable. The fundamental problem of high SPE impedance may be solved in the future, but right now these batteries, in an HEV, would have to be operated at elevated temperatures in order to realise reasonable conductivities, which drop sharply below ~65°C. This technology, like Li-ion, is being developed actively for DOE/PNGV, but it will require several technical breakthroughs to become commercially viable.

2.4. Battery designs for HEVs

The DOE/PNGV guidelines will likely guide HEV development in the U.S. for the next decade or two and it is likely that the battery choice for near-term development will be NiMH and for the longer term it will be Li-ion. Having said this, it is not likely that either technology will meet all of the Performance Goals set out, but these will likely be modified or abandoned (as was done in the USABC EV Programme) as a matter of expendiency at some point. In other parts of the world, automakers will likely develop more practical vehicles that are not constrained by the tight requirements of the DOE/PNGV Performance Goals. This has already begun, as hybrid passenger vehicles from not only the Big Three but also Nissan, Toyota, Honda, Renault, BMW and Audi — just to name a few — are in the late stages of development or are commercially available. These first vehicles will use VRLA, NiCd and NiMH batteries that do not meet the DOE/PNGV Goals but function quite well in their respective vehicles [33,34].

From a battery standpoint, the key technical design issues for HEV development are the energy:power balance and the size/weight. Ultimately, requirements for auxiliary components such as chargers and thermal management hardware and overall cost will be of paramount importance. Size and weight are not nearly as critical in HEVs as in EV designs, due to the presence of the primary power source. In an EV, weight, in particular, matters greatly because the battery is carrying itself about and this directly reduces efficiency. In an HEV it is a bit more complicated, because the size and design of the battery can have a large impact on the performance and efficiency of the heat engine, as shown conceptually in Fig. 4. Moreover, the battery is relatively small and it is being "carried" by the more efficient heat engine for much of the time. It appears that, at least for the FR design, DOE/PNGV has pushed the size and weight down to a point where the battery has to work too hard (with resultant shortened life) and/or the heat engine has to function too much of the time (thus reducing efficiency and increasing emissions). This statement is predicated on the assumption that the "total available energy" in Tables 1 and 2 and in Fig. 12 is about one-half that of the battery as a whole. If it were only 20–30% of the total (which may be the case for some candidate battery chemistries) a larger battery would be called out but, then, it would be difficult or impossible to achieve the size, weight and cost goals and the battery efficiency would be poor. For the SR architecture, a larger battery is, indeed, called out and it appears that it is sized correctly for such use. However, the size, weight and cost constraints are severe.

The energy:power balance is not skewed toward power as much as might be assumed. Power is clearly more important for the FR battery, but significant energy will also be required for all-electric operation in inner-city and stop-and-go driving. The specific energy of the SR battery must be greater than that for the FR (and is high enough to eliminate battery technologies such as VRLA and NiCd), but roughly the same power levels must be available from both designs. As has been noted, battery design always involves compromises between energy and power outputs. If energy is optimised power is reduced — and vice-versa. Therefore, it is likely that the general designs for the FR and SR batteries will be quite different. They may also be different technologies at the end of the day when cost, safety, environmental and recycling issues (factors which are given little weight during development) come into play. Given this, the following speculations on possible battery designs may be useful.

2.4.1. The power-assist, or FR battery design

In general terms, this is a relatively small battery with an energy:power balance skewed toward power. It is coupled with a relatively large heat engine (see Section 2.1.3.1). It provides auxiliary power when the demand for driving exceeds the output of the heat engine. In some designs such as Ford's LSR hybrid [33] it is also called upon to provide all of the power when the vehicle is stopped and is starting up again, with the heat engine off. This type of usage pattern requires a reasonably large battery to provide at least a 5–10 mile all-electric driving range, as in city traffic there may not be significant charging opportunities from the heat engine.

The DOE/PNGV Performance Goals specify a battery having a "total available energy" of 0.3 kW h, with a rated capacity of at least double to triple that implied. Given the weight limit of 40 kg and the stated "minimum" pulse-power requirements, the battery needs to provide specific power levels of significantly less than 1 kW kg^{-1} (actually, 750) for 10–18 s. Going to the "desired" Performance Goals, the discharge power is still at ~ 1 kW kg^{-1}, but the regen called for is ~ 2–4 kW kg^{-1}. From the 300 W h available energy and the weight and volume specifications, specific energy and energy density values of 7.5 W h kg^{-1} and 9.4 W h l^{-1} are calculated — just for the available energy. If the usable energy is one-half to one-third of the total, values of 15–22.5 W h kg^{-1} and 18.8–28.2 W h l^{-1}, respectively, result. These requirements are not stringent and all of the battery technologies considered would be able to easily meet the energy goals. The "desired" DOE/PNGV Performance Goals would be considerably more difficult to achieve for both specific power and specific energy, as weight is reduced and available energy is increased substantially. Given an estimated full capacity of 1.5 kW h, the required specific energy for the battery would be 42.9 W h kg^{-1}. This is achievable for a number of the battery technologies, even VRLA and NiCd, but when the specific power requirement of 2–4 kW kg^{-1} for charge acceptance is factored in only the lithium technologies and, possibly, NiMH remain. Similar calculations done for energy density show that the "minimum" and "desired" levels can be met more easily, as can those for power density.

