

Rapid Recharge Capability of Valve Regulated Lead Acid Batteries For EV & HEV Applications

Frank A Fleming^a, Philip Shumard^a, Blake Dickinson^b

^a *Hawker Energy Products Inc., 617 N. Ridgeview Drive, Warrensburg, MO USA*

^b *AeroVironment Inc., 825 Myrtle Avenue, Monrovia, CA USA*

Abstract

Range limitation is a significant drawback to the successful commercialization of Electric Vehicles (EV's). 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. First rapid recharge; i.e. recharge the battery as close as possible to the same time period as it takes to fill the petrol tank of an internal combustion engine (ICE) powered vehicle. Whilst not extending the vehicle range as such, this approach does enable high usage of the vehicle without having unduly long recharge times. The ability of the battery to accept rapid recharge is paramount for this approach. Second, development of a Hybrid Electric Vehicle (HEV). The demand on the battery for this approach 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 VRLA Genesis[®] battery in meeting these requirements.

Keywords: Rapid Recharge; Electric Vehicle; Hybrid Electric Vehicle; Valve Regulated Lead Acid; Efficiency.

1. Introduction

The battery type employed for this study is the commercially available Genesis[®] product. The Genesis[®] battery is of a prismatic VRLA construction using absorbed 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. Pure lead-tin technology reduces the corrosion rate of the positive grid material, as well as the rate of hydrogen evolution and dry out. The reduced rate of positive grid corrosion allows the use of thinner current collecting grids and electrodes. The use of thin electrodes, and therefore more electrodes, reduces 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 HEV applications.

In order to quantify the ability and limitations of the Genesis[®] battery in these applications, a series of tests have been conducted. The specific parameters studied are recharge time & 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 rapidly recharged is a highly desirable property for two reasons. First, it reduces the time to charge, from a low state-of-charge to almost fully recharged, in the order of minutes, thereby effectively extending the driving range of an EV employing such batteries. Second, it is now well established that rapid recharge increases the cycle life of lead-acid batteries by helping to maintain an electro-active positive active mass (PAM).

In order to determine the effect of rapid recharge on Genesis[®] batteries a series of charging experiments were conducted on the Genesis[®] 12V42Ah product utilizing up to 9C₁ current availability.

The procedure for each test iteration was to first discharge the battery at the C₁ rate (1 hour discharge rate) to an end of discharge voltage of 1.75 volts per cell (VPC). The discharge was then immediately followed by a rapid recharge with a charge voltage limit of 2.45VPC and a current limit as required for that test iteration. No

temperature compensation of charge voltage was used. The battery temperature was monitored by imbedding the end of a thermocouple probe into the lead strap which makes the electrical connection between the center cells.

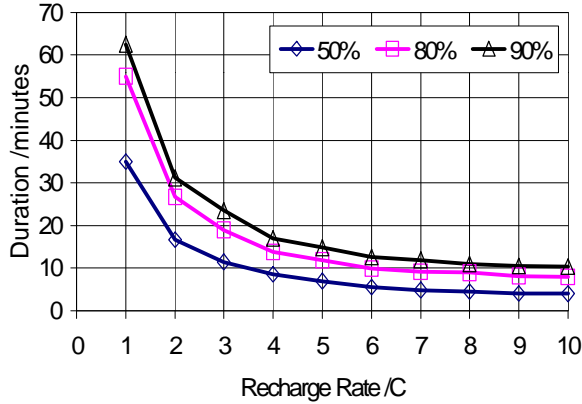


Figure 1: Charge Time as a function of recharge rate

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.

Figure 1 shows the time required to return each of these levels as a function of recharge rate. The recharge rate is shown in terms of multiples of the C_1 rate.

Note that the graph shows time required to return the percentage of amp hours, which were removed, rather than the time required to get to a specific state of charge. The difference between the percent of the capacity returned and the state of charge achieved represents charge inefficiencies.

