Plug-In Hybrid Electric Vehicle Battery Test Results

2004 Final Report

Technical Report

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1008764

Final Report, March 2005

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Plug-In Hybrid Electric Vehicle Battery Test Results: 2004 Final Report, EPRI, Palo Alto, CA: 2005. 1008764.

REPORT SUMMARY

EPRI has initiated a detailed test program to evaluate candidate batteries for use in Plug-in Hybrid Electric Vehicles (PHEVs). The focus of the initial battery-testing phase of the project was to generate cycle life and performance data to further PHEV battery testing in general and the performance of specific batteries for the PHEV Sprinter Van in particular.

Background
The performance and cycle life durability of advanced batteries are critical factors that affect all aspects of the design, operation, and economics of PHEVs. At this time, there is little specific information regarding the performance and durability of currently available production advanced chemistry Nickel Metal Hydride (NiMH) and Lithium Ion (Li Ion) batteries over a characteristic PHEV duty cycle. Obtaining this information is critical to both near-term programs like the EPRI/DaimlerChrysler PHEV Sprinter program and future efforts to develop PHEV technology.

Objective
To test advanced batteries using operation characteristics specific to the operation of PHEVs using a test profile developed for the EPRI/DaimlerChrysler PHEV Sprinter.

Approach
EPRI has developed a PHEV battery test profile using dynamic simulations of the PHEV Sprinter Van to capture the battery demands and operational characteristics of the battery. Southern California Edison (SCE) has modified this test profile to work reliably using standard test equipment over a long-term test cycle. The information and results from the use of this test procedure will be applied to the development of generalized PHEV test procedures acceptable to a wide variety of stakeholders and applicable to all PHEVs.

Results
SCE verified the performance of the test profile and developed a full test procedure. SCE has initiated long-term cycle life testing of two PHEV batteries, a VARTA NiMH system and a SAFT Lithium Ion system. Testing is expected to continue throughout 2006.

EPRI Perspective
This report summarizes the initial phase of battery testing commenced by EPRI and Southern California Edison. Future updates will provide additional data on the ongoing performance of the test batteries. For information on EPRI's PHEV Sprinter program, see EPRI report 1011045 .

Keywords
Nickel metal hydride
Lithium Ion

Battery cycle life
Plug-in hybrid electric vehicle
Charge depleting
Charge sustaining

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INTRODUCTION

Introduction

EPRI has initiated a detailed test program to evaluate candidate batteries for use in Plug-in Hybrid Electric Vehicles (PHEVs). The performance and cycle life durability of advanced batteries are critical factors that affect all aspects of the design, operation, and economics of PHEVs.

To date, there is little specific information regarding the performance and durability of currently available production advanced chemistry Nickel Metal Hydride (NiMH) and Lithium Ion (Li Ion) batteries over a characteristic PHEV duty cycle. Obtaining this information is critical to both near-term programs like the EPRI/DaimlerChrysler PHEV Sprinter program and future efforts to develop PHEV technology.

EPRI has developed a comprehensive multi-phase plan to evaluate the capabilities of available production batteries when subjected to PHEV operation. The components of this plan are:

1. Develop battery test profiles that accurately represent the dynamic loads experienced by the battery in a PHEV.
2. Begin initial cycle-life and performance testing of suitable candidate batteries. The initial partner for this testing is Southern California Edison's (SCE) Electric Vehicle Technical Center.
3. Work with stakeholders, including battery companies, hybrid system and vehicle manufacturers, utilities, and government labs to develop industry-wide test procedures similar those existing for power assist hybrids and battery electric vehicles.
4. Initiate and conduct large-scale, long-term battery testing and national laboratories and utilities.
5. Analyze and report on battery test results, including technical recommendations for PHEV design and operation to maximize battery durability.

This report is an update on the second stage of this plan—initial battery testing at Southern California Edison.

Initial Battery Testing Phase

The focus of the initial battery testing phase is to generate cycle life and performance data that is beneficial to the understanding of PHEV battery testing in general, the performance of specific batteries in the PHEV Sprinter Van in particular.

Battery Test Site – Southern California Edison Electric Vehicle Technical Center

SCE was selected as the initial test site for this phase of the project. SCE personnel have extensive expertise in battery testing and the Electric Vehicle Technical Center in Pomona, California is equipped with state-of-the-art testing equipment and the necessary environmental chambers to run a carefully controlled test. EPRI and SCE have a longstanding relationship which will facilitate the necessary adjustments and modifications that are inevitably necessary when implementing a new test procedure.

It is important to note that full cycle-life tests of vehicle batteries are of long duration. The current schedule for the initial testing is shown in Appendix A. The project is currently set to end in January, 2007.

PHEV Battery Candidates

Initial testing is focused on the two battery technologies selected for the first prototype PHEV Sprinter vehicles. These two technologies are NiMH batteries from VARTA and Lithium Ion batteries from SAFT. The details of these two candidates are provided later in this chapter and listed in Table 1-5.

Plug-In HEV Sprinter Van Design and Specification

The DaimlerChrysler Sprinter Van is a multipurpose commercial van designed for a number of diverse tasks. The vehicle is available in numerous configurations including panel van (shown in Figure 1-1), passenger van, ambulance, work truck, and shuttle bus. The Sprinter is available in wheelbase lengths of 3.0 to 4.0 meters with gross vehicle weight (GVW) of up to 6.0 metric tons.

EPRI and DaimlerChrysler have developed a Plug-in Hybrid Electric Vehicle (PHEV) concept for the Sprinter in an effort to reduce the emissions, fuel consumption, and operating costs of the vehicle while maintaining equivalent or superior functionality and performance. EPRI and DaimlerChrysler have finalized a PHEV Sprinter configuration with the goal of achieving 20 miles (32 km) of operating range in its pure electric mode. The vehicle is also capable of extended operation between recharging by featuring a charge-sustaining hybrid operating mode with up to 50% higher fuel economy than the conventional Sprinter vehicle.

It is projected that the utilization of grid electricity combined with the improved efficiency will significantly reduce the greenhouse gas emissions and criteria pollutants produced by the vehicle, especially in dense urban areas. The primary objective of this project is to demonstrate the capability of the PHEV Sprinter concept to provide these environmental benefits while reducing lifecycle operating costs in a typical commercial setting.

Figure 1-1
DaimlerChrysler Sprinter Van

Hybrid Powertrain Design

The PHEV Sprinter concept is a parallel, pre-transmission hybrid configuration based upon current production Sprinter powertrain components. The powertrain layout is shown in Figures 1-2 and 1-3. The combustion engine output shaft (engine crankshaft) is connected to an integrated clutch and electric motor system. The automated clutch engages and disengages the engine as determined by the hybrid control strategy. When engaged, engine output power flows through the electric motor into the input shaft of a five-speed automatic transmission. The electric motor is capable of powering the vehicle in a pure electric mode, but is always active in hybrid mode to provide regenerative braking and power assist. A hybrid system controller schedules engine operation, motor torque, and transmission shifting to optimize performance and efficiency.

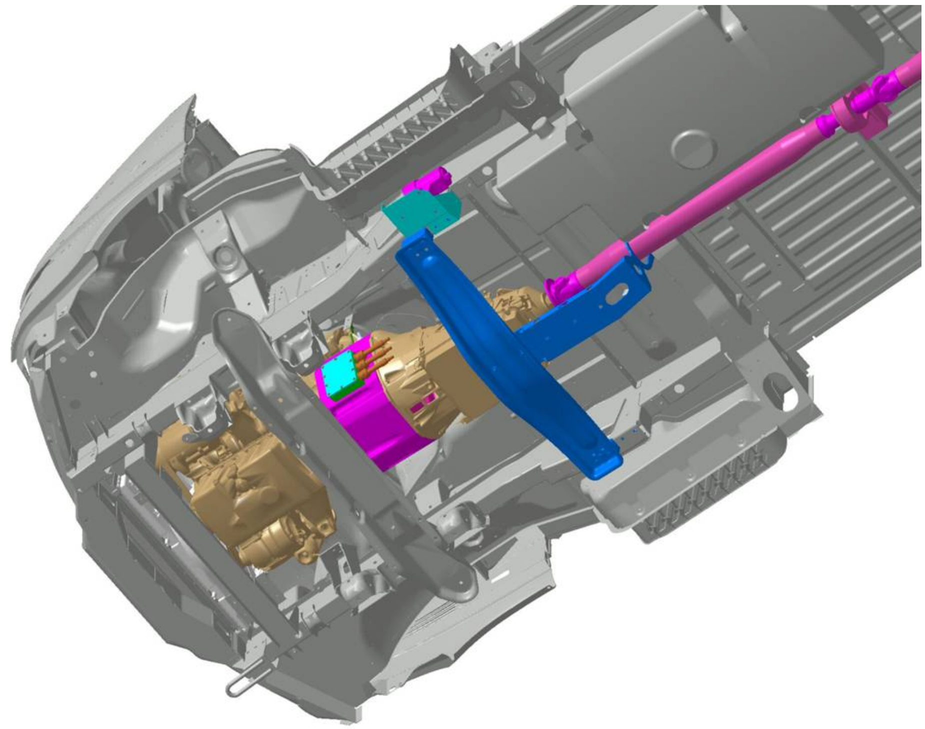

Figure 1-2
Underbody view of Sprinter Van with hybrid powertrain.

