Nickel-Metal Hydride Batteries For ZEV-Range Hybrid Electric Vehicles

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Abstract

Hybrid electric vehicles with significant all-electric range provide a promising alternative to zero emission vehicles (ZEVs) without the problem of the limited range of electric vehicles. Ovonic nickel-metal hydride (NiMH) batteries feature a combination of high power and energy density ideal for ZEV-range hybrid electric vehicles. A series of high-power, high-energy batteries ranging in size from 20 Ah to 90 Ah are available for this application. The specific power exceeds 500 W/kg and the specific energy approaches 70 Wh/kg. These batteries have been integrated into a series of charge-depletion hybrid vehicles, including a compact sedan, mid-size sedan, and a large sport-utility vehicle, each demonstrating a significant ZEV-range. A Toyota Prius hybrid vehicle retrofitted with 20 Ah Ovonic batteries demonstrated an equivalent ZEV range of 25 miles. A Mercury Sable, converted to a charge-depletion hybrid by the University of California at Davis (UCD), demonstrated a ZEV range of 60 miles with 60 Ah Ovonic batteries. A Chevrolet Suburban, converted by UCD into a charge-depletion hybrid vehicle powered by 90 Ah Ovonic batteries, provided a ZEV range of over 60 miles.

Introduction

Electric vehicles have been promoted as the ultimate means to address serious vehicular air pollution issues due to their lack of tailpipe emissions. This led to the California ZEV mandate calling for 10% of the 2003 vehicles to be zero emission. Electric vehicles would also reduce the US dependence on foreign oil and improve the US balance of trade situation. Unfortunately, the current technological status of electric vehicles and batteries does not provide for the same range performance that consumers are accustomed to with conventional internal combustion engine vehicles. Recent marketing difficulties have largely been ascribed to the lower range of electric vehicles.

Power-assist hybrid electric vehicles such as the Toyota Prius and the Honda Insight have been promoted as an effective way to improve vehicle efficiency and simultaneously reduce the production of greenhouse gases. With careful engineering of the internal combustion engine (ICE) power train, these vehicles can also provide for reduced noxious emissions. However, concerns remain about the incremental nature of this approach and the problem of significant vehicular emissions due to deterioration of the ICE power train late in the life of these vehicles.

Is it possible to achieve reduction in pollution comparable to that inherent with electric vehicles together with the range possible with convention ICE vehicles? This requires a hybrid electric vehicle with significant ZEV range, and thus a battery with high energy density as well as high power. These requirements are well met by nickel-metal hydride batteries developed by Ovonic Battery Company (OBC) (1-3).

Zev-Range Hybrid Electric Vehicles

Hybrid electric vehicles comprise a wide range of designs utilizing electric drive in combination with a fuel engine either in series or parallel or series-parallel combinations. An important design criterion is the relative size of the battery and the engine (4). At one extreme, power-assist HEVs such as the Toyota Prius and the Honda Insight utilize small batteries to assist acceleration and store regenerative braking energy. This improves fuel efficiency. However, they do not utilize grid electricity or provide for ZEV range.

This paper focuses on ZEV-range HEVs, also variously referred to as charge-depletion HEVs, range-extender HEVs, plug-in HEVs, or battery-dominant HEVs. These utilize large batteries that are charged with grid electricity and can be operated in all-electric mode to provide a significant ZEV range. Thereafter, in hybrid mode operation, the engine is utilized to extend the range beyond that provided by the battery energy. In HEV mode, the engine efficiency is maximized by utilizing electric assist for acceleration. Further gains in fuel economy are obtained by storing regenerative brake energy in the battery. This provides for significantly improved fuel economy and emissions reductions over a conventional ICE vehicle even after full utilization of the ZEV range.

The advantages of charge-depletion HEVs have been demonstrated in recent PNGV FutureCar competitions sponsored by the Department of Energy. A converted Ford Taurus developed by Lawrence Technological University of Southfield, Michigan, captured second place in the 1996 PNGV FutureCar Challenge (5, 6). Utilizing 15 kWh of Ovonic NiMH EV batteries, this vehicle, called Hyades, demonstrated a fuel economy of over 50 mpg and a ZEV range of 70 miles. In 1997, the University of California at Davis (UCD) won the FutureCar competition with another Ford Taurus converted to a charge-depletion HEV (7). This vehicle, called the Joule, utilized 15 kWh of Ovonic NiMH EV batteries to demonstrate a highway/city fuel economy of 63/42 mpg and a ZEV range in excess of 80 miles.

