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Rapid recharge capability of valve-regulated lead-acid batteries for electric vehicle and hybrid electric vehicle applications

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Abstract

Range limitation is a significant drawback to the successful commercialization of electric vehicles (EVs). An apt description of an EV is ‘a high performance vehicle with a one-gallon fuel tank’. In the absence of a ‘super battery’, there are at least two approaches to resolving this drawback. The first approach is rapid recharge, i.e., recharging the battery as close as possible to the same time period as it takes to fill the petrol tank of an internal-combustion-engined (ICE) vehicle. Whilst not extending the vehicle range as such, this approach does enable high usage of the vehicle without experiencing unduly long recharge times. The ability of the battery to accept rapid recharge is paramount for this approach. The second approach is the development of a hybrid electric vehicle (HEV). In this case, the demand on the battery is the ability to provide, and also absorb from regenerative braking, high specific peak-power levels over a wide range of battery state-of-charge. This paper describes the ability, and indeed limitations, of the valve-regulated Genesis® lead-acid battery in meeting such requirements.

Keywords: Efficiency; Electric vehicle; Hybrid electric vehicle; Lead-acid battery; Rapid recharge; Valve-regulated

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1. Introduction

The type of lead-acid battery employed in this study is the commercially available Genesis® product. This battery is of a prismatic valve-regulated (VRLA) construction and uses absorptive glass-mat separators. Whilst the Genesis® design allows for an oxygen-recombination cycle similar to other VRLA products, it is different in that it utilizes pure-lead–tin technology for the grids. This reduces the corrosion rate of the positive grid material, as well as the rates of hydrogen evolution and dry-out. The improved corrosion resistance allows the use of thinner current-collecting grids and electrodes. The employment of thin electrodes, and therefore more electrodes, decreases the internal resistance of the battery and increases the reactive surface-area of the active material. Low internal resistance and high reactive surface-area are prerequisite features for batteries operated in fast charge and hybrid electric vehicle (HEV) applications. In order to quantify the ability and limitations of the Genesis® battery in such applications, a series of tests has been conducted. The specific parameters studied are recharge time and charge efficiency as a function of current availability, and efficiency during HEV cycling as a function of state-of-charge (SoC).

2. Rapid recharge

The ability of the battery to be recharged rapidly is a highly desirable property for two reasons. First, it reduces the charging time from a low SoC to almost full charge to the order of minutes and, thereby, effectively extends the driving range of an electric vehicle (EV) which employs such batteries. Second, it is now well established that rapid recharge increases the cycle-life of lead-acid batteries by helping to maintain an electroactive positive active mass (PAM). In order to determine the effect of rapid recharge on Genesis® batteries, a series of charging experiments has been conducted on the Genesis® 12V42Ah product and has utilized up to $9C_1$ current availability.

The procedure for each test was, first, to discharge the battery at the C_1 rate (i.e., 1-h discharge rate) to an end-of-discharge voltage of 1.75 V per cell (VPC). The discharge was then immediately followed by a rapid recharge with a charging voltage limit of 2.45 VPC and a current limit as required for the test. The charging voltage limit was not temperature compensated. The battery tem-

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perature was monitored by embedding the end of a thermocouple probe into the lead strap which provides the electrical connection between the centre cells. Data recorded included the time required to return 50, 80, and 90% of the capacity removed during the prior discharge and the increase in battery temperature during the recharge.

The time required to return each of the set levels of capacity is shown in Fig. 1 as a function of recharge rate. The recharge rate is given in terms of multiples of the C_1 rate. Note that, the plots show the time required to return the percentage of ampere-hours which were removed, rather than the time required to get to a specific SoC. The difference between the percentage of the capacity returned and the SoC achieved represents the charge inefficiency. The data demonstrate clearly that the Genesis® battery is extremely capable of being rapidly recharged. For example at the $6C_1$ recharge rate, 80% of the capacity, from 0% SoC, can be returned in approximately 10 min and 50% in only 5 min. This performance demonstrates, particularly if an EV is operating under a partial state-of-charge (PSoC) strategy, that it is possible to recharge an EV within the same timeframe as is required to fill a conventional ICE vehicle with petrol. Extended EV testing, conducted by Arizona Public Service (APS) and Electric Transportation Applications (ETA), has demonstrated the capability of the Genesis® batteries to operate under a fast recharge regime of $5C_1$, often with up to four recharges per day. The battery pack delivered a total of 15 258 Ah (462 times the $1C_1$ rate) in accumulating 27 000 km on the EV [1].