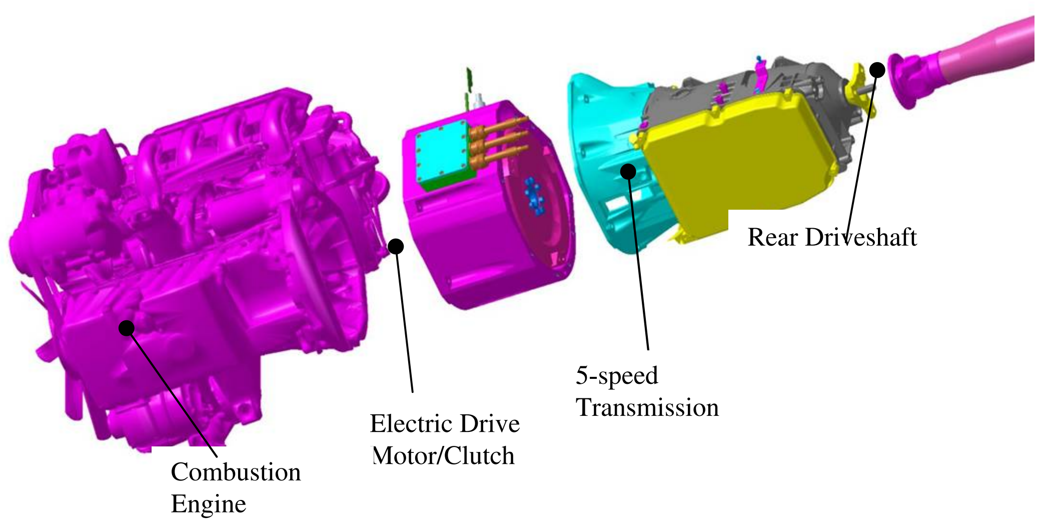

Figure 1-3
Close-up view of integrated parallel hybrid powertrain

Electric Drive Motor

The electric motor (Figures 1-4 and 1-5) is an advanced design from ZF Sachs developed specifically for this project. The electric drive motor is a permanent magnet, synchronous machine with peak design power of 98 kW. The motor is extremely compact, with a targeted motor length of a little as 100 mm. ZF Sachs uses an outer rotor with a high pole count to produce high torque and smooth operation.

The motor features an integrated automated clutch to control the operation of the combustion engine. This clutch can be opened to allow for operation in electric mode or closed to engage the engine for hybrid mode. During the proof-of-concept phase, a Mercedes-Benz automated clutch will be used for this powertrain.

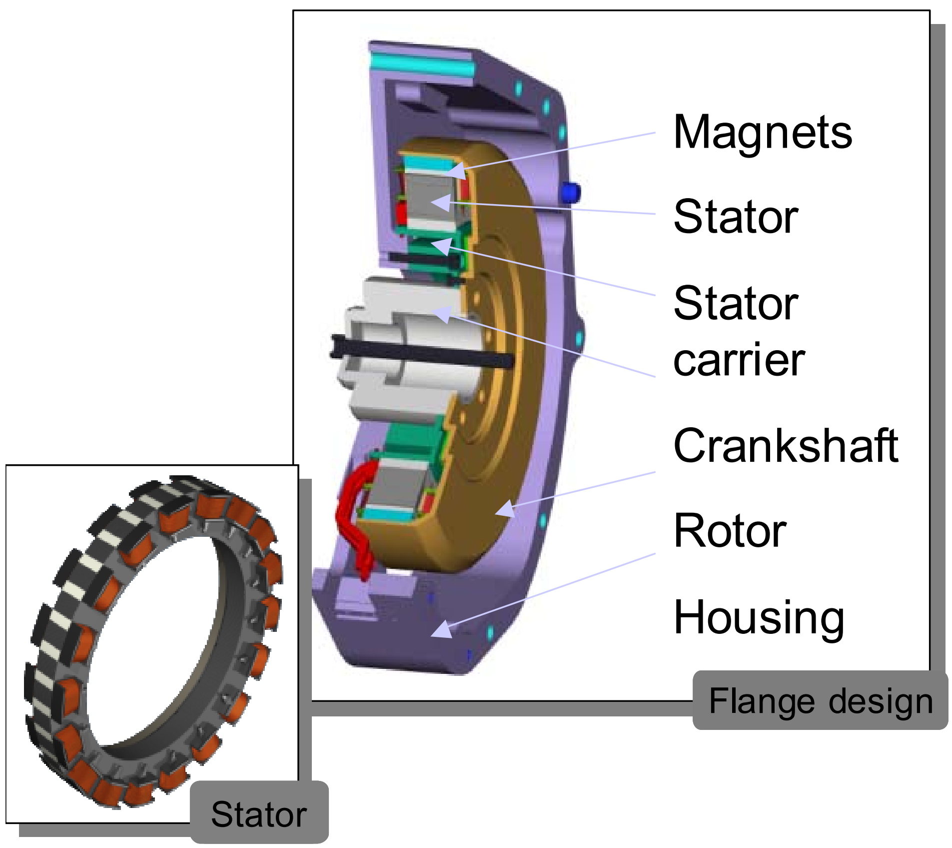

Figure 1-4
Outer rotor design of ZF Sachs synchronous machines with permanent magnet excitation.

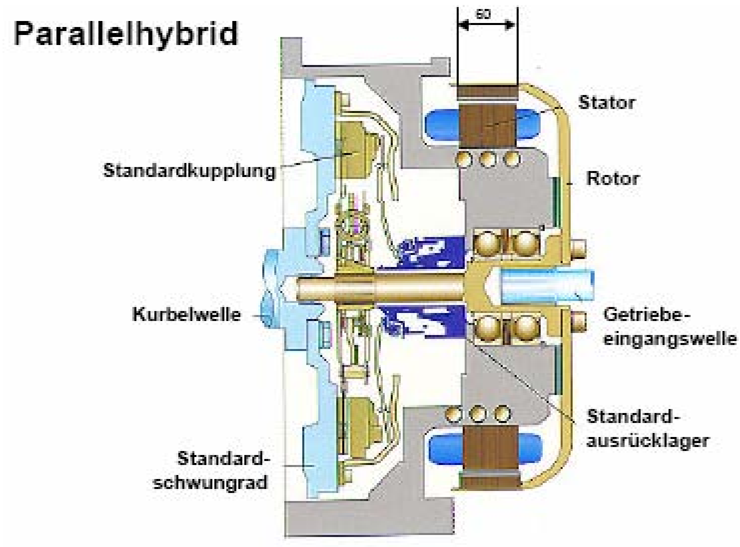

Figure 1-5
Alternate illustration of electric motor showing integrated clutch for combustion engine engagement and disengagement.

Energy Storage System

The first group of Sprinter PHEV prototypes will use two different advanced battery chemistries, Nickel Metal Hydride and Lithium Ion. In addition to the laboratory testing outlined in this document, both battery technologies will be evaluated as part of the Sprinter demonstration program.

Nickel Metal Hydride Battery System

The Sprinter concept uses an advanced Nickel Metal Hydride battery system from VARTA. The NiMH chemistry is currently the most durable and proven available for this project. The first 1-2 vehicles will use VARTA's modular battery design for ease of packaging and operation in the early POC vehicles. The modular design uses blocks of 36 cells[1] connected together in series to form the entire pack. The blocks are easily replaceable, and each has an independently controlled cooling fan.

The VARTA battery system for the Sprinter will consist of 280 cells (seven 40-cell blocks) at a nominal voltage of 336 volts. The pack energy capacity is 14.0 kWh using 40 amp-hour cells. Peak power is estimated at 70-80 kW. After the initial POC vehicle, VARTA and EPRI will work to develop an integrated packaging system and enclosure that will minimize pack mass and volume burden[2]. In addition, the current VARTA prototypes are metal-cased cells that will be replaced with plastic case, 4-cell monoblocks after the initial packs are delivered.

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[1] Each block is two modules from an electrical standpoint (measurement of voltage and temperature).

[2] Mass burden and volume burden are terms used to characterize the added mass and volume from battery enclosure hardware and structure.

Figure 1-6
VARTA 4-cell, plastic-case, 40 amp-hour NiMH module (below) and modular pack system (above) with eight 36-cell blocks.

VARTA NiMH batteries have been independently tested to 5000 deep cycles to 80% depth-of-discharge (DOD). VARTA has provided a warranty on the prototype cells for between 2000 to 4000 deep cycles, depending on operating temperature. VARTA provides an integrated battery monitoring system (BMS) that tracks pack health and provides instantaneous operating data (available energy and power, battery state-of-charge, etc) via CANbus to the hybrid controller.

Plug-in HEV Sprinter Specification

Vehicle and Powertrain Component Specifications

The following tables contain the vehicle and powertrain specifications for the first three to five Sprinter PHEV Proof-of-Concept vehicles. The specifications are the result of several months of collaborative design work between the project partners, including EPRI, DaimlerChrysler, and key suppliers ZF Sachs, VARTA, and SAFT.