The biggest advantage of a ZEV-range HEV is its ability to drive in all-electric mode in order to minimize emissions. A distribution of commuter miles traveled daily with data derived from the 1990 National Transportation Survey is shown in Fig. 1. The average mileage driven by consumers is only 45 miles. Thus, ZEV-range HEVs with an all-electric range of over 50 miles would allow most commuters to operate in all-electric mode and reduce tailpipe emissions to zero. Those commuting 50-100 miles would still utilize 50 miles of ZEV range prior to operation of the engine, resulting in more than a 50% reduction in emissions, assuming the same efficiency as conventional ICE vehicles. However, the efficiency is significantly improved due to HEV operation, resulting in further reductions in tailpipe emissions. Still further reductions will result from reductions in the proportion of cold engine operation. With an 80-mile ZEV range, over 90% reduction in tailpipe emissions and more than 50% reduction in greenhouse gas generation is possible.

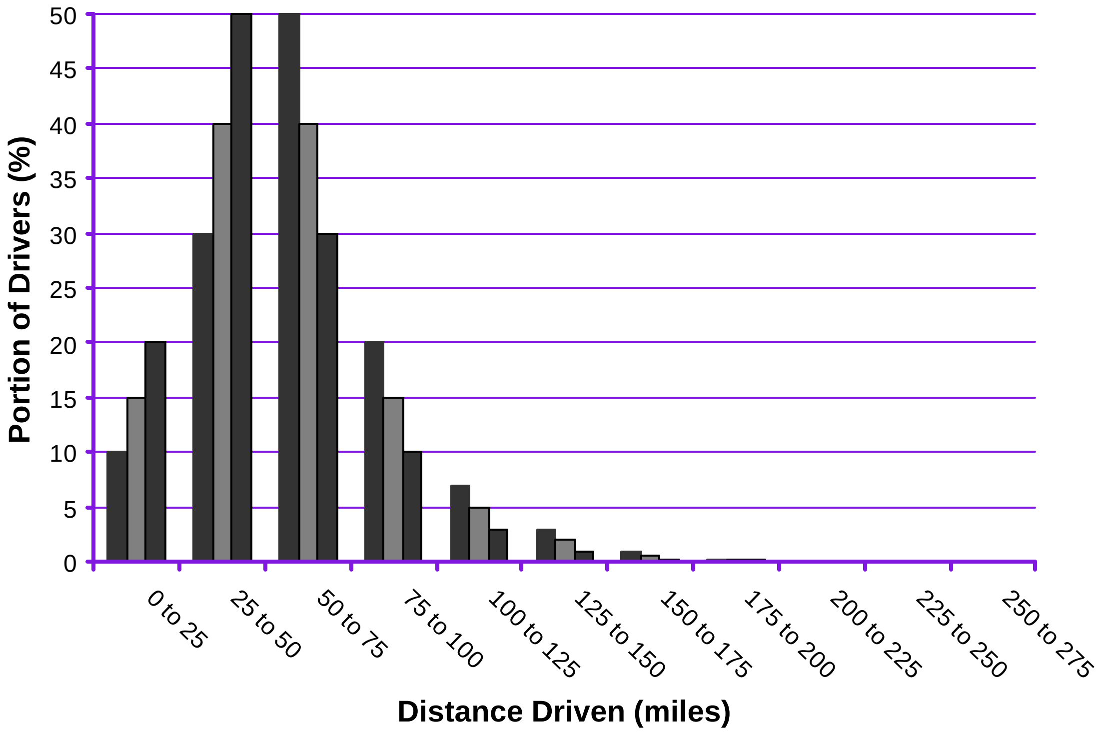

Figure 1
Distribution of Commuter Miles Traveled Daily

To obtain the maximum advantages of the ZEV-range HEV, an all-electric range at least on the order of the average commuter driving distance is recommended. In the US, that range is around 45 miles. In other locations, such as Europe, the average commute distance is considerably less, requiring a lower ZEV-range for effective reduction in tailpipe emissions. Additionally, there is a trend appearing in Europe with several major cities designating parts of the downtown area as “emission-free” zones due to severe air-pollution problems. ZEV-range HEVs could be driven in these areas while operating in all-electric mode. Thus, 20 miles ZEV range may be very effective in some cases.