As previously described, the temperature rise during the recharge period was also monitored. The peak battery temperature for each charge rate was recorded as a function of this rate and is presented in Fig. 2. It should be noted that the battery temperature for each test was stabilized at ambient prior to the discharge and the subsequent rapid recharge. It was found that increasing the current availability during the constant-voltage recharge period resulted in an increase in the maximum internal battery temperature (Fig. 2).

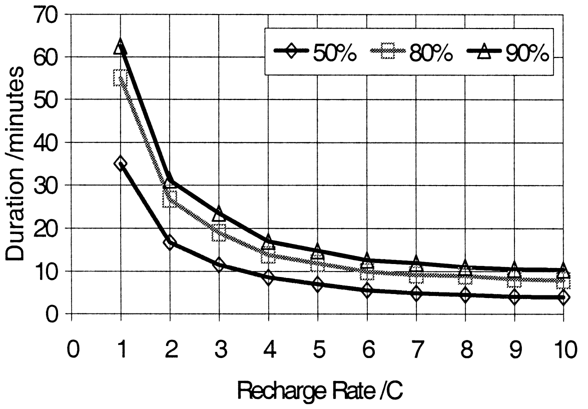

Fig. 1. Charge time as a function of recharge rate.

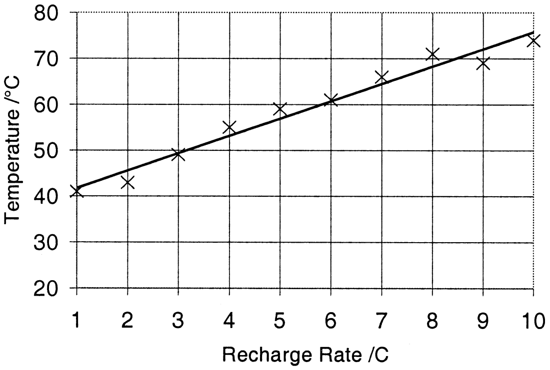

Fig. 2. Peak battery temperature as a function of charge rate.

The peak internal temperature of the battery during the fast recharge period roughly coincides with the battery voltage reaching the 14.7 V (2.45 VPC) limit, i.e., the point at which the charging current decays from its maximum value. This may be seen in Fig. 3 which shows that the battery peak internal temperature, at the $6C_1$ rate of recharge, reaches a maximum of 60°C shortly after the voltage reaches the 14.7 V limit.

Simplistic thermal analysis of this data, based on ‘resistive’ heat generated within the battery, i.e., I^2Rt, requires a value for the d.c. resistance of the battery whilst being charged. This resistance, for both charge and discharge, is presented in Fig. 4 as a function of the %SoC. The data were derived by dividing the voltage response, the consequence of an imposed constant-current transient, by the magnitude of the imposed current. This procedure is described below in more detail.

The above results show that the magnitude of the discharge d.c. resistance is largely independent of the %SoC of the battery. The value of the resistance is roughly double that of the discharge resistance up to approximately 75% SoC, but then rapidly increases.