Clearly, as can be seen from Figure 1, the Genesis[®] VRLA battery is extremely capable of being rapidly recharged. For example at the $6C_1$ recharge rate, 80% of the capacity, from 0% state of charge (SOC), can be returned in approximately 10 minutes and 50% in only 5 minutes. These figures demonstrate, particularly if the EV is operating under a partial state of charge (PSOC) strategy, that it is possible to recharge the EV within the same timeframe as is required to fill a conventional ICE vehicle with petrol. Extended electric vehicle testing, conducted by Arizona Public Service (APS) and

Electric Transportation Applications (ETA), have demonstrated the capability of the Genesis[®] batteries to operate under a fast recharge regime of $5C_1$, often with up to 4 recharges per day. The battery pack delivered a total of 15,258 Ah (462 times the $1C_1$ rate) in accumulating 16,846 miles on the electric vehicle [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 charge rate and is presented in Figure 2. It should be noted that the battery temperature for each test iteration was stabilised at ambient prior to the discharge and the subsequent rapid recharge.

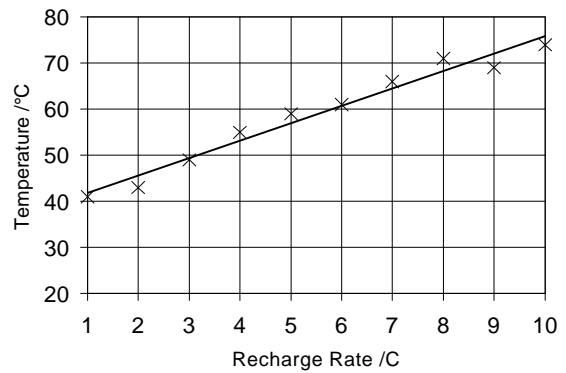


Figure 2: Peak Battery Temperature as a function of Charge Rate

Figure 2 shows that increasing the current availability during the constant voltage recharge period results in an increase in the maximum internal battery temperature.

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

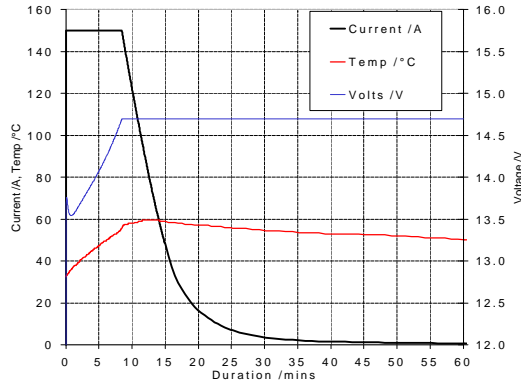


Figure 3: Peak Battery Temperature at a Recharge Rate of 6C₁

Simplistic thermal analysis of this data, based on 'resistive' heat generated within the battery, i.e. I^2Rt , requires a value for the DC resistance of the battery whilst being charged. Figure 4 shows the DC resistance of the battery, for both charge & discharge, as a function of %SOC. This data was derived by dividing the voltage response, as a consequence of an imposed current transient, by the magnitude of the imposed current. This procedure is described in more detail in section 3.0.

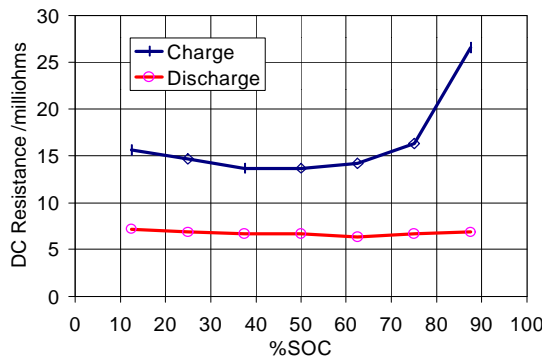


Figure 4: DC Resistance During Charge And Discharge

The above figure shows that the magnitude of the discharge DC resistance is largely independent of the %SOC of the battery. The value for the charge DC resistance is roughly double that of the discharge resistance up to approximately 75% SOC, after which it rapidly increases in magnitude.

Using the thermodynamic and resistive values in table 1, for the 12V battery module, it is possible

to model the internal temperature of the battery:-

Average DC charge resistance from 10 to 75% SOC	15 mΩ
Heat capacity, C _p (calculated from the battery components) [2]	3.2 Wh/h/°C
Heat dissipation rate, Heat _{out} (measured)	1.8 W/°C

Table 1: Thermodynamic and DC Resistance values for the Genesis[®] 12V42Ah Module

The temperature rise as a consequence of resistive heating alone can be estimated according to:-

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

Where,

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

Time (t) is considered only between time, t = 0, i.e. at the commencement of charge and the time at which the battery voltage reaches the limiting value of 14.70VPC, t = t_i, 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 6C₁ 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 additional sources of heat that need to be considered are both chemical and, are therefore, enthalpic:-

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 replenishes sulphuric acid, of a high

concentration, within the pores of the electrodes. This concentrated acid diffuses into the bulk electrolyte, water in the case of a deeply discharged battery, where it readily mixes resulting in a more dilute acid with subsequent heat generation.. This heat generation is referred to as the Heat of Dilution, ΔH_{dil} . Typically, for concentrated acid of 6-7 Molar mixing with water, the magnitude of ΔH_{dil} is approximately 5 Wh/mol of acid [3].