The lower weight, volume, and cost of a smaller battery pack also favor the development of HEVs with a lower ZEV range. Additionally smaller battery packs require less power to charge, enabling the use of smaller and cheaper chargers. Alternatively, smaller packs are more adaptable to rapid recharge due both to the lower heat rejections requirements of smaller packs and the lower power charge power required. A 20-mile ZEV-range vehicle charged at work and at home could provide the same emissions benefits as a 40-mile ZEV-range vehicle charged only at home.

In response to concerns about the feasibility of the 2003 ZEV mandate, automakers have petitioned the California Air Resources Board (CARB) for options including hybrid electric vehicles, which are viewed as more practical in the short term than pure EVs. Recognizing the emissions advantages possible, CARB has modified the mandate to allow partial ZEV credits for HEVs. They also recognize the importance of ZEV range in emissions reductions and partial ZEV credits are scaled according to the ZEV range.

Ovonic Batteries For HEV Applications

A hybrid electric vehicle with significant ZEV range requires batteries with high energy density in order to provide significant ZEV range simultaneously with high power to provide high efficiency and good acceleration in hybrid mode of operation. Ovonic NiMH EV batteries lead the industry in energy density. Our production batteries are rated at 70 Wh/kg. We also have prototype EV batteries at 80 Wh/kg, and advanced prototype EV batteries at over 90 Wh/kg. Ovonic technology in consumer cells has achieved over 100 Wh/kg (8).

From its EV battery technology, Ovonic Battery Company has developed a series of high power batteries with excellent characteristics for charge depletion HEV applications. Specifications are provided in Table 1 for several of these batteries ranging in capacity from 20 to 90 Ah. These batteries have a power capability of about 550 W/kg at 50% DOD. Higher power versions approaching 1000 W/kg are now in the final stages of development and should be available for prototype battery packs later this year. These Ovonic HEV batteries also exhibit high specific energy, approaching 70 Wh/kg for the 60 and 90 Ah batteries. The range in size and capacity allows for hybridization of a wide variety of vehicle platforms from the compact car to the largest sport utility vehicles.

Table 1
Ovonic Battery Company Family of Batteries for Hybrid Electric Vehicles

	12HEV20	6HEV28	12HEV45	12HEV60	12HEV90
Nominal Voltage *(V)*	12	6	12	12	12
Nominal Capacity *(Ah)*	20	28	45	60	90
Dimensions					
Length *(mm)*	340	195	340	385	385
Height *(mm)*	91	81	135	119	168
Width *(mm)*	75	102	75	102	102
Weight *(kg)*	5.4	3.6	8.4	11.6	16.8
Volume *(L)*	2.3	1.6	3.4	5.0	6.1
Nominal Energy* *(Wh)*	250	175	560	750	1125
Specific Energy *(Wh/kg)*	46	50	67	65	67
Energy Density *(Wh/L)*	110	110	165	150	184
Peak Power *(kW)**	3.0	2.0	4.6	6.4	8.4
Specific Power *(W/kg)*	550	550	550	550	500
Power Density *(W/L)*	1290	1240	1360	1280	1370

* Capacity and Energy measurements at C/3 rate and power measurements from 10 sec pulses at 50% DOD at 35°C battery temperature.

These batteries were specifically designed for ZEV-range HEV applications by combining high power capabilities and high specific energy. The high discharge power capability for discharge and charge provides for acceleration performance comparable to that of conventional ICE vehicles. The high charge power capability provides for efficient acceptance of regenerative braking energy. The high energy content provides for a significant all-electric range.

High power for discharge and charge are available over a wide range of state of charge (SOC) as shown in Fig. 2. A power performance in excess of 500 W/kg is available over the entire range from 0 to 70% depth of discharge (DOD). For HEV charge-sustaining operation at 20% SOC (80% DOD), a power performance of 450 W/kg is available. Thus, it would be reasonable to utilize 80% or more of the battery energy in charge depletion mode to achieve maximum ZEV range. High charge power over a wide SOC range provides for excellent recovery of regenerative braking energy throughout HEV operation.