Using the thermodynamic and the resistive values listed in Table 1, for the 12-V battery module, it is possible to model the internal temperature of the battery. The tempera-

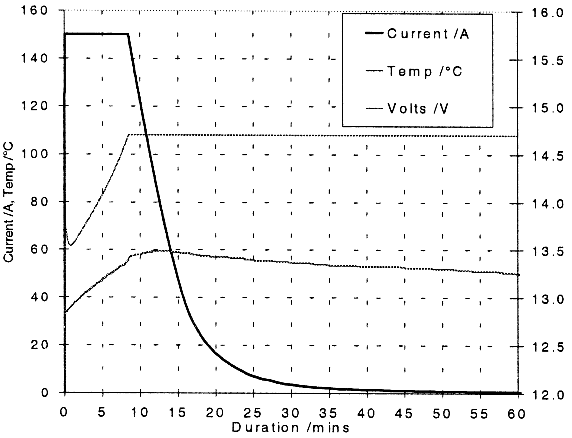

Fig. 3. Peak battery temperature at a recharge rate of $6C_1$.

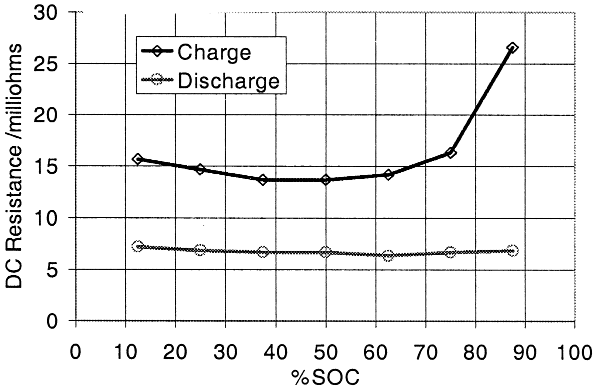

Fig. 4. D.c. resistance during charge and discharge.

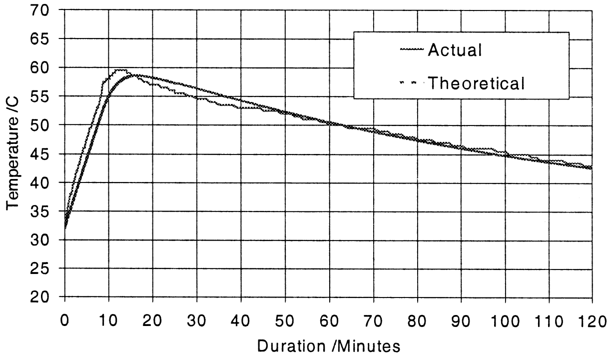

Fig. 5. Measured and calculated temperature profile during 6C$_1$ charge.

ture rise as a consequence of resistive heating alone can be estimated according to:

$$\Delta T = C_p \Sigma(\text{Heat}_{\text{in}} - \text{Heat}_{\text{out}}) \quad (1)$$

where

$$\text{Heat}_{\text{in}} = I^2Rt \quad (2)$$

Time (t) is considered only between $t = 0$ (i.e., at the commencement of charge) and the time at which the battery voltage reaches the limiting value of 14.70 VPC, $t = t_1$, i.e., during the initial constant-current phase.

Using this iterative technique, the calculated maximum temperature is found to be only 50°C for the 6C$_1$ charging rate, i.e., approximately 10°C less than that observed experimentally. Furthermore, this difference is also present, in relative proportions, when applying the above mathematical model to the other recharge current limits. This anomaly suggests that additional sources of heat generation, other than resistive, are present during the charging period. The other sources of heat that need to be considered are chemical and, therefore, are enthalphic.

1. Recombination. Up to the point where the voltage limit is reached, the amount of charge into the battery is only 75% of what was taken out on the previous discharge. It is therefore unlikely that recombination has contributed a significant portion of the total heat input to the battery.

2. Heat of dilution. Recharging a VRLA battery produces sulfuric acid, of a high concentration, within the pores of the electrodes. This concentrated acid diffuses into the bulk electrolyte, which is water in the case of a deeply discharged battery, where it readily mixes and results in a more dilute acid with subsequent heat generation. This heat generation is referred to as the heat of dilution, ΔH_{dil}. Typically, when concentrated acid of 6–7 M is mixed with water, the magnitude of ΔH_{dil} is approximately 5 W h per mol of acid [3].