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

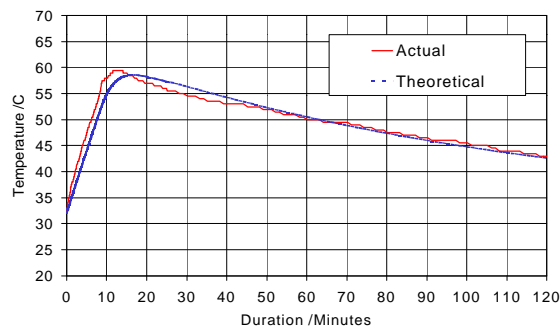


Figure 5: Measured And Calculated Temperature Profile During $6C_1$ Charge

The significance of the heat of dilution may be of greater importance when considering fast recharge in traditional battery powered EV's than in high power HEV operation. For fast recharge in 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. For HEV's, 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. In pure EV's, the charge efficiency will have a direct impact on the operational cost of

the vehicle. In HEV's, 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 understanding of the effect of %SOC on charge efficiency is useful in determining the state of charge that can be practically achieved during fast charging of pure electric vehicles. Trying to charge beyond these 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. In hybrid electric vehicles this understanding is critical in sizing the battery and optimizing its use. System optimization requires that the battery operate most of the time in the range of acceptable recharge efficiency. In order to insure that this objective is achieved, it is critical that both the acceptable range of state of charge is known, and that the battery is sized to operate in this range.

There are two terms used to describe charge efficiency, 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 State of Charge (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 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[®] VRLA batteries is as follows: -

1. Fully discharge the battery at the 25A rate (approximately $1C_{1.5}$) to an end of discharge voltage of 1.75 VPC.
2. Recharge the battery to a set percentage charge return, as required for that particular test iteration, at a constant voltage of 2.45VPC and with a current limit of either $1C_1$, $3C_1$ or $8C_1$ (30, 90 or 240A), once again as required for that particular test iteration.
3. Discharge the battery to an end of discharge voltage of 1.75 VPC at the 25A rate.
4. Recharge the battery, using the manufacturers recommended recharge algorithm, prior to proceeding to the next

test iteration.

- In order to achieve a more consistent estimate of the coulombic and energy efficiency, each point in the test matrix was repeated at least five times until the respective efficiency value stabilizes.

Figure 6 shows a sample of the results from one point in the test matrix. The coulombic efficiency, initially greater than 100%, and energy efficiency decrease for the first few cycles and then reach an approximate steady state value after 5 cycles. This anomaly has been previously reported [4].

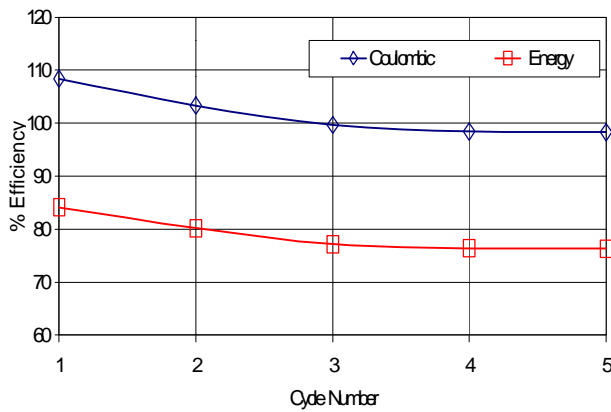


Figure 6: Coulombic and Energy Efficiency at 8C₁ Charge Rate and 55% Charge Return

This behavior warrants further investigation although it can possibly be explained by a progressive increase in battery temperature during the 5 fast charging periods. The stabilization of the charge efficiency after 4-5 cycles indicates that the temperature of the battery has possibly stabilized.

Figure 7 shows the stabilized coulombic efficiency of the Genesis[®] VRLA battery as a function of charge rate and percentage charge returned under the above experimental conditions.