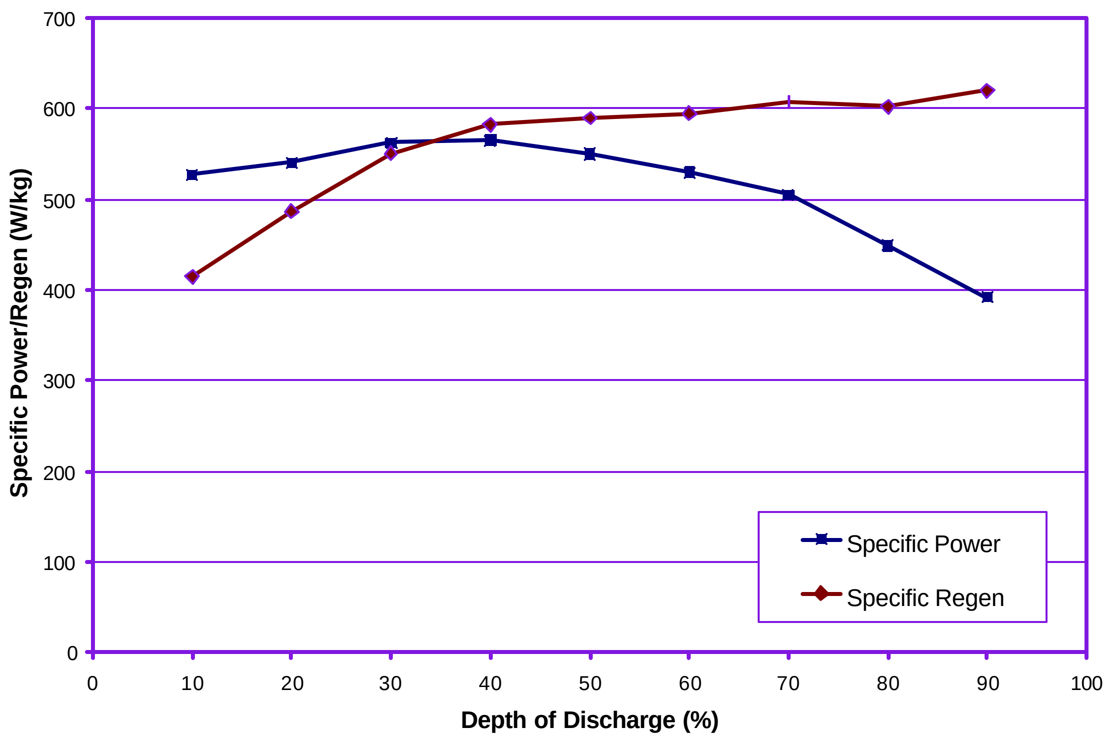

Figure 2
Specific Power vs. Depth of Discharge for Ovonic HEV Batteries

The high discharge power and high charge power capability translate into high efficiency in HEV applications. For modeling purposes, power for charge and discharge is characterized with open circuit potential and resistance values as a function of state of charge with the resistance for charge and discharge being equal. As reported previously (9), the battery efficiency is dependent on the control strategy of the vehicle and the way the battery is being used. During HEV charge-sustaining mode operation, the efficiency is typically 90-95%. During ZEV-mode operation, the efficiency is lowered due to coulombic losses during overcharge. A round-trip battery energy efficiency is typically 80-85%. The efficiency for overall charge-depletion HEV operation is intermediate between these values depending on the vehicle operating strategy and the usage including the range of the trips.

Ovonic-Powered Toyota Prius HEV

In 1998, Ovonic Battery Company acquired a Japanese version of the Toyota Prius for development and demonstration purposes. We were able to confirm the Toyota performance specifications. The acceleration from 0 to 60 mph took about 14 seconds. The city/highway mileage under the US FTP driving cycle was about 50 mpg. During moderately aggressive city driving conditions in actual use in the Detroit area, we found the acceleration was often further limited by something called "turtle mode" where the performance is reduced due to limitations in the power and energy performance of the Panasonic batteries used by Toyota. The 0 to 60 mph acceleration time in the "turtle mode" was increased up to as much as 20 seconds.

