Development of Production-Intent Plug-In Hybrid Vehicle Using Advanced Lithium-Ion Battery Packs with Deployment to a Demonstration Fleet

DE-FC26-08NT04386

Final Technical Report

General Motors LLC (GM)

September 30, 2008 – September 30, 2013

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Project End Date: *9/30/13*

EXECUTIVE SUMMARY

The primary goal of this project was to speed the development of one of the first commercially available, OEM-produced plug-in hybrid electric vehicles (PHEV). The performance of the PHEV was expected to double the fuel economy of the conventional hybrid version. This vehicle program incorporated a number of advanced technologies, including advanced lithium-ion battery packs and an E85-capable flex-fuel engine. The project developed, fully integrated, and validated plug-in specific systems and controls by using GM's Global Vehicle Development Process (GVDP) for production vehicles. Engineering Development related activities included the build of mule vehicles and integration vehicles for Phases I & II of the project. Performance data for these vehicles was shared with the U.S. Department of Energy (DOE). The deployment of many of these vehicles was restricted to internal use at GM sites or restricted to assigned GM drivers. Phase III of the project captured the first half or Alpha phase of the Engineering tasks for the development of a new thermal management design for a second generation battery module. The project spanned five years. It included six on-site technical reviews with representatives from the DOE. One unique aspect of the GM/DOE collaborative project was the involvement of the DOE throughout the OEM vehicle development process. The DOE gained an understanding of how an OEM develops vehicle efficiency and FE performance, while balancing many other vehicle performance attributes to provide customers well balanced and fuel efficient vehicles that are exciting to drive. Many vehicle content and performance trade-offs were encountered throughout the vehicle development process to achieve product cost and performance targets for both the OEM and end customer. The project team completed two sets of PHEV development vehicles with fully integrated PHEV systems. Over 50 development vehicles were built and operated for over 180,000 development miles. The team also completed four GM engineering development Buy-Off rides/milestones. The project included numerous engineering vehicle and systems development trips including extreme hot, cold and altitude exposure. The final fuel economy performance demonstrated met the objectives of the PHEV collaborative GM/DOE project. Charge depletion fuel economy of twice that of the non-PHEV model was demonstrated. The project team also designed, developed and tested a high voltage battery module concept that appears to be feasible from a manufacturability, cost and performance standpoint. The project provided important product development and knowledge as well as technological learnings and advancements that include multiple U.S. patent applications.

Project Details

Phase I – Engineering Development of Year 1 Mule Vehicles

Phase I of the project captured the first half of the Engineering tasks for the development of key plug-in technologies. Engineering Development is a structured process for meeting requirements by selecting, modifying, and optimizing through analyses, demonstrations, inspections, and/or tests. A key feature of GM's Global Vehicle Development Process (GVDP) is the coordinated Engineering release of specific parts of the vehicle to allow for the proper integration of those parts. At each release, math models virtually integrate and analyze the assembly for compliance to requirements. In addition to several stages of virtual analyses, two different physical builds also supported Engineering Development. Phase I of the project used the first physical build to produce mule vehicles using early "beta" hardware, which represented design-intent parts.

During this phase, a battery technology Center of Excellence was established at the University of Michigan (UMICH), with assistance from the Michigan Economic Development Corporation (MEDC), in order to speed advances in battery technologies. The learning from this center was injected into GM's ongoing PHEV research and development.

Phase II – Engineering Development of Year 2 Integration Vehicles

Phase II of the project captured the second half of the Engineering tasks for the development of key plug-in technologies. A key feature of GVDP is the coordinated Engineering release of specific parts of the vehicle to allow for the proper integration of those parts. At each release, math models virtually integrated and analyzed the assembly for compliance to requirements. In addition to several stages of virtual analyses, two different physical builds also supported Engineering Development. Phase II of the project used the second physical build to produce 29 integration vehicles using "gamma" hardware, which represented design-intent and process-intent parts. These integration vehicles served as Engineering Development vehicles as well as the Phase II demonstration fleet under the project.