Table 1-1
Vehicle Specifications for Sprinter Van

Base Vehicle	Dodge Sprinter 2500 Van
Wheelbase	3,550 mm[3]
Overall Length	5,640 mm
Overall Width	1,930 mm
Overall Height	2,360 mm
Interior Volume	10.4 m^3
Gross Vehicle Weight	3,880 kg
Payload (approximate)	1,500 kg
Seating	1 + 2 (one driver seat, two passenger seats)
Wheels	16 inch aluminum
Tires	P225/75 R16
Rear Axle Ratio	3.72:1
Air Conditioning	Yes
Seat Heating	Yes
Electric Windows	Yes
Remote Controlled Power Locks	Yes
Auxiliary Components – Power Steering	Electrically-Driven Hydraulic Power Assist
Auxiliary Components – Brake Assist	Electric Vacuum Pump
Auxiliary Components – Low-Voltage Power Supply	DC-DC voltage converter

[3] This specification is different for the Kansas City proof-of-concept vehicle. This vehicle will be a 4,000 mm wheelbase paratransit vehicle with a custom body. The dimensions of this vehicle will be determined by the bodybuilder. All other specifications, as well as the hybrid powertrain system, are the same.

Table 1-2
Internal Combustion Engine Specifications

Manufacturer		Mercedes-Benz	Mercedes-Benz
Engine Model		M111E	OM647DELA
Fuel Type		Gasoline	Diesel
Engine Type		Spark-Ignition	Compression-Ignition
No. of Cylinders		4/in-line	5/in-line
Bore	(mm)	90.9	88.0
Stroke	(mm)	88.4	88.3
Displacement	(cm^3)	2295	2686
No. of valves		4 per cylinder 2 intake/2 exhaust	4 per cylinder 2 intake/2 exhaust
Aspiration		Natural	VTG Turbocharger
Engine Management		Electronically-controlled fuel injection and ignition	Common Rail Direct Injection (CDI)
Output at	(kW/hp) (rpm)	105/143 5000	115/156 3800
Maximum Torque at	(Nm) (rpm)	215 3200-4700	330 1600-2400

Table 1-3
Transmission Specifications

Manufacturer	Mercedes-Benz
Type	Automatic
Transmission Model	NAG1
Number of Speeds	5
Shift Control	Electronically-Controlled Shifting
Gear Ratios	3.595, 2.186, 1.405, 1.000, 0.831
Final Drive Ratio	4.11:1

Table 1-4
Electric Drive Motor Specifications

Manufacturer		ZF Sachs
Type		3 Phase Synchronous Brushless Permanent Magnet
Continuous Power at	(kW) (rpm)	54 2500-5000
Peak power at	(kW) (rpm)	70 2500-5000
Torque at	(Nm) (rpm)	175 0-2500
Peak Torque at	(Nm) (rpm)	230 0-2500
Voltage Range	(VDC)	250-450
Cooling		Glycol/Water

Table 1-5
Battery System Specifications

Manufacturer		SAFT	VARTA Autobatterie GmbH
Battery Chemistry		Lithium Ion	Nickel Metal Hydride
No. of Cells		102	280
Nominal Voltage	(VDC)	367	336
Cell Capacity	(Ahrs)	41	40
Energy Capacity	(kWh)	15.1	14.0
Peak Power	(kW)	100	80
Package		6-cell module	40-cell block (2 modules)
Module Dimensions	(mm)	190x123x242	507x354x290
Total System Weight	(kg)	180	352
Cycle Life		3000 (80% DOD)	3000 (80% DOD at 35°C)
Cooling		Liquid	Air BMS-controlled individual electric fans
Battery Monitoring		SAFT BMC with voltage, current, and temperature sensing	VARTA BMS 5.P with voltage, current and temperature sensing
Charger		3.3 kW Conductive 208-240 VAC Input	3.3 kW Conductive 208-240 VAC Input

2
PLUG-IN HYBRID ELECTRIC VEHICLE BATTERY TEST PROCEDURE OVERVIEW

Introduction

This chapter is a summary of the analysis and development behind the test profiles and procedures used to test advanced batteries for PHEV operation. This work originated with the report, "Test Profile Development for the Evaluation of Battery Cycle Life for Plug-In Hybrid Electric Vehicles[4]."

Dynamic Vehicle Simulation

A dynamic simulation of the fuel economy, performance and control system of the PHEV Sprinter has been constructed to study the characteristics of the PHEV Sprinter. This simulation is constructed within the MATLAB/Simulink programming environment, and uses some components of the PNGV Systems Analysis Toolkit (PSAT)[5]. PSAT is a platform for the development and simulation of the vehicle system and can model system dynamics, control algorithms, vehicle energy consumption and component-level thermodynamics. The PSAT model of the PHEV Sprinter is being developed by EPRI in coordination with DaimlerChrysler corporate research and the DaimlerChrysler KEN division.

The simulation is made up of a network of components that interact with one another through exchanges of effort and flow and through analog and digital control signals. The battery system component is based on a linear internal resistance model that uses data provided by the battery manufacturer. Other components use proprietary DaimlerChrysler performance data and physical models of the component properties. As yet, the vehicle level accuracy of the model has not been rigorously validated, but the results qualitatively compare favorably to fuel economy data provided by DaimlerChrysler.

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[4] EPRI Product ID 1002228

[5] The development of the PNGV Systems Analysis Toolkit (PSAT) was initiated in 1995 by USCAR and contracted to Southwest Research Institute. Argonne National Laboratory redesigned the software in 1999, focusing on integrated analysis, hardware-in-the-loop, and validation activities. Based loosely upon the ADVISOR modeling format and Graphical User Interface (GUI), PSAT boasts such improvements as forward-looking modeling capabilities, greater detail in control systems, and greater flexibility for expansion through modularity. ANL has continuously updated and improved the model through current version 5.1, and the model architecture has been verified with real-world data from dynamometer testing of Toyota Prius and Honda Insight vehicles. See Hardy, K., Rousseau, A., PSAT, *Argonne's Vehicle System's Modeling Tool*, www.psat.anl.gov/pdfs/psat-review.pdf

The vehicle simulation uses the same modes of control and energy management as the PHEV Sprinter vehicle. Energy management control for the PHEV Sprinter simulation is divided into two modes of operation: Charge Depleting (CD) Mode and Charge Sustaining (CS) Mode. For the development of the battery test profile, it is assumed that CD mode is an electric only driving mode (ZEV mode).[6]

Battery Test Cycle Specification

Drive Cycle Specification

A portion of the INRETS URB1 vehicle test cycle (see Figure 2-1for its key characteristics) is used to define the battery power profile. The INRETS URB1 cycle is chosen because it represents "real-world" driving, being derived from measurements of the speed of actual vehicles engaged in urban driving.

The final 181.5 seconds of the INRETS URB1 drive cycle is used as the basis of the battery test cycle for both charge depleting and charge sustaining modes. The section of the INRETS URB1 cycle to be used is the period between 528.5 and 710 seconds, as shown in Figure 2-1 and Figure 2-2. This section of the drive cycle was chosen for four reasons:

1. The period of the section of the INRETS URB1cycle is 181.5 seconds. Southern California Edison EV Technical Center test engineers have suggested that the time period of the battery test cycle be around 200 seconds. A 181.5 second test period allows for repetition of the cycle roughly 27 times during the charge depleting section of the test profile. Division of the battery test profile into small segments causes less variation in the energy throughput from the battery under test in charge depletion mode.[7]

2. Peak accelerations and peak battery power demands are well distributed within the drive cycle sample. There are 3 events in the CD test cycle where the battery power demand is greater than or equal to 80% of the peak battery power demand. Again, distribution of the peak battery power demand events within the cycle causes less cycle-to-cycle variation in the battery testing.

3. The drive cycle includes stop/start sections at the beginning and end of the cycle, so repetition of the drive cycles does not cause a discontinuity in vehicle speed or battery power demand.

4. The energy consumption over this portion of the cycle is comparable to the vehicle energy consumption over the entire cycle, as shown in Table 2-1.

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[6] The ZEV capability of the production PHEV Sprinter is under continued review. The results of the PHEV Sprinter development may be a low-speed ZEV-capable vehicle instead of the high-speed ZEV-capable vehicle that is assumed for this analysis.

[7] See Appendix 1 for justification of this statement.