After testing the Prius as delivered, we removed the Panasonic NiMH battery pack and replaced it with Ovonic NiMH HEV batteries. Because of the superior power density, energy density, and packaging efficiency of Ovonic batteries, we were able to triple the power and energy of the battery pack by utilizing only about 20% more volume. The performance of our batteries in comparison to the original Panasonic batteries is given in Table 2.

Table 2
Battery Pack Specifications for Toyota Prius HEV Powered by Ovonic and Panasonic Batteries

Battery Characteristic	Ovonic	Panasonic
Battery Cell Type	Prismatic HEV20	Cylindrical D
Module Type	7HEV20	6-cell string
Number of Modules	40	40
Nominal Capacity	20 Ah*	6.5 Ah
Nominal Pack Voltage	288 V	288 V
Total Energy	6.0 kWh*	1.8 kWh
Specific Energy	38 Wh/kg	24 Wh/kg
Energy Density	50 Wh/L	18 Wh/L
Peak Power	65 kW*	21 kW
Specific Power	400 W/kg	280 W/kg
Power Density	540 W/L	210 W/L
Pack Weight	160 kg**	75 kg**
Pack Volume	120 L**	100 L**

* Capacity and Energy measurements at C/3 rate and power measurements from 10 sec pulses at 50% DOD at 35°C battery temperature.

** Includes modules and pack hardware

The vehicle performance improvement through the use of Ovonic batteries is summarized in Table 3. Our batteries provided improved acceleration performance through the elimination of “turtle mode” even under very aggressive city driving. The hill climbing ability was also dramatically improved. Finally, the additional energy provides for an equivalent ZEV range of over 25 miles.

Table 3
Toyota Prius Vehicle Performance Comparison

Performance Characteristic	Ovonic-Powered Prius	Panasonic-Powered Prius
Turtle Mode	None	Frequent
Acceleration Time (0 to 60 mph)	14 sec (motor limited)	14-20 sec (battery limited)
Hill Climbing Ability (time on grade)	>3X	Limited
Equivalent ZEV Range	> 25 miles	< 7 miles
Fuel Economy* (US City-Hwy)	70-80 mpg	50 mpg

* Charge depletion operation for first gallon

The improvements in the vehicle fuel economy were also achieved due to changes in the control strategy of the vehicle. Changes in the control strategy were achieved by alteration of battery voltage and current signal inputs going to the vehicle control system. We were then able to operate in a charge-depletion mode and utilize wall charge energy. Having higher battery power available allowed us to increase the engine turn-on speed (the vehicle speed when engine engages). It also minimized the use of the engine in its least efficient range of operation, thus improving the operating efficiency of the vehicle. However, the biggest impact on fuel economy and emissions came from the increased proportion of tractive power and energy provided by the electric drive train. The electric drive including the motor, inverter and batteries is more efficient then the heat engine.

We also equipped this vehicle with a charger to allow for energy input through wall charging. By utilizing electrical energy from a full charge of the battery, the fuel economy was improved so that 70-80 miles could be obtained under the FTP cycle on the first gallon of gasoline. Furthermore, the charger is able to operate at both 110 V and 240 V inputs, thus allowing high versatility for the vehicle with opportunistic charging within the existing electric grid infrastructure.

Under normal usage, a driver would recharge the pack from the grid every day. However, if a long range is desired, the vehicle can continue to run in charge-sustaining mode for up to 500 miles with slightly lower fuel economy. Thus the fuel economy is maximized for the great majority of vehicle miles traveled on a daily basis (Fig. 1) while at the same time providing the utility of long range needed occasionally.

Although 25 miles of equivalent ZEV range could be utilized under charge-depletion conditions, an actual usable ZEV range would require a more powerful drive train with about 50 kW of power. In Table 4, we show what would be possible with the Prius if a 50 kW drive train were installed.