Phase III – Battery Thermal Development of Alpha Module

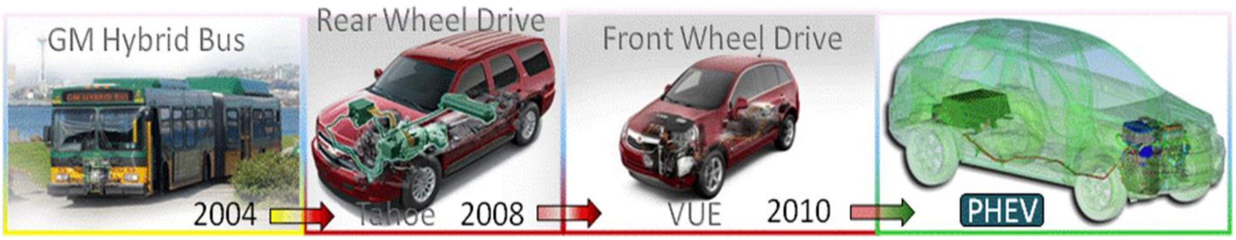
Phase III of the project captured the first half or Alpha phase of the Engineering tasks for the development of a new thermal management design for a second generation battery module. The new thermal management design for the battery module is targeted for introduction with GM's second generation battery. This new design will incorporate reduced complexity that will permit a more cost efficient design. Thermal management of batteries is essential to performance. Effective thermal management ensures the maintenance of proper operating temperatures thus increasing range, reliability and durability. GM conducted a demonstration of the module capabilities in the presence of DOE personnel at a GM facility during Phase III.

Scope of Work

Phase I & II – Engineering Development of Year 1 Mule Vehicles & Year 2 Integration Vehicles

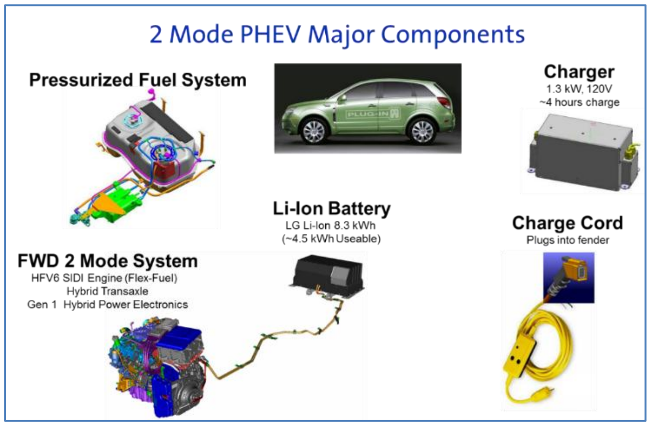
A Plug-In Hybrid Electric Vehicle (PHEV) is a vehicle which includes a blended gas and electric drive propulsion system. The primary focus of a PHEV is to focus on petroleum displacement compared to a non-electrified hybrid vehicle and NOT necessarily maximizing EV range. In other words, great fuel economy, not EV only driving. EV only driving requires many vehicle attributes and systems working together including a large energy/power battery. However, vehicle architecture and size constraints limit how large of a battery can be engineered into a given vehicle design.

GM's approach for this project was to build upon the success of the GM 2-mode strong hybrid family launched in the 2008 Chevy Tahoe and GMC Yukon RWD programs and the production-ready 2010 Saturn VUE 2-Mode hybrid.