Table 1
Thermodynamic and d.c. resistance values for Genesis® 12V42Ah Module

Average d.c. charge resistance from 10 to 75% SoC	15 mΩ
Heat capacity, C_p (*calculated from battery components*) [2]	*3.2 W h / h /°C*
Heat dissipation rate, Heat_{out} (*measured*)	1.8 W/°C

By adding the heat of dilution as an additional heat source to Eq. (1), a reasonable agreement between actual and theoretical internal temperature is determined, as demonstrated in Fig. 5.

The significance of the heat of dilution may be of greater importance in the case of fast recharge of traditional battery-powered EVs than in high-power HEV operation. With fast recharge of a traditional battery-powered EV, the heat of dilution can significantly add to the overall heating of the battery pack, in a very short period, and needs to be considered when thermally managing the battery. With HEVs, however, brief periods of fast recharge are often accompanied by brief periods of discharge. This means that the heat generated as a result of dilution during the charge periods is endothermically dissipated during the discharge periods.

3. Charge efficiency during rapid recharge

Charge efficiency is a critical factor when dealing with either hybrid or pure electric vehicles. With pure EVs, the charge efficiency will have a direct impact on the operational cost of the vehicle. With HEVs, it will effect the range and performance of the vehicle. In either case, higher charge efficiency will result in a more viable vehicle.

It is important to understand the relationship between charge efficiency, %SoC and charge rate. An appreciation of the effect of %SoC on charge efficiency is useful in determining the SoC which can be practically achieved during fast charging of pure EVs. Trying to charge beyond this practical limit results in a loss of operating time from the vehicle and loss of opportunity time on the charger with little resulting increase in %SoC. For HEVs, this understanding is critical in sizing the battery and optimizing its use. System optimization requires that the battery operates for most of the time in the range of acceptable recharge efficiency. In order to insure that this objective is achieved, it is critical that the acceptable range of SoC is known, and that the battery is sized to operate in this range.

There are two terms used to describe charge efficiency, namely, energy efficiency and coulombic efficiency. Energy efficiency is the ratio of energy discharged from the battery divided by the energy required to bring it back to the initial SoC. Energy efficiency is useful for determining the cost of recharging the battery and the amount of waste heat that will be generated. Coulombic efficiency is the ratio of the coulombs discharged from the battery divided by the coulombs required to bring it back to the initial SoC.

The experimental procedure employed for determining the energy and coulombic efficiency of the Genesis® battery is as follows.

(i) Fully discharge the battery at 25 A (approximately $1C_{1.5}$ rate) to a voltage of 1.75 VPC.

(ii) Recharge the battery to a set percentage charge return, as required for the particular test, at a constant voltage of 2.45 VPC and with a current limit of either $1C_1$, $3C_1$ or $8C_1$ (30, 90 or 240 A), once again as required for the particular test.

(iii) Discharge the battery to 1.75 VPC at the 25-A rate.

(iv) Recharge the battery, using the manufacturer's recommended recharge algorithm, prior to proceeding to the next test.

(v) In order to achieve a consistent estimate of the coulombic and energy efficiency, repeat each point in the test matrix at least five times until the respective value of the efficiency stabilizes.

The results from one point in the test matrix are presented in Fig. 6. The coulombic efficiency, initially greater than 100%, and the energy efficiency both decrease during the first few cycles and then reach approximately steady-state values after five cycles. This anomaly has been reported previously [4]. Such behaviour warrants further investigation, although it can possibly be explained by a progressive increase in battery temperature during the five fast-charging periods. The stabilization of the charge efficiency after 4 to 5 cycles indicates that the temperature of the battery has also stabilized.