Table 4
Projected Prius HEV Performance with 50 kW Drive Train

Performance Characteristic	Ovonic-Powered Prius	Panasonic-Powered Prius
Turtle Mode	None	Frequent
Acceleration Time (0 to 60 mph)	12 sec (motor limited)	14-20 sec (battery limited)
Hill Climbing Ability (time on grade)	>3X	Limited
Equivalent ZEV Range	> 25 miles	None
Fuel Economy* (US City-Hwy)	75-80 mpg	50 mpg

* Charge depletion operation for first gallon

Ovonic Powered HEV Sable

Similar benefits of ZEV-range HEVs can be achieved in larger vehicle platforms, such as mid-size sedans and sport utility vehicles (SUVs). The 1999 UCD FutureCar team converted a Mercury Sable Aluminum Intensive Vehicle with the goals of tripling the fuel economy and qualifying for 0.9 Partial zero emissions vehicle credits in California (10). The new vehicle, Coulomb, is powered by a 75 kW Unique Mobility electric motor and a Subaru 32 kW gasoline engine coupled to a continuously variable transmission. For the electric energy storage system, an Ovonic NiMH HEV battery pack was selected. The 60 Ah battery was best suited for this application because of its high energy density for extended ZEV range (up to 65 miles) and high power density for acceleration and peak loads. The specifications of this battery pack are summarized in Table 5.

Table 5
Coulomb HEV Battery Pack Specifications

Module Type	14HEV60
Nominal Module Voltage	14.4 V
Number of Modules	22
Nominal Pack Voltage	317 V
Nominal Capacity*	60 Ah
Nominal Energy*	19.8 kWh
Power *	130 kW
Mass (modules only)	306 kg

* Capacity and energy measurements at C/3 rate and power measurements from 10 sec pulses at 50% DOD at 35°C battery temperature.

To achieve their goals, UCD implemented a charge depletion control strategy. The essential component of the control strategy is the combination of the engine turn-on speed and the depth of discharge of the batteries. Figure 3 shows the relationship of these elements as used in Coulomb (11). The vehicle operates in ZEV mode during high states of charge (approximately the first 65 miles of travel) therefore eliminating tailpipe emissions from most typical driving patterns, as discussed earlier. During highway driving and low battery states of charge, the vehicle operates in engine-assisted or charge-sustaining HEV modes, respectively. These modes allow the vehicle's range to be limited by the fuel storage capacity only and not the battery pack energy.