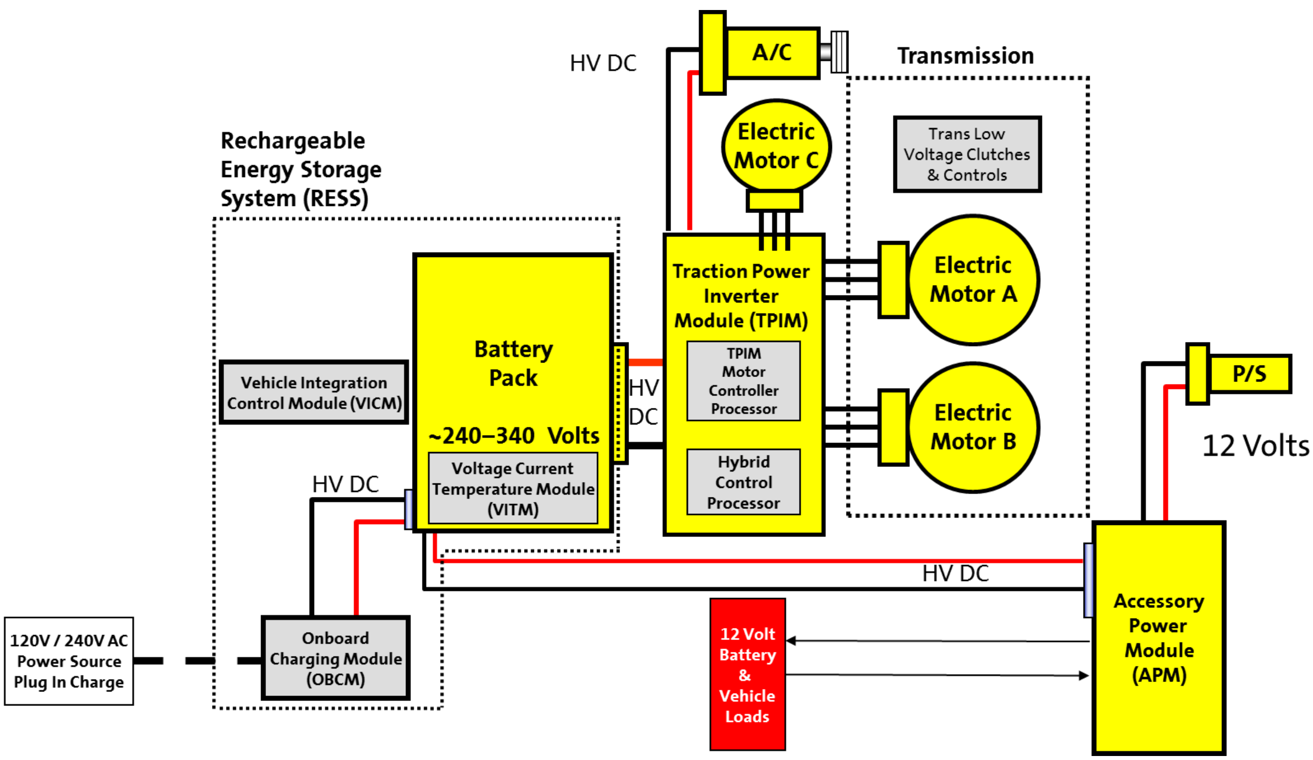


GM's PHEV application is an extension of the 2-mode hybrid charge sustaining technology consisting of:

- Two electric motors/generator for traction and regenerative braking
- Two fixed mechanical gears for performance and fuel economy
- Replaced nickel metal hydride power battery pack with lithium-ion energy battery pack
- Addition of a plug-in charge receptacle and cord-set along with an on-board charger
- PHEV vehicle & propulsion controls operating real-time and optimized for fuel economy
- PHEV specific ancillary vehicle systems engineered to support the new vehicle duty cycle and extended engine-off operation demanded by charge depletion vehicle operation
    - This included a pressurized fuel storage system, electric thermal pumps, electric AC/heating systems and enhanced battery thermal managements systems



PHEV System Overview



The achievement of fuel economy targets was the fundamental objective for this project. The ultimate goal was to achieve double the charge depletion fuel economy of the 2 mode hybrid. Highway FE performance was not the primary objective but GM targeted an improvement here as well. Determining charge depletion FE targets and assessing FE label performance was difficult at the time due to emerging fuel economy label definition and unknown customer expectations for blended PHEVs.

Vehicle Model Progression

The PHEV Vehicle Development team transitioned to a new compact cross-over architecture due to shifts in perceived market position needs as the project progressed. The revised architecture incorporated both current hybrid designs and enhanced hybrid components and systems. To confirm that overall vehicle performance targets were achievable, a virtual analysis was completed to ensure satisfaction of the engineering requirements. The design and engineering of the Year 1 Mule vehicles was completed and the team initiated additional vehicle builds. Production program approval was received and overall program timing for the revised architecture was established.

Project Summary

The project team developed and demonstrated production capable PHEVs. These PHEVs demonstrated incorporated advanced lithium-ion batteries and e85 capable flex fuel engines. The project team also focused on the development, integration and validation of new plug-in specific systems and controls using the GM vehicle development process. New plug-in vehicle enabling systems developed under the project included a charge depletion fuel economy operation and controls strategy, the use of lithium-ion batteries including the hardware and attendant controls system, a plug-in charging system, and vehicle and powertrain controls system integration.