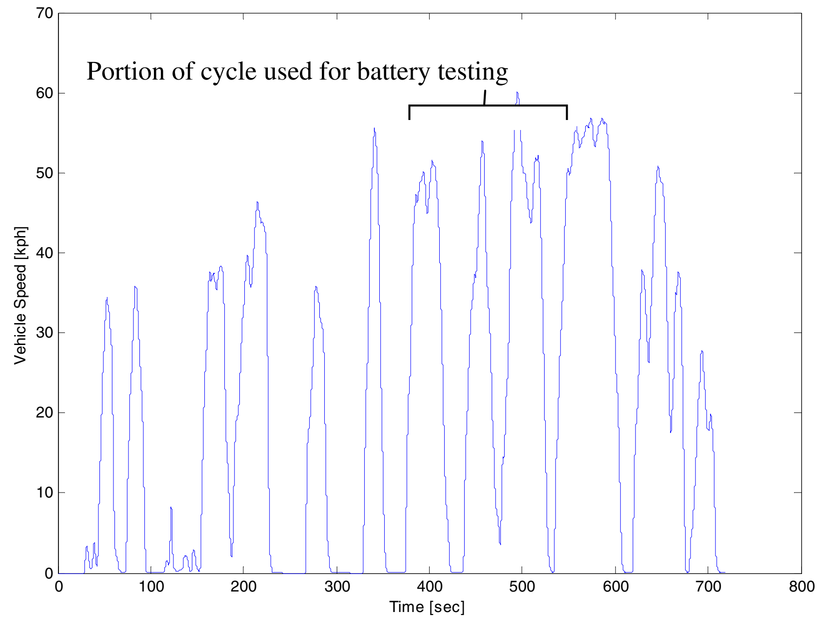

Figure 2-1
Full INRETS URB1 vehicle test cycle

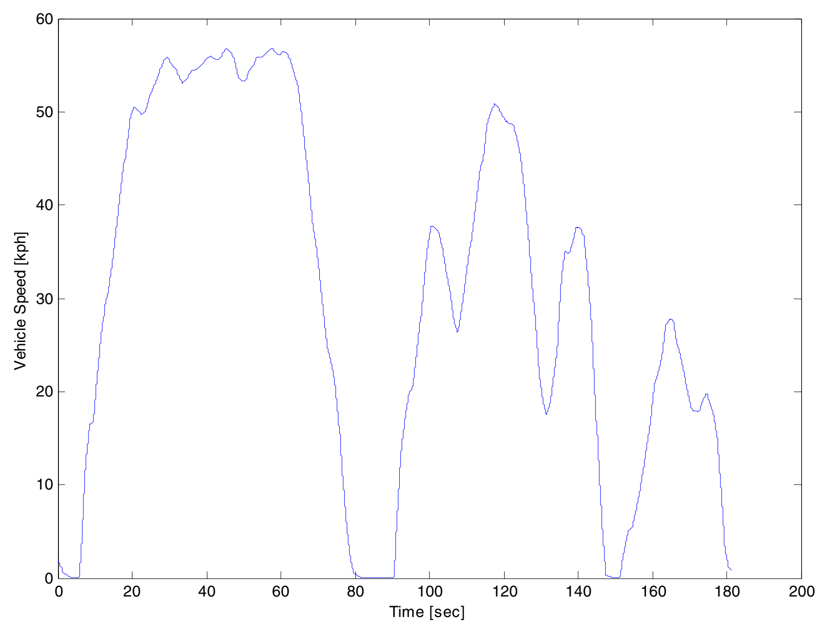

Figure 2-2
Sample of INRETS URB1 cycle used for battery testing

Table 2-1
Characteristics of INRETS URB1 and Sampled INRETS URB1 Drive Cycles

	INRETS URB1 Drive Cycle	Sampled Drive Cycle	Units
Length of Cycle	719	181.5	[sec]
Simulated Distance Traveled	4.19	1.54	[km]
ZEV Energy Consumption	311	279	[Wh/km]
ZEV Average Power Consumption	6.5	8.5	[kW]

Battery Test Cycle Specification

A profile of the battery power used by the vehicle can be derived by using this section of the INRETS URB1 drive cycle as an input to the dynamic vehicle simulation.[8] For the charge depleting battery mode test profile, the vehicle simulation is programmed to use only battery energy to drive the vehicle (ZEV mode). For the charge sustaining battery mode test profile, the vehicle simulation is programmed to maintain the battery SOC over the course of the battery test cycle. The output of the dynamic simulation is a trace of battery power demand as a function of time, sampled at 100 Hz.

SCE has suggested that an acceptable sampling period for input to the battery testing machinery is approximately 2 seconds. The simulation output must be filtered to meet the requirements of the battery testing machinery, while maintaining as many of the features of the original battery power demand as is possible. To maintain the relevant features of the PHEV battery power traces, the output data from the dynamic simulation is manually filtered, sampled at variable frequency and reconstituted with a zeroth order hold. Figure 2-3 shows a close-up view of a portion of the filtered and unfiltered battery test cycle. This figure shows that manual filtering of the battery power demand data can preserve the battery power transients due to vehicle acceleration/regen and engine on/off control, but cannot preserve the transients that are due to shifting (~5Hz) or PI speed controller dynamics (~1Hz).

The battery power demand is expressed in terms of battery pack output power for 280 NiMH cells or 102 Li Ion cells. Actual battery testing will most likely be done at the module level, so power demand levels must be adjusted accordingly.

[8] Although the test profile is derived from a dynamic simulation of the PHEV Sprinter using the Varta NiMH battery pack model, it is proposed that the battery power demand be used for testing of both the NiMH and Li Ion batteries.

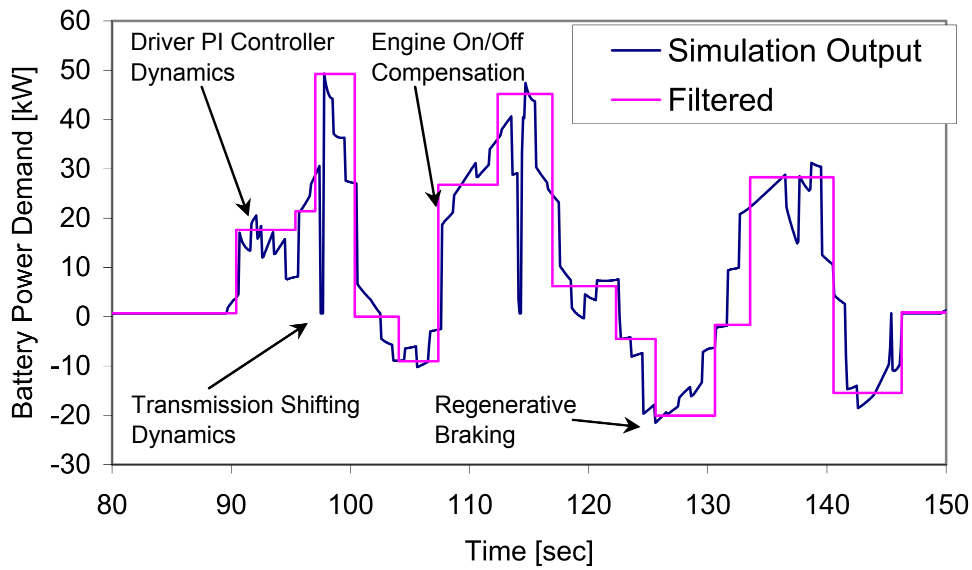

Figure 2-3
Enlargement of filtered and unfiltered battery test cycle

Comparisons of the battery power output from the simulation and the filtered, resampled battery test cycle are presented in Figure 2-4 and Figure 2-5. Figure 2-6 shows the histograms of the filtered battery test profile period. From the histograms and Table 2-2, it is clear that the sample period varies between 2 and 14 seconds and that there are roughly 50 samples for each battery test cycle. The filtered battery test cycles can now be implemented on SCE's test equipment.

Over the course of the charge sustaining cycle, the testing will either slightly charge or slightly discharge the battery, depending on inaccuracies in the modeling, changes in the internal resistance of the batteries, etc. The proposed charge-sustaining battery test cycle should serve as the basis of the actual battery test cycle, but may be adjusted to compensate for any charging or discharging that may occur during charge sustaining testing.

Charge Depletion/Charge Sustaining Mode Proportioning

The number of CD (ZEV) cycles is determined by the capacity of the battery under test and the fraction of battery capacity that is discharged per cycle. In the proposed test cycle, the initially fully charged battery is discharged until 20% SOC is reached. After reaching 20% SOC, the battery is operated in the charge sustaining battery test cycle.

In principle, the number of charge sustaining battery test cycles (that is, the length of the charge-sustaining time period) could be selected as desired. However, because that number will impact battery life, its selection as part of the test profile must be governed by the requirement that the profile represent battery operation in typical urban PHEV driving. Accordingly, it is proposed that the number of charge sustaining battery test cycles be determined by subtracting the mileage covered in the charge-depleting battery mode test cycle from the expected average daily mileage of a Sprinter van.