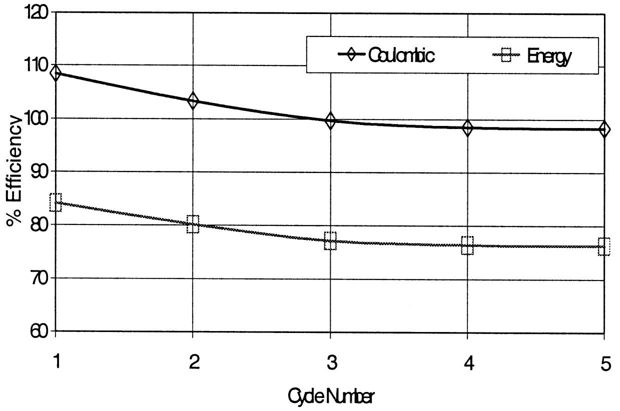

Fig. 7. Stabilized coulombic efficiency as a function of charge rate and charge return.

The stabilized coulombic efficiency of the Genesis® battery is shown in Fig. 7 as a function of charge rate and percentage charge returned under the above experimental conditions. Clearly, the battery demonstrates a stabilized coulombic efficiency of 100%, from a full DoD, at charge returns below 40%. At charge returns greater than 40%, from a full DoD, the stabilized coulombic efficiency falls below 100%, as may well be expected due to increasing recharge inefficiencies. As the recharge current rate increases, the stabilized coulombic efficiency decreases further at charge returns above 40%. The stabilized energy efficiency of the battery under the same fast-charging conditions further exemplifies the situation (see Fig. 8).

In summary, a lower recharge current rate provides a higher energy efficiency. This may be explained by the fact that the lower recharge currents spend less time at the

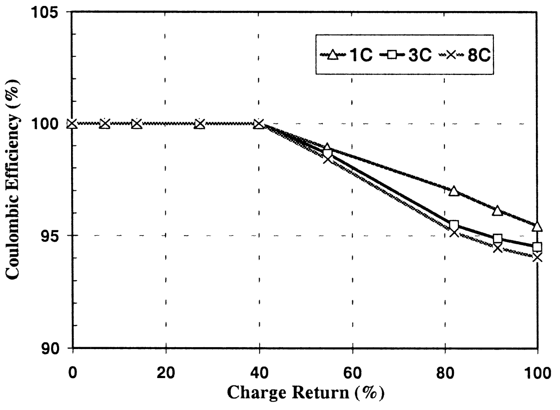

Fig. 6. Coulombic and energy efficiency at $8C_1$ charge rate and 55% charge return.

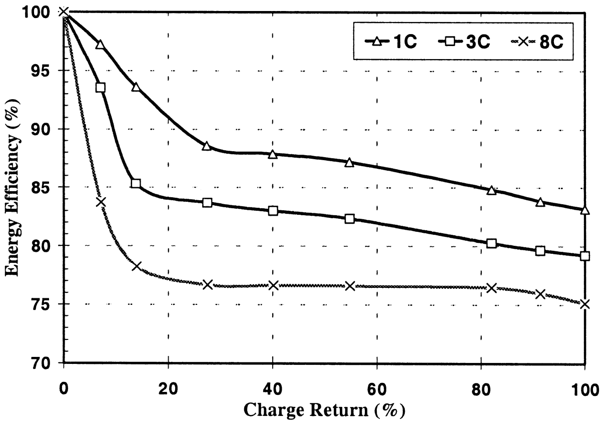

Fig. 8. Energy efficiency as a function of charge rate and percentage charge return.

rectifier voltage limit, i.e., the battery remains longer in the current-limit regime, and hence below the rectifier voltage limit, which reduces the overall energy input.

4. Energy efficiency during hev operation

One of the most important performance characteristics of a HEV battery is its ability to deliver and receive power (bi-directional power capability) within appropriate voltage limits. This bi-directional power capability, along with other effects such as coulombic efficiency, determine the energy efficiency and cooling requirements of the battery. Increasing the fuel economy (increased kilometres per litre) of the HEV is very dependent on the energy efficiency of the battery. A first-order approach to determining the energy efficiency and cooling requirements of the battery is to measure its effective internal resistance over the chosen driving cycle.