- **Timeline:**
    - September 30, 2008 – September 30, 2013

- **DOE Interaction and Monitoring**
    - 6 technical on-site reviews with GM & the DoE including coincident vehicle demonstrations
    - Vehicle data summaries from engineering development fleet including detailed lithium-ion battery scorecard data from GM to the DoE
    - Fuel economy collaboration and testing at Argonne National Laboratories using OEM PHEV
    - One unique aspect of the GM/DOE collaborative project was the involvement of the DOE throughout the OEM vehicle development process. The DOE gained an understanding of how an OEM develops vehicle efficiency and FE performance, while balancing many other vehicle performance attributes to provide customers well balanced and fuel efficient vehicles that are exciting to drive. Many vehicle content and performance trade-offs are encountered throughout the vehicle development process to achieve product cost and performance targets for both the OEM and end customer
    - **The final fuel economy performance demonstrated met the objectives of the PHEV collaborative GM/DoE project. Charge depletion fuel economy of twice that of the non-PHEV model was demonstrated**

- **Completed Builds**
    - **Two physical builds completed of PHEV development vehicles with fully integrated PHEV systems**
        - **Over 50 development vehicles were built and operated for over 180,000 development miles.**
    - **The team also completed four GM engineering development Buy-Off rides/milestones**
    - Numerous engineering vehicle and systems development trips were completed including extreme hot, cold and altitude exposure

- **Final Result**
    - The final fuel economy performance demonstrated met the objectives of the PHEV collaborative GM/DOE project. Charge depletion fuel economy of twice that of the non-PHEV model was demonstrated

Phase III – Battery Thermal Development of Alpha Module

Objective

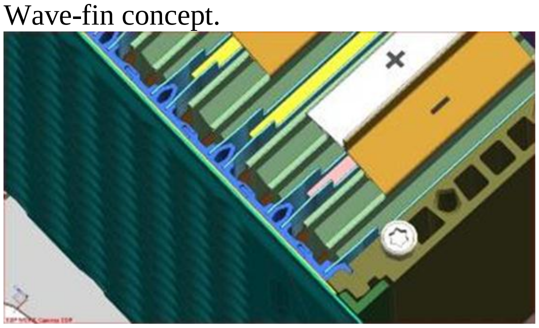
The mission for this portion of the project was to engineer, develop prototype properties and prove a solid fin concept design while ensuring the design can be packaged and manufactured at the lowest possible cost and mass.

Background

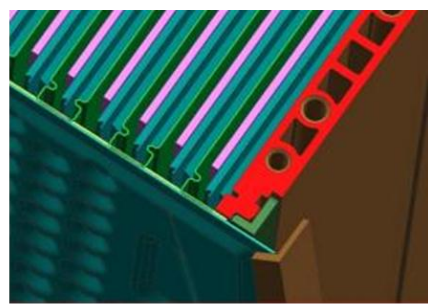
To enable lower cost GM decided to leverage solid fin heat exchange design (as opposed to "liquid" fins where coolant flows within the fins). This would allow for a simpler design execution with less number of seals required. However the cooling efficiency would not be as good as the liquid fins.

Within GM there were a couple of concepts already developed:

1. Work Package E
2. Wave-fin concept.



Work Package E



Wave-fin

Design Imperatives

The following imperatives were targeted at the project initiation stage.
The module design should be:

- Allow for packaging within pack (with all hosing) and with necessary clearances to the cover
- Meet test plan requirements (structural, thermal, safety etc.)
- Achieve significant cost reduction
- Reduce mass by 10% (Baseline EREV Gen 1)
- Allow for the manufacture of 100,000 vehicles per year (Robust GD&T strategy)
- Design to include bolt down directly into tray
- Design for P2.5 cells, package protect for P2.6 cells

Project definition (Scope and Deliverables)

The project scope was defined as follows:

Phase 1 – Concept Generation Feasibility: Ideation & brainstorming for multiple battery module concepts based on existing solid fin design concepts. Analyze and compare feasibility of these solid fin designs and down-select to one concept.

Phase 2 – Detailed Design: Conduct detailed design and engineering analysis to meet module performance metrics and manufacturability requirements.