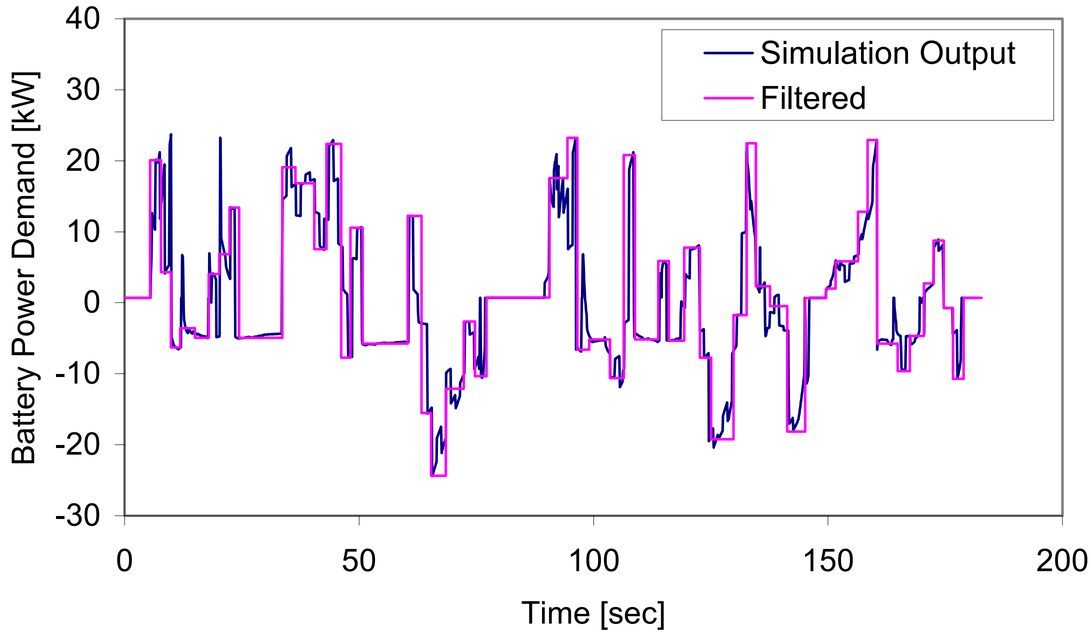

Figure 2-4
Charge-sustaining simulation output and filtered battery test cycle

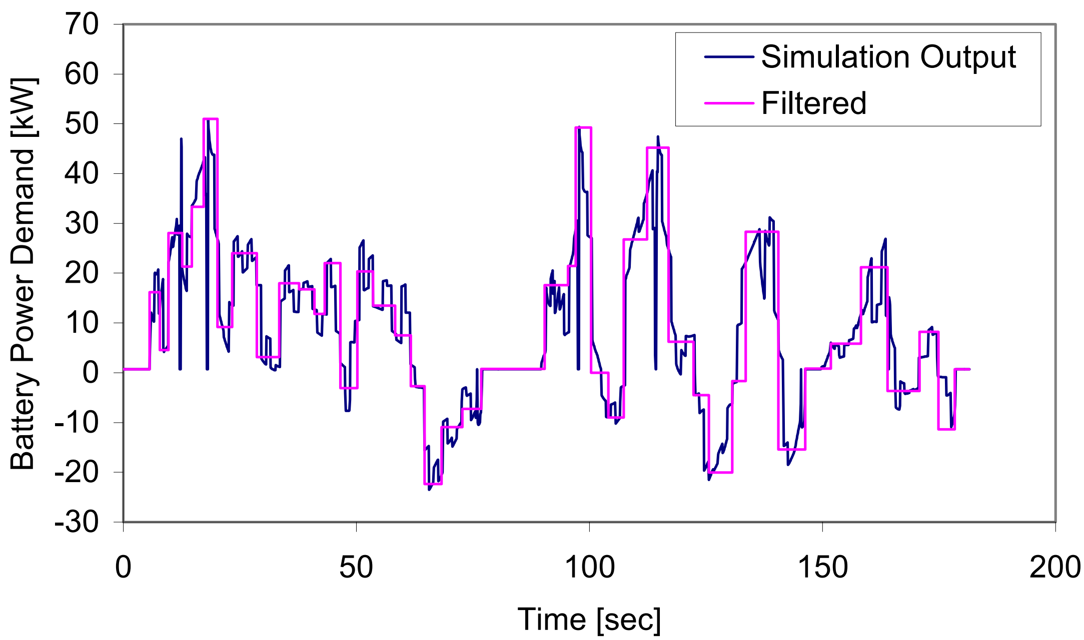

Figure 2-5
Charge-depleting simulation output and filtered battery test cycle

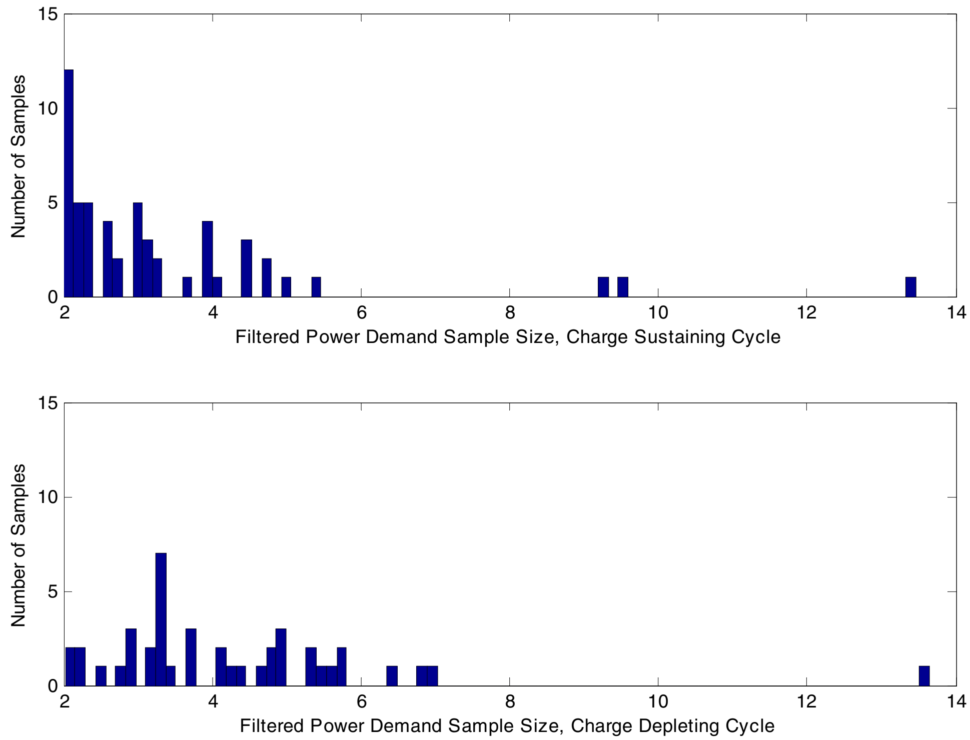

Figure 2-6
Histogram of sample size for filtered battery test cycle

We propose to select the number of charge sustaining battery test cycles such that the total battery charge profile yields a simulated mileage of 50 miles. About 2/3 (~68%) of all vans covered in the 1997 Vehicle Inventory and Use Survey drive less than 50 miles per day.[9] To reach a total of 50 miles per battery test cycle, the 24 charge depleting cycles are combined with 28 charge sustaining cycles for a total of 50 miles and 2.6 hours of urban driving.

Charging Profile

The charge sustaining mode battery cycle test is followed by the battery charging profile. The specification of the battery charging profile is guided by the requirement that the charging rate be as fast as possible while still being compatible with the battery supplier recommendations for maintaining battery life. The battery system should be charged as quickly as is feasible to reduce the charge/discharge cycle period and to increase the rate of battery cycling.

[9] 1997 Economic Census, Vehicle Inventory and Use Survey, p. 3, 63

Table 2-2
Additional information about sampled battery test cycles

	Charge Depleting (ZEV)	Charge Sustaining (CSHEV)	Units
Number of Samples	44	55	[-]
Number of Samples of less than 2 sec period	0	0	[-]
Smallest Sample Period	2.04	2.01	[sec]
Assumed Battery In/Out Energetic Efficiency	N/A	93.1%	[E_{out}/E_{in}]
Peak Output Power Filtered/Simulated	51.0/52.6	23.3/23.7	[kW]
Peak Regenerative Power Filtered/Simulated	-22.4/-23.5	-24.4/-24.4	[kW]

On the basis of the preliminary information provided by the battery manufacturers, the proposed charging recommendations are that the VARTA NiMH batteries (in pack form) be charged at a constant 5.28kW continuously until 100% SOC is reached. 5.28kW represents a 6.6kW charger operating at 80% efficiency. We propose that the Saft Li Ion batteries be charged using Saft's recommended charging algorithm. The peak charging power for this algorithm is 5.04kW. These proposed algorithms take 2.5hrs and 3.6hrs respectively for the NiMH and Li Ion packs. If battery charging algorithms exist that are of shorter duration, but are recommended by the battery manufacturer to not reduce battery life, those algorithms may be substituted for those proposed here.

Battery Test Profile Specification

The Battery Test Profile is constructed by assembling the charge-depleting battery test cycles, the charge-sustaining battery test profiles and the charging profile into a single discharge/charge cycle. The Battery Test Profile lasts 5.1 hours for the NiMH battery and 6.3 hours for the Li Ion battery, as shown in Table 2-3. With roughly an hour allowed for chemical and thermal stabilization of the battery, four battery charge/discharge cycles per day can be accomplished for the NiMH battery and more than 3 charge/discharge cycles per day for the Li Ion battery. Four test cycles per day for seven days per week is equivalent to PHEV battery operation for 73,000 vehicle-miles per year, or nearly 150,000 miles over the two-year lifetime of the project.

A plot of the composite battery test profile for the NiMH pack is presented in Figure 2-8. Red vertical lines mark the transition between charge-depleting, charge-sustaining, and charging regimes and the end of test condition.