The energy efficiency is equal to the product of the polarization efficiency and the coulombic efficiency. The polarization efficiency is related to the effective internal resistance of the battery. The lower the effective internal resistance, the lower the voltage swings during charging and discharging and the higher the polarization efficiency. The effective internal resistance is the sum of the electronic, ionic and electrokinetic resistances of the battery. Coulombic losses occur as a consequence of charge inefficiencies, i.e., the occurrence of side reactions such as gas evolution and grid corrosion. The coulombic and polarization efficiencies are functions of, amongst a variety of other parameters, temperature, %SoC, operational strategy and age of the battery. Low polarization efficiency can be mitigated by, for instance, better current collection or increased electrode surface-area. Coulombic efficiency can be improved with better active material utilization, optimum recharging strategies, or improved thermal management.

An effective method for measurement of battery efficiency is to operate the battery on the specific vehicle's power profile, e.g., a Federal Urban Driving Schedule (FUDS) or some other driving cycle, and operate the auxiliary power unit (APU) or an emulation of the APU with its particular control strategy. The efficiency can then be found as a function of operating conditions such as %SoC and battery temperature.

The procedure for determining the effective internal resistance and consequently the energy efficiency of the Genesis® batteries on such a FUDS HEV cycle is as follows.

(i) Fully charge the battery using the normal charge procedure.
(ii) Discharge the module to the first ampere-hour depletion point, which is defined as the ampere-hours removed from the battery, at the $1C_1$ rate, from a fully charged state. This is based on a 4-Ah increment, i.e., an approximately 12.5% capacity increment.
(iii) Cycle the module on the FUDs cycle until it reaches the 'target' temperature of 35°C.
(iv) Upon reaching the 'target' temperature, cycle the battery over one further FUDS HEV.
(v) Further discharge the battery at the $1C_1$ rate, until the next ampere-hour depletion point is reached.
(vi) Record electrical and temperature data two to three times per second.

In order to calculate the charge and discharge resistance, during HEV cycling, a scatter plot of battery voltage vs. current, both charge and discharge, is made for the FUDS cycle. The scatter plot (polarity plot) for the Genesis battery on a FUDS cycle at 16.0 Ah (50% SoC) depletion and 35°C is shown in Fig. 9. Making the assumption that:

$$V = I \times R_{\text{Effective}} + V_{\text{ocv}} \tag{3}$$

where: I is the current in amperes (positive for charge and negative for discharge); $R_{\text{Effective}}$ is the effective or total d.c. resistance of the battery during charge or discharge; V_{ocv} is the open-circuit voltage of the battery at the given %SoC. Linear regression analysis of the battery operating voltage versus the charge and discharge current yields a slope which is equal to $R_{\text{effective}}$ and the y-intercept which is equal to V_{ocv}. $R_{\text{effective}}$ is then calculated for both charge and discharge at each ampere-hour depletion point, i.e., %SoC.

The effective charge and discharge resistance, as well as the energy efficiency, is given in Fig. 10 as a function of ampere-hour depletion. The effective discharge resistance is fairly flat; it is independent of ampere-hour depletion or %SoC, unlike the charge resistance which clearly is dependent on ampere-hour depletion or %SoC, particularly at a high %SoC. The energy efficiency is shown to peak at just over 87% between 8 and 16 Ah depletion, i.e., between 75 and 50% SoC, where the charge and discharge resistances are at a minimum. Furthermore, the battery returns a very respectable energy efficiency of over 85%

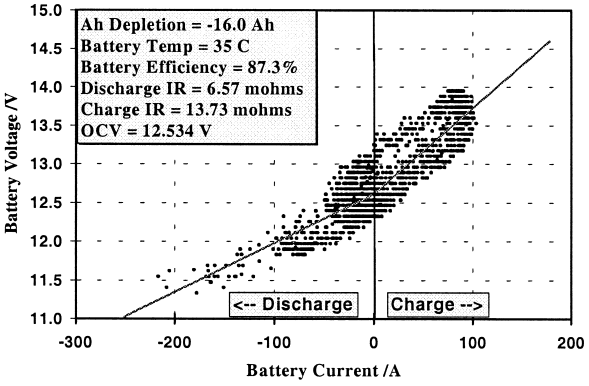

Fig. 9. Polarity plot of Genesis® module on FUDS HEV cycle.