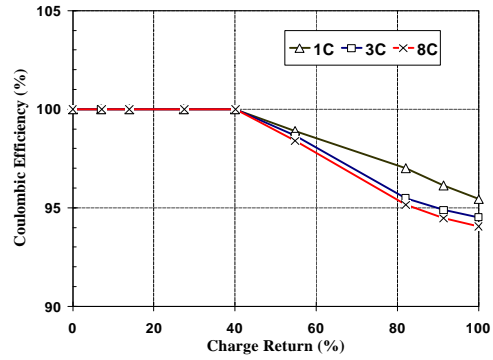


Figure 7: Stabilized Coulombic Efficiency as a Function of Charge Rate and Charge Return (%)

Clearly, the battery demonstrates a stabilized coulombic efficiency of 100%, from a full depth of discharge, at charge returns below 40%. At charge returns greater than 40%, from a full depth of discharge, the stabilized coulombic efficiency drops below unity, as may well be expected due to increasing recharge inefficiencies. As the recharge current rate increases the stabilized coulombic efficiency further decreases at charge returns below 40%

Figure 8, which shows the stabilized energy efficiency of the VRLA battery under the same fast charging conditions, further exemplifies the situation.

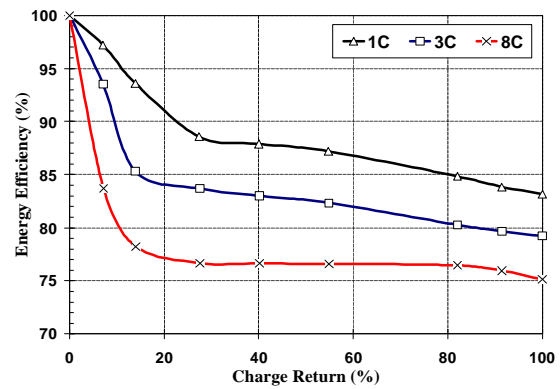


Figure 8: Energy Efficiency as a Function of Charge Rate and %Charge Return

Now, clearly the lower recharge current rate exhibits the higher energy efficiency. This may be interpreted by the fact that the lower recharge currents spend less time at the rectifier voltage limit, i.e. the battery remains in current limit longer, hence below the rectifier voltage limit, thus reducing the overall energy input.

4. Energy Efficiency during HEV Operation

One of the most important performance characteristics of a hybrid vehicle 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 mpg) of the hybrid vehicle 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 determine its effective internal resistance over the chosen driving cycle.

The energy efficiency is equal to the polarization efficiency times the coulombic efficiency. The polarization efficiency of a battery is related to the effective internal resistance of the device. 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 with, 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 Drive Cycle (FUD's) 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[®] VRLA batteries on such a FUD's HEV cycle is as follows: -

1. Fully charge the battery using the normal charge procedure.
2. Discharge the module to the first Amp-hour depletion point, which is defined as the Amp-hours removed from the battery, at the 1C₁ rate, from a fully charged state. This was based on a 4Ah increment, i.e. approximately 12.5% capacity increment.
3. Cycle the module on the FUD's cycle until it reaches the "target" temperature of 35°C.
4. Upon reaching the "target" temperature the battery is then cycled over one further FUD's HEV.
5. The battery is then further discharged, at the 1C₁ rate, until the next Ah depletion point is reached.
6. Electrical and temperature data is recorded 2 to 3 times per second.

In order to calculate the charge and discharge resistance, during HEV cycling, a scatter plot of battery voltage V's current, both charge and discharge, is made for the FUD's cycle. Figure 9 shows the resultant scatter plot (Polarity Plot) for the Genesis battery on a FUD's cycle at 16.0Ah (50% SOC) depletion and 35°C.

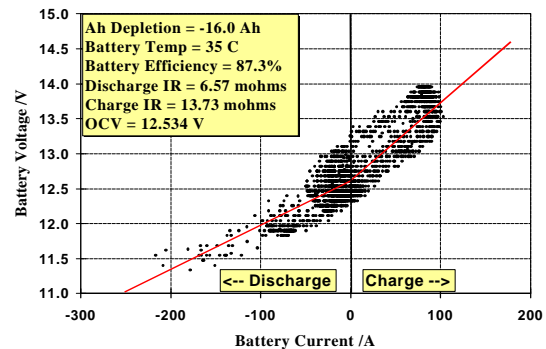


Figure 9: Polarity Plot of the Genesis[®] Module on FUD's HEV Cycle.