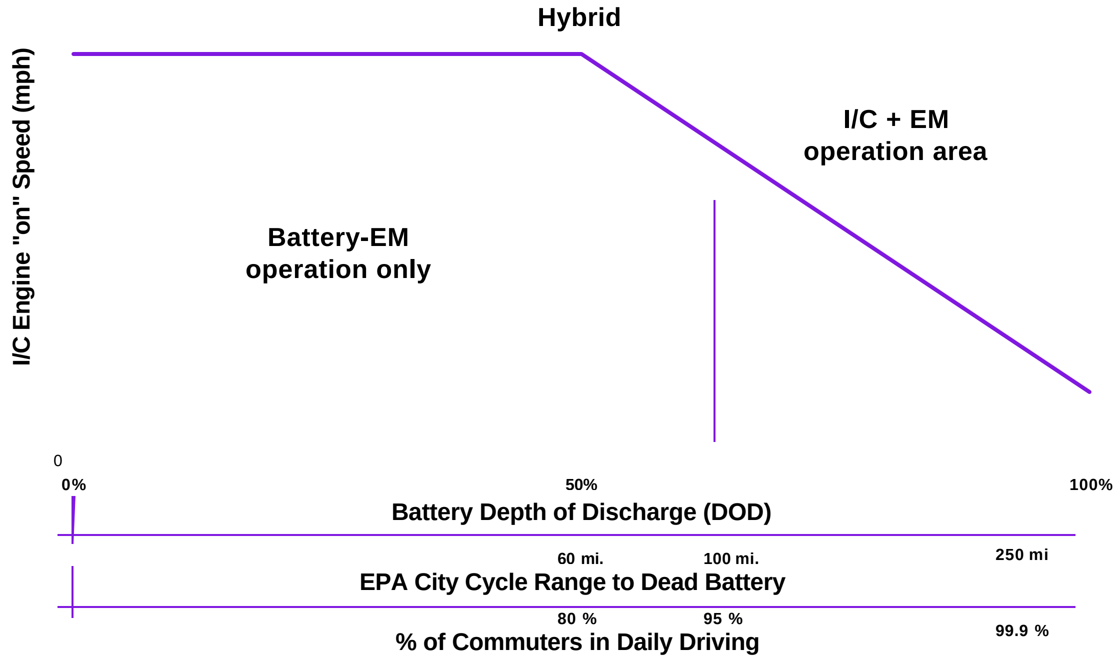

Figure 3
Charge-Depletion HEV Engine Control Strategy

A charge depletion strategy in combination with vehicle modifications increased Coulomb's energy efficiency to 62 mpg (equivalent) from 25 mpg. The 11-second acceleration time from 0 to 60 mph was an improvement from 12.5 second. In addition to an 80-mile ZEV range, super ultralow emissions during engine operation are achievable with simple engine controls and standard catalysts. Zero evaporation is also possible without charcoal canisters due to the small fuel tank needed.

Ovonic Powered HEV Sport Utility Vehicle

The largest segment of the passenger vehicle market today is comprised of light duty trucks and sport utility vehicles (SUV). These vehicles also have an increased demand for fuel and higher overall tailpipe emissions. Hybridization of these platforms may have a larger impact on environmental benefits and reduction of total oil consumption. The benefits are further maximized with a capability for substantial ZEV range.

Sequoia is a modified Chevrolet Suburban, developed by UC Davis, that demonstrates the feasibility of a cleaner, more efficient SUV with the use of a charge-depletion concept power by Ovonic NiMH batteries. Sequoia utilized two power trains to achieve four-wheel drive and provide substantial towing capacity (12). In addition, the charge depletion control strategy allows Sequoia to obtain high efficiency during both normal and high-power operations. Table 6 summarizes the projected vehicle performance.

Table 6
Projected Performance of UCD Sequoia HEV

Performance Characteristic	Simulation
Equivalent Energy Efficiency	28 mpg
Greenhouse Gas Reduction	56%
ZEV Range	66 mi.
FUDS and FHDS range	326 mi.
Acceleration (0-60 mph)	8.55 sec
Curb Weight	2630 kg

A relatively small Saturn 1.9L DOHC gasoline engine is coupled with a 75 kW Unique Mobility brushless DC motor to provide rear wheel drive. A second 75 kW DC motor is coupled via a planetary reduction to the front differential and provides power to the front wheel drive shaft. The motors are powered by a high-power 29 kWh Ovonic nickel-metal hydride battery pack. The specifications for the battery pack are given in Table 7.

Table 7
Sequoia HEV Battery Pack Specifications

Module Type	13HEV90
Nominal Module Voltage	13.2 V
Number of Modules	24
Nominal Pack Voltage	317 V
Nominal Capacity*	90 Ah
Nominal Energy*	29 kWh
Power*	185 kW
Mass (modules only)	442 kg

* Capacity and Energy measurements at C/3 rate and power measurements from 10 sec pulses at 50% DOD at 35°C battery temperature.

The battery selected for this application was the Ovonic NiMH HEV90 battery that has been optimized for both pulse power and high energy density. This battery provides the Sequoia with sufficient energy storage for a long ZEV range, over 60 miles. High specific power provides 150 kW shaft power for acceleration and towing capacity while enabling rapid recovery of regenerative braking energy.

In conjunction with the vehicle modifications, a charge-depletion strategy reduces greenhouse gas emissions by 66%. The emissions levels of the Sequoia would be lower than a Honda Insight for trips under 140 km.

Conclusions

The concept of ZEV-range hybrid electric vehicles makes it possible to achieve reduction in pollution comparable to that inherent with pure electric vehicles together with the range and utility possible with conventional ICE vehicles. It is a compromise that promises acceptance by all stakeholders, the environmentalist, the car companies and finally the consumers. These vehicles require batteries with a combination of high energy and high power at the same time. Ovonic Battery Company has developed a family of batteries to meet the needs of the ZEV-range hybrid. A wide range of capacity is available for different types of vehicles. A 20-mile equivalent ZEV range has been demonstrated by retrofitting a Toyota Prius HEV with Ovonic batteries. A ZEV range of 60 miles was similarly demonstrated in a mid-size sedan and a large sport utility vehicle. These vehicles, powered by Ovonic batteries, are opening new possibilities to market environmentally clean and energy-efficient vehicles for the new millennium.

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