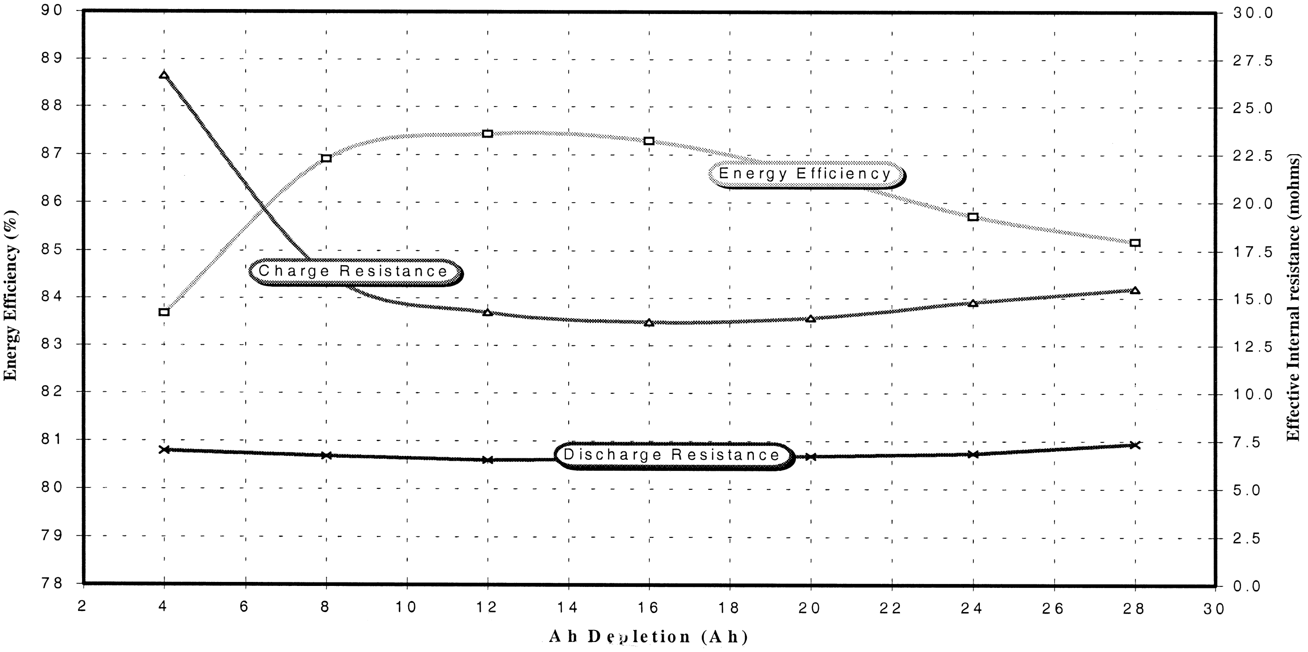

Fig. 10. Energy efficiency and charge and discharge resistance as a function of ampere-hour depletion.

between a wide range of SoC from approximately 10 to 80%.

The energy efficiency discussed so far is the energy efficiency at the battery level, i.e., it is the ratio of energy removed from the battery to the energy put back into the battery. The efficiency which is important at the vehicle level is the energy-storage system efficiency, i.e., the ratio of energy removed from the storage system to the energy that the vehicle offers to the storage system from regenerative braking events and the APU. The energy that is 'offered' to the storage system is not always accepted. To protect the battery from overvoltage and damage, the vehicle's control system may divert some of the regenerative braking or APU energy to the conventional brakes or, in some cases, to a bypass resistor. An example of this behaviour is demonstrated in Fig. 11, which shows the battery voltage, charge–discharge power, and vehicle regenerative power for a particular HEV duty cycle. The regenerative braking efficiency is defined as the ratio of charging energy accepted by the energy-storage system to