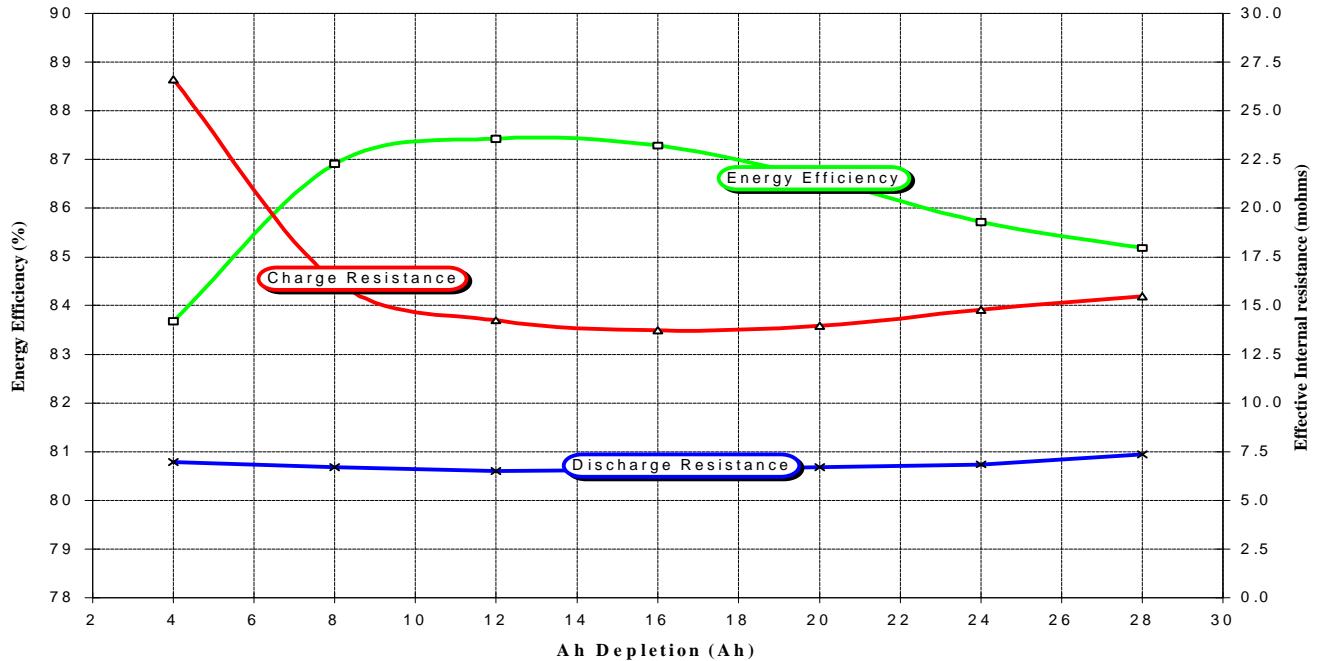


Figure 10: Energy Efficiency and Charge and Discharge Resistance as a Function of Ah Depletion

Making the assumption that,

$$V = I \times R_{\text{Effective}} + V_{\text{OCV}} \text{ ----- (2)}$$

Where,

I is the current in amps (positive for charge and negative for discharge)

$R_{\text{Effective}}$ is the effective or total DC resistance of the battery during charge or discharge

V_{OCV} is the open circuit voltage of the battery @ that %SOC.

Linear regression analysis of the battery operating voltage versus the charge and discharge current yields a slope that is equal to $R_{\text{Effective}}$ and the y-intercept equal to V_{OCV} . $R_{\text{Effective}}$ is then calculated for both charge and discharge at each Ah depletion point, i.e. %SOC.

Figure 10 shows the effective charge and discharge resistance as well as the energy efficiency as a function of Ah depletion. The effective discharge resistance is fairly flat;

independent of Ah depletion or %SOC, unlike the charge resistance which clearly is dependent on Ah depletion or %SOC, particularly at a high %SOC. The energy efficiency is shown to peak at just over 87% between 8Ah and 16Ah depletion, i.e. between 75% to 50% SOC, where the charge and discharge resistances are at a minimum. The battery, furthermore, returns a very respectable energy efficiency of over 85% between a wide range of SOC from approximately 10% to 80%.