It must be kept in mind that all of this must be done while the battery stays within the 300–400 V operational window. Inspection of the DOE/INEEL PNGV Battery Test Manual [22] reveals that the charge and discharge efficiencies of the battery design will determine greatly what total battery capacity is needed to provide the "total available capacity" called out. The more stable the voltage regulation of the battery on charge and discharge as a function of SOC, the more efficient the design and the greater will be the available energy fraction. Thus, a technology like VRLA with a relatively poor specific energy but excellent voltage stability may do very well in an FR design due to its wide available SOC operating window, which yields a relatively high "total available energy" fraction. Conversely, a relatively large, heavy Li-ion FR battery may be required due to a small SOC operating window that results from poor voltage regulation. This is achievable due to Li-ion's high specific energy, but size and cost may be excessive. Thus, energy efficiency as a function of state of charge is an extremely important design parameter, one that will impact directly on the size and weight (and, hence, the cost) of the battery.

What is needed, then, for the current (or "minimum") power-assist, or FR, HEV configuration is a high-power battery with rather ordinary specific-energy and energy-density characteristics. Specialty VRLA, NiCd, NiMH and Li-ion batteries may satisfy these requirements. Later, at the "desired" levels both power and energy are increased significantly, to levels that might only be met by Li-ion or Li-polymer.

Whatever the chemistry, something like a 1.5–3.0 kW h power-assist battery is likely to be needed in practice, largely due to the need for all-electric stop-and-go city driving. With the emphasis on power output and voltage stability, it would be an ultra-thin-plate product with low impedance and substantial current-path design to accommodate the high power demands. Clearly, a 3.0 kW h battery would not meet the DOE/PNGV weight and volume specifications but it would result in longer battery life and greater vehicle efficiency, primarily due to its ability to capture greater percentages of regen and allow the heat engine to operate less of the time and more efficiently.

2.4.2. The dual-mode, or SR battery design

As noted in Section 2.1.3.1, this is a larger battery than for the FR design. It is usually run in series with a relatively small heat engine (about equal in power output to the battery), so it is in use much of the time. It would be $\sim 1/5$th to 1/3rd the size and weight of a standard EV battery. It would be used to provide 25–30 miles of all-electric driving range for use in ZEV zones and to capture virtually all of the regen energy. It is in use more of the time than a power-assist battery and it is worked harder; it still needs significant power capabilities, but from a design standpoint it is more energy-intensive.

The DOE/PNGV Performance Goals call out an available energy of 3 kW h near-term and 3–8 kW h in the future. This would correspond to total battery capacities of 6–9 kW h near-term and as much as 16–24 kW h in the future. It is unclear in the DOE/PNGV specifications whether the allowable weight (65 kg) is for the 3 kW h of "available energy"/6 kW h total energy or if one would add 30 kg to the 65 for the 6 kW h of total energy. As the available energy is 10 times that of the FR battery, it is assumed that the allowable weight is $30 + 65 = 95$ kg. Similarly, the volume allowed would be $40 + 24 = 54$ l, both for the "minimum" values. Given these values, the 6 kW h battery would have specific energy and energy density levels of 63.2 W h kg^{-1} and 111 W h l^{-1}. The maximum specific power and power densities required for regen uptake are 740 W kg^{-1} and 1,130 W l^{-1} for near-term batteries — values close to those required in the FR battery. In the "desired" battery, the required specific power for regen would be on the order of 2 kW kg^{-1} and for a total battery capacity of 6 kW h the specific energy would be 120 W h kg^{-1}. The only battery technology that could achieve this would be a fully optimised Li-ion product, with both high energy and power capabilities.

The near-term DOE/PNGV Goals are more representative of a real-world HEV SR battery, at specific energy and power levels of 63 W h kg^{-1} and 740 W kg^{-1}, respectively. In current designs, these goals could marginally be met by NiMH and easily by Li-ion. However, given the poor low- and high-temperature performance and cost of these chemistries their commercial viability is clouded. For the low-cost VRLA technology, the power capabilities are easily achievable, but the specific energy is not. A realistic VRLA SR battery would have a total capacity of ~7.7 kW h and weigh ~154 kg (at 50 W h kg^{-1}, which is, admittedly, optimistic), with a volume of 67 l. Taking the DOE guidelines for added weight and volume above the baseline 3 kW h for the SR battery, a 7.7 kW h package would have an allowable weight of 109 kg and an allowable volume of 75.2 l ("minimum" goals). Such a battery would almost certainly be the lowest-cost of any of the technologies and it would probably be able to meet both the near- and long-term discharge and regen power goals set out by DOE.

The DOE/PNGV Performance Goals have been held up to significant criticism in this paper, partly because they do not appear to be self-consistent but also because they stress small battery sizes for both the FR and SR products, presumably to keep weight to a minimum. There is value in this in that it acts as a powerful driver for improvements in the various battery technologies, but it also excludes some that are the most realistic near-term candidates in a number of ways, namely VRLA and NiCd. Fortunately, a large number of passenger vehicle manufacturers worldwide are developing hybrids [33,34] (unlike the case for EV development) and several are now in limited production. As is often the case, commercial pressures will dictate which technologies succeed and which fail. It will be interesting, indeed, to see which batteries are adopted for large-scale production and how their power characteristics compare to the DOE/PNGV Goals.

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