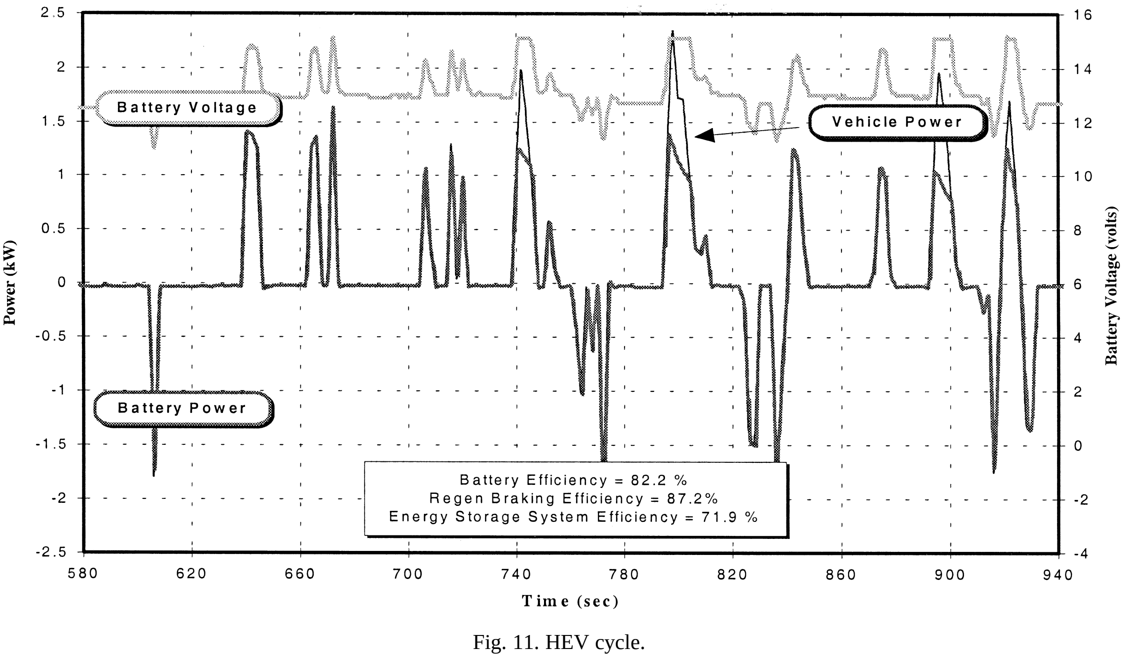

Fig. 11. HEV cycle.

the charging energy offered by the vehicle. Thus, the energy storage-system efficiency is equal to the battery efficiency multiplied by the regenerative braking efficiency. The battery voltage is limited to a maximum of 15.0 V (2.50 VPC) for the nominal 12-V Genesis® battery. Whenever the battery reaches 15.0 V, the battery power is reduced to maintain the voltage limit. The difference between vehicle power and battery power is the power which has to be dissipated by the conventional brakes or other means. The battery efficiency is shown to be a respectable 82.2% for this type of cycling, but the energy-storage system efficiency is much lower at 71.9% because the battery is not able to accept all the regenerative braking energy.

5. Conclusions

1. The Genesis® battery has demonstrated, in laboratory testing, to be extremely capable of accepting recharge currents of up to $9C_1$. Field testing undertaken to date has shown good operational battery life when employing rapid recharging at rates up to $5C_1$.

2. The amount of heat generated within the battery increases with increasing recharge rate. An additional heat source which needs to be considered, particularly under rapid recharge conditions, is the heat of dilution resulting from the mixing of the replenished concentrated acid with the bulk dilute electrolyte.

3. Both the coulombic and energy efficiencies of the Genesis® battery decrease as the rapid recharge rate is increased.

4. The energy efficiency of the Genesis® battery, when operated on a HEV FUDS cycle, is greater than 85% over a wide range of SoCs from 10 to 80%. This demonstrates its suitability for HEV operation.

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