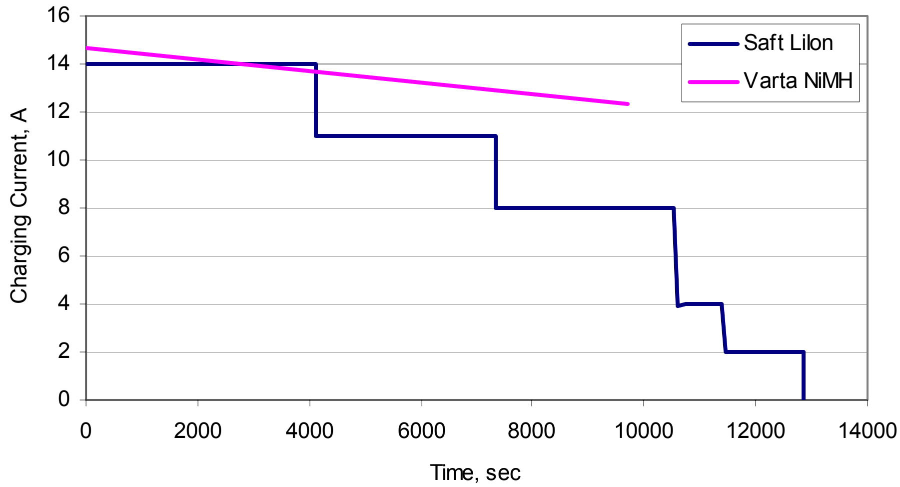

Figure 2-7
Proposed Charging Algorithms Varta NiMH Constant Power Charging and Saft Proprietary Charging Algorithm

Table 2-3
Summary of Key Battery Profile Characteristics

	NiMH Battery Test Profile	Li Ion Battery Test Profile	Units
Number of Cycles of CD Battery Test	25.1	25.1	[-]
Time of CD Batt. Test Cycling	1.3	1.3	[hrs]
Energy Consumed in CD Batt. Test Cycling	10.4	10.8	[kWh]
Number of Cycles of CS Batt. Test	27	27	[-]
Time of CS Batt. Test Cycling	1.4	1.4	[hrs]
Energy Consumed in CS Batt. Test Cycling	~0	~0	[kWh]
Charging Time	2.5	3.6	[hrs]
Total Batt. Test Profile Time	5.1	6.3	[hrs]

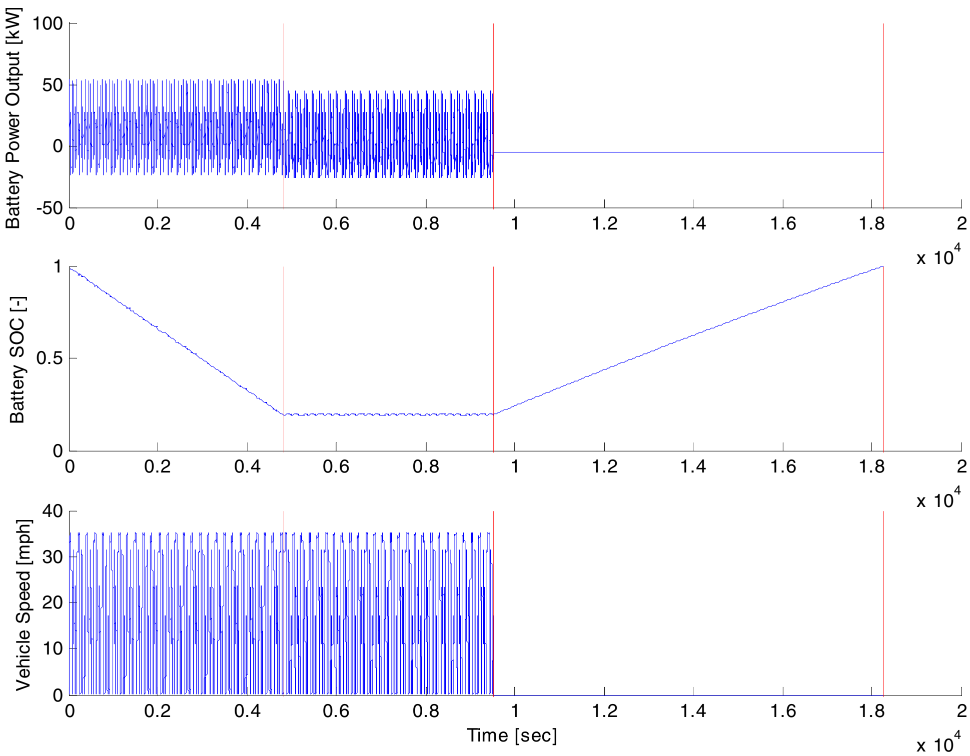

Figure 2-8
Composite Battery Charge/Discharge Profile for VARTA NiMH pack

Battery Characterization Tests

The battery will be subjected to a series of battery characterization tests to track the state of health of the battery as it ages. The following proposed characterization tests are to be performed 5 times per year:

- USABC Peak Power Test[10]
- Hybrid Pulse Power Characterization Test[11]

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[10] USABC Electric Vehicle Battery Test Procedures Manual, Rev. 2, p. 9.

[11] PNGV Battery Test Manual, Rev. 3, p. 4.

3 BATTERY TEST PROGRAM UPDATE

The testing of candidate batteries at SCE is in its early stages, and this report provides an update on current progress. Upcoming reports will further detail the results and performance of the batteries prior to the end of testing. The degradation of batteries in durability testing is progressive in nature, and these interim reports will provide important results on battery performance even prior to the end of testing.

Test Procedure Verification

SCE was tasked with the practical implementation of the test profile developed by EPRI. Test equipment limitations and other factors require careful calibration of the test profile to maintain consistent cycle-to-cycle discharging and charging of the batteries. SCE developed the following procedure for receiving and testing batteries:

1. Receive Batteries at SCE
   - Inspect battery
   - Obtain and verify required documentation
2. Test Setup
   - Install battery in test chamber
   - Connect Battery Management System (BMS) and check for proper communication
3. Hydraulic Setup (if required)
   - Connect hydraulic circuit and check for leaks
   - Verify proper flow rate
4. Safety Review
5. Preliminary Charge
   - Conduct a preliminary charge of the batteries
   - Check all data to confirm battery and charge algorithm proper operation
   - Conduct additional charge cycles until charge algorithm is validated
6. Preliminary Cycling
   - Conduct a preliminary charge
   - Conduct several discharges to a maximum of 80% DOD to validate test script

7. Preliminary Capacity Tests
   - Conduct two capacity tests to confirm battery name plate capacity
   - Conduct additional capacity test if test results are not consistent
8. Life Cycle Test
   - Conduct life cycle test for a duration of 20 months
   - Perform period RPT (approximately every 2 months)
     - C/1 Capacity Test
     - C/3 Capacity Test
     - Peak Power Test (USABC Manual)
     - HPPC Test (PNGV Manual – dual mode test)
9. Dismantle Test Setup
   - Disconnect electrical and hydraulic connection to battery modules
   - Ship battery to manufacturer for post-mortem analysis

Calibration and Verification of Procedures

SCE completed calibration and verification of the test procedure algorithms in the last quarter of 2004. Each battery manufacturer provides a Battery Management System (BMS) with its battery to perform system monitoring, charge control, and other necessary functions. The industry-wide communication standard is CAN (Controller Area Network). SCE added CAN functionality to its test bench for this project and developed the necessary software drivers to properly communicate with each battery and its BMS.

Status Report on Each Candidate Battery

VARTA DPN1 Nickel Metal Hydride Battery

SCE received a single VARTA DPN1 40-cell battery module and BMS. SCE installed the battery in the test cell, established communication with the BMS and commenced testing. Initial performance tests for peak power (Table 3-1) and capacity (Table 3-2) show that the battery meets advertised specifications for power and energy content. These performance tests will be repeated at defined intervals and are important metrics of battery health. Important milestones for battery degradation are often regard to be at both 90% and then 80% of initial power and energy, although the battery may still function reliably in any particular application.

Table 3-1
VARTA DPN1 NiMH Battery Peak Power Test

DOD (%) \ Cycle #	4
0	11.410
10	11.077
20	10.968
30	10.930
40	10.844
50	10.667
60	10.469
70	10.182
80	9.466

Table 3-2
VARTA DPN1 NiMH Battery Capacity Test

Cycle #		4
C/ 1 Capacity Test	Ah Out (Ah)	39.38
	kWh Out (kWh)	1.91
	Start Temperature (°C)	30.00
	End Temperature (°C)	30.00
	Min. Pack Voltage (V)	0.97
	Max. Delta Voltage (V)	0.07
C/ 3 Capacity Test	Ah Out (Ah)	41.09
	kWh Out (kWh)	2.06
	Start Temperature (°C)	29.00
	End Temperature (°C)	26.00
	Min. Pack Voltage (V)	0.97
	Max. Delta Voltage (V)	0.06

SCE commenced long-term cycling of the VARTA battery on December 23rd, 2004. On January 11th, 2005, after 61 cycles, testing was halted due to the apparent failure of one or more cells within the module.

VARTA made a subsequent recommendation to replace the battery with a new module. VARTA had made an expected upgrade to their NiMH technology, replacing the single, metal-case 40 Ahr cell design with a four-cell plastic monoblocks. In addition, a number of necessary calibrations to the charge and discharge algorithms were made during the initial tests, therefore SCE and EPRI determined that the best way to proceed was to restart a fresh test with a new battery.