The energy efficiency we have talked about so far is the energy efficiency at the battery level i.e. the ratio of energy removed from the battery to the energy put back into the battery. The efficiency that is important at the vehicle level is the energy storage system efficiency; 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 over-voltage and damage the vehicle control system may divert some of the

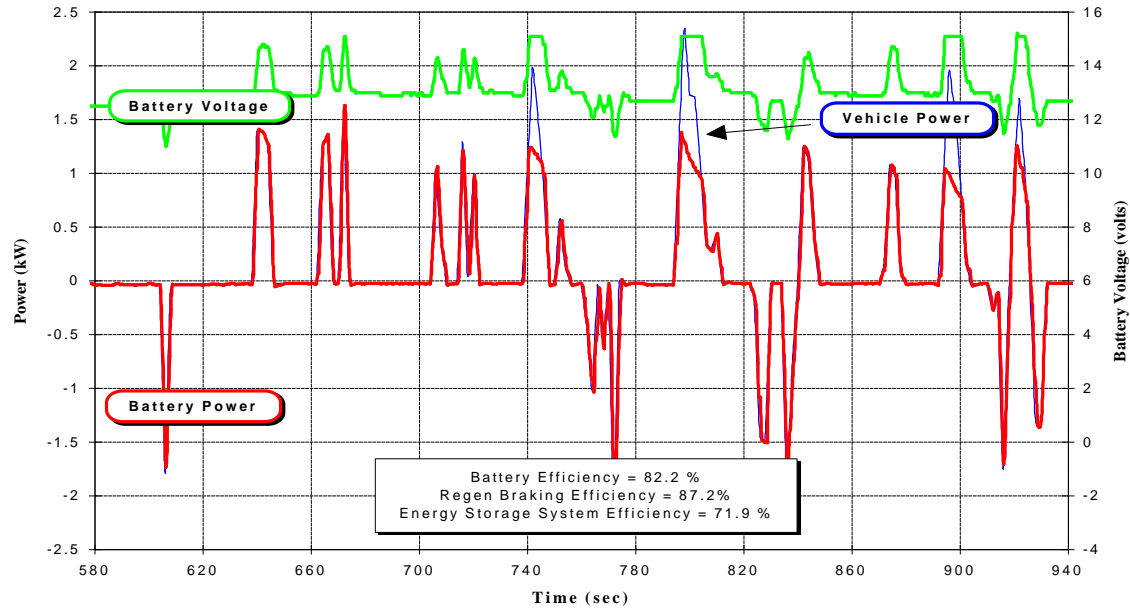


Figure 11: HEV Cycle

regenerative braking or APU energy to the conventional brakes or in some cases a bypass resistor.

An example of this behavior is demonstrated in Figure 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 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 15.0V (2.50VPC) for the nominal 12V Genesis® VRLA battery. Whenever the battery reaches 15.0V the battery power is reduced to maintain the voltage limit. The difference between vehicle power and battery power is the power that 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 was found to be much lower at 71.9 % because the battery was not able to accept all the regenerative braking energy.

5. Conclusions

1. The Genesis® VRLA battery has demonstrated, in laboratory testing, to be extremely capable of accepting recharge currents of up to $9C_1$. Field testing, to date has shown good operational battery life employing rapid recharging at up to $5C_1$.
2. The amount of heat generated within the battery increases with increasing recharge rate. An additional heat source that 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® VRLA battery reduce as the rapid recharge rate is increased.
4. The Genesis® VRLA battery energy efficiency, when operated on a HEV FUDS cycle, is greater than 85% over a wide range of SOC's from 10% to 80% demonstrating it's suitability for HEV operation.

References

- [1] ALABC Project Number A001.1 “EV Range And Battery Cycle Life Improvement Through Fast Charging And Partial State Of Charge Operation”. Progress Report No. 2: November 1, 1997 to April 30, 1998.
- [2] Karl Matthes, Barbara Papp and Robert F. Nelson. “Recombination Chemistry and Thermal Management in Sealed Lead-Acid Systems.” Power Sources 12. Proceedings of the 16th International Powers Sources Symposium 1988.
- [3] Hans Bode. Lead-Acid Batteries, pp 50-53. Willey-Interscience Publication.
- [4] Sexton, E. and Olson, J.; “Coulombic Efficiency of a Sealed, Thin Plate, Spiral Lead-Acid Battery”; in Proceedings of Thirteenth Annual Battery Conference; Long Beach CA; January 1998.