SAFT VL 41 M Lithium Ion Battery

SCE received three six-cell SAFT lithium ion battery modules in late 2004. Unlike a typical NiMH BMS, lithium ion batteries must be rigorously managed by a control system. Safety requirement dictate extensive procedures for the cell-level charge management and protection from overcharge or overdischarge. Achieving a proper communication exchange with the SAFT BMS was a time consuming but necessary step prior to any testing. In addition, SCE designed and installed a temperature-controlled hydraulic cooling system for these liquid-cooled batteries.

As of the publication of this report, the initial testing of the lithium ion test pack was just getting underway. Initial results are not yet available, but the test is expected to be well underway during the next update in approximately six months.

Summary and Next Steps

The initial phase of battery testing is in the earliest stages. Configuring the testing equipment to communicate properly with the BMS of each battery was a time consuming but necessary task. The test procedure has performed well in its early stages. The early cell failure of the VARTA DPN1 battery was disappointing, but it was quickly replaced with the newest DPN2 design from VARTA and the test restarted. The actual amount of test time lost due to this failure is small, and this initial test of the DPN1 provided for a valuable opportunity to refine the test procedure and then restart the long-term test with a fresh battery that represents the latest design from VARTA.

The SAFT battery required extensive work to effectively communicate with its sophisticated BMS. Now that this capability has been developed, future tests, both at SCE and at other sites can progress more quickly.

The important achievement of this stage was the implementation and verification of the test profile developed by EPRI for the PHEV Sprinter. The process established to use dynamic vehicle simulations to develop a battery load profile and then manage this profile in a test cell is easily transferable to future test procedures.

A technical update of the battery test progress and the ongoing performance of the VARTA NiMH and SAFT Li Ion test batteries will be published in the fourth quarter of 2005.

A

BATTERY TEST SCHEDULE

ID	Task Name
1	*Project Start*
2	*Test completion*
3	*Battery Reception (Technology 1 - NiMH)*
4	*Battery Reception (Technology 2 - Li-Ion)*
5	**Algorithm Design & Validation**
6	Preliminary algo. design & testing
7	Setup algo. test pack (Panasonic NiMH)
8	**Battery testing**
9	RPT
10	Life cycle test for 2 weeks
11	Algorithm final revision & validation
12	**Technology 1 (VARTA NiMH) - Life Cycle Test**
13	Battery installation
14	BMS Communication setup
15	Proper operation verification
16	Test algorithm setup
17	Test algorithm validation
18	*Llife cycle testing on original battery*
19	Battery replacement
20	**Battery testing**
21	Preliminary RPT
22	Life cycle test for 20 months
23	Periodic RPT
24	**Technology 2 (SAFT Li-Ion) - Life Cycle Test**
25	Battery installation
26	Water cooling setup
27	Proper operation verification
28	Test algorithm setup
29	Test algorithm validation
30	**Battery testing**
31	Preliminary RPT
32	Life cycle test for 20 months
33	Periodic RPT
34	**Data Analysis & Reporting**
35	Status Report 1
36	Status Report 2
37	Status Report 3
38	Status Report 4
39	Status Report 5
40	Final Report
41	**Project Review Meetings**
42	Preliminary Review Meeting
43	Review Meeting 1
44	Review Meeting 2
45	Review Meeting 3
46	Review Meeting 4
47	Review Meeting 5
48	Final Review Meeting

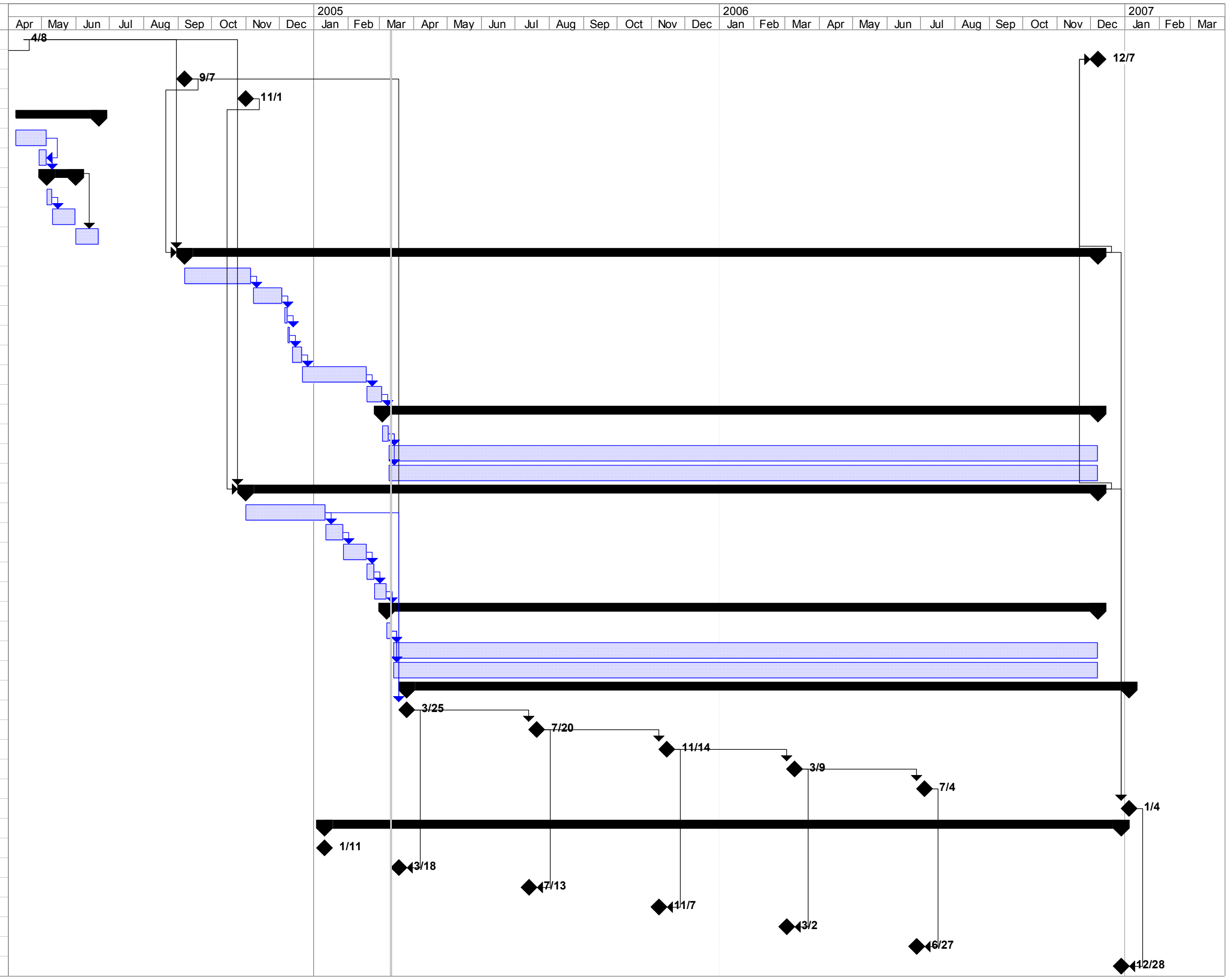

Figure A-1
Battery test schedule at Southern California Edison Electric Vehicle Technical Center

B
NOMENCLATURE

Vehicle Test Cycle – The vehicle test cycle is a profile of vehicle speed as a function of time. The vehicle test cycle used for this analysis is the INRETS URB1.

Battery Test Cycle – The battery test cycle is the smallest section of data that represents battery power demand as a function of time. The period of the battery test cycle is roughly 200 seconds. The battery test cycle is derived from a dynamic simulation of the vehicle following a section of the INRETS URB1 vehicle test cycle. There is a battery test cycle for CD Mode and for CS Mode

Battery Test Profile – The battery test profile is a concatenation of the battery power demands from the CD Mode, the CS Mode, the charging mode and the rest period. The Battery Test Profile is the largest unit of repeating battery power demand. One cycle of the Battery Test Profile represents one daily charge discharge cycle of the PHEV Sprinter battery system.

C
PHEV SPRINTER BATTERY TEST CYCLE DATA FILE

Table C-1
Test Cycle Data for Sprinter Battery Test Profile

Charge Sustaining				Charge Depleting			
Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)
0.00	0.70	103.50	-5.15	0.00	0.70	107.37	-9.02
5.44	0.70	103.50	-10.63	5.62	0.70	107.37	26.77
5.44	20.08	106.45	-10.63	5.62	16.19	112.35	26.77
7.80	20.08	106.45	20.81	7.83	16.19	112.35	45.20
7.80	4.30	108.85	20.81	7.83	4.54	116.96	45.20
9.86	4.30	108.85	-5.15	9.88	4.54	116.96	6.20
9.86	-6.27	113.82	-5.15	9.88	28.08	122.30	6.20
11.89	-6.27	113.82	5.88	12.63	28.08	122.30	-4.50
11.89	-3.57	116.04	5.88	12.63	21.30	125.62	-4.50
15.02	-3.57	116.04	-5.35	14.70	21.30	125.62	-20.07
15.02	-4.95	119.35	-5.35	14.70	33.31	130.60	-20.07
17.97	-4.95	119.35	7.79	17.24	33.31	130.60	-1.64
17.97	4.03	122.67	7.79	17.24	51.00	133.55	-1.64
20.18	4.03	122.67	-7.73	20.18	51.00	133.55	28.32
20.18	6.80	125.07	-7.73	20.18	9.17	140.55	28.32
22.38	6.80	125.07	-19.22	23.32	9.17	140.55	-15.44
22.38	13.41	129.86	-19.22	23.32	24.04	146.27	-15.44
24.42	13.41	129.86	-1.72	28.66	24.04	146.27	0.85
24.42	-4.95	132.63	-1.72	28.66	3.11	151.80	0.85

Table C-1 (continued)
Test Cycle Data for Sprinter Battery Test Profile

Charge Sustaining				Charge Depleting			
Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)
33.64	-4.95	132.63	22.46	33.46	3.11	151.80	5.85
33.64	19.09	134.65	22.46	33.46	17.97	158.25	5.85
36.41	19.09	134.65	2.31	37.70	17.97	158.25	21.18
36.41	16.84	137.60	2.31	37.70	16.78	163.96	21.18
40.46	16.84	137.60	-0.46	41.01	16.78	163.96	-3.67
40.46	7.53	141.29	-0.46	41.01	11.79	170.78	-3.67
43.04	7.53	141.29	-18.16	43.23	11.79	170.78	8.22
43.04	22.39	145.16	-18.16	43.23	22.01	174.84	8.22
46.18	22.39	145.16	0.66	46.54	22.01	174.84	-11.39
46.18	-7.73	149.59	0.66	46.54	-3.07	178.34	-11.39
48.20	-7.73	149.59	1.98	50.23	-3.07	178.34	0.70
48.20	10.57	151.61	1.98	50.23	20.35	181.50	0.70
50.78	10.57	151.61	5.81	53.55	20.35		
50.78	-5.75	156.41	5.81	53.55	13.45		
60.37	-5.75	156.41	12.81	58.34	13.45		
60.37	12.22	158.43	12.81	58.34	7.51		
63.32	12.22	158.43	22.92	61.66	7.51		
63.32	-15.52	160.46	22.92	61.66	-2.71		
65.35	-15.52	160.46	-5.75	64.61	-2.71		
65.35	-24.37	164.88	-5.75	64.61	-22.36		
68.48	-24.37	164.88	-9.64	68.29	-22.36		
68.48	-12.09	167.47	-9.64	68.29	-10.92		
72.35	-12.09	167.47	-4.69	72.72	-10.92		
72.35	-2.64	170.48	-4.69	72.72	-7.23		
74.75	-2.64	170.48	2.71	76.77	-7.23		

Table C-1 (continued)
Test Cycle Data for Sprinter Battery Test Profile

Charge Sustaining				Charge Depleting			
Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)	Time (sec)	Battery Power (kW)
74.75	-10.37	172.50	2.71	76.77	0.73		
77.14	-10.37	172.50	8.78	90.41	0.73		
77.14	0.73	174.65	8.78	90.41	17.62		
90.60	0.73	174.65	-0.73	95.39	17.62		
90.60	17.57	176.68	-0.73	95.39	21.42		
94.47	17.57	176.68	-10.70	97.45	21.42		
94.47	23.25	178.89	-10.70	97.45	49.24		
96.53	23.25	178.89	0.70	100.37	49.24		
96.53	-6.61	181.50	0.70	100.37	0.02		
99.08	-6.61			104.06	0.02		
99.08	-5.15			104.06	-9.02		

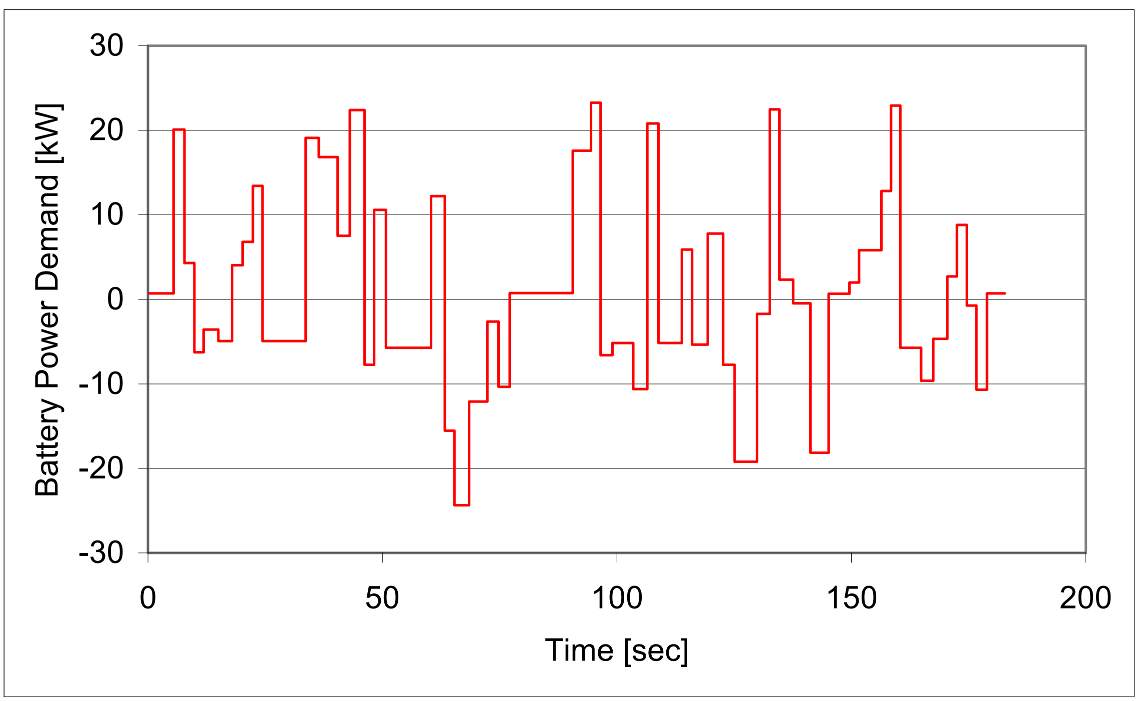

Figure C-1
Charge Sustaining PHEV Battery Testing Cycle

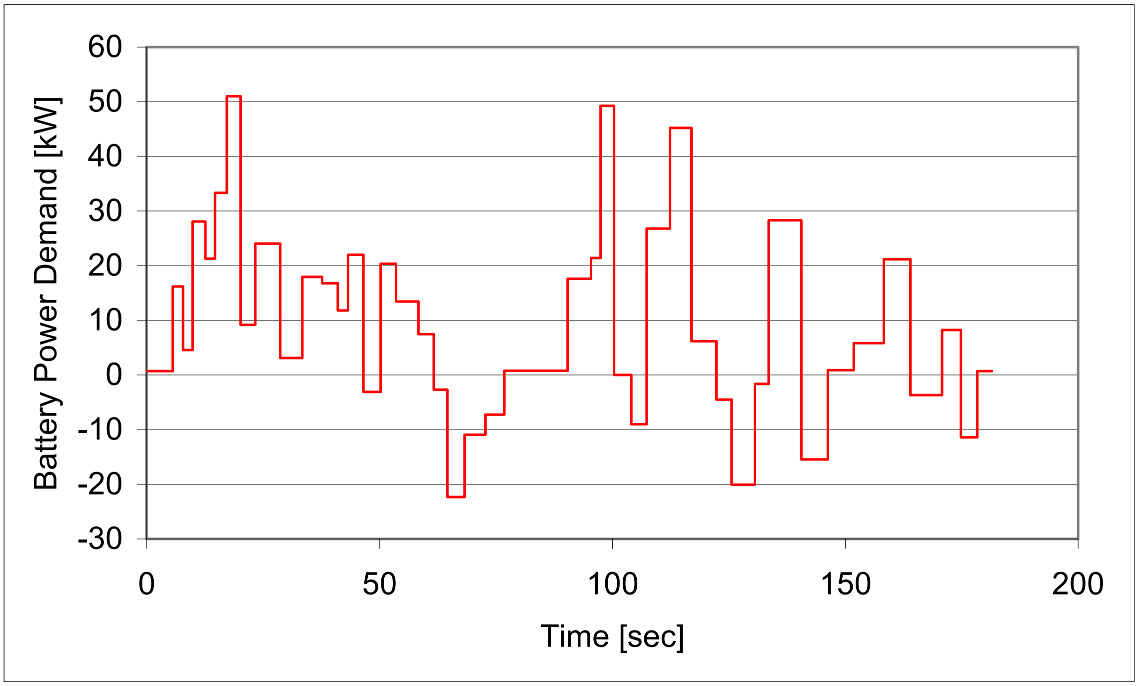

Figure C-2
Charge Depleting PHEV Battery Testing Cycle

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The Electric Power Research Institute (EPRI), with major locations in Palo Alto, CA, and Charlotte, NC, was established in 1973 as an independent, non-profit center for public interest energy and environmental research. EPRI brings together member organizations, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of power generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents over 10% of EPRI's total R&D program.

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