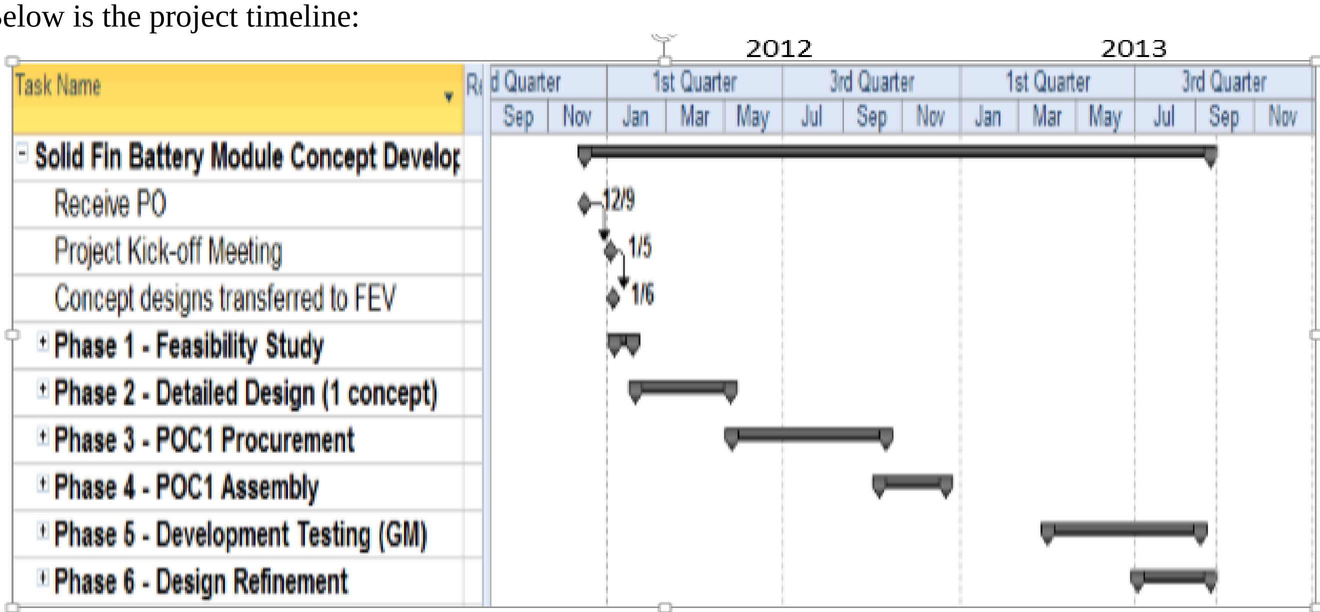
Phase 3 – POC Component Procurement: Requisition prototype components of down-selected concept from technically capable suppliers.

Phase 4 – POC Assembly: Assemble prototype modules/sections (different sizes) from these components to enable building 2 sections and 3 modules.

Phase 5- Development Testing: Test and develop the prototypes for critical functions – thermal, structural and safety performance

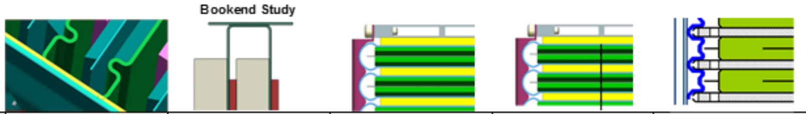
Phase 6 – Design Refinement: Improve the initial design to deliver a refined design, based on above test results and physical evaluations.

Below is the project timeline:



Concept Selection

Multiple concepts were developed reviewed and investigated between the GM and FEV teams. A Pugh matrix was developed that allowed a relative assessment of these against each other for key critical performance areas.



	Wave-fin Concept	Wave-fin Concept Bookend Study	Solid-fin Concept	Split-fin Concept	Snap-fit Concept
QITD	179	190	222	222	242
Thermal Performance Risks	Worst	Moderate	Best	Best	Moderate
Packaging	Moderate	Worst	Moderate	Best	Worst
Mechanical	Best	Best	Moderate	Worst	Worst
Manufacturability	Worst	Worst	Moderate	Best	Moderate
Assembly	Worst	Worst	Moderate	Best	Best
Serviceability	Moderate	Moderate	Moderate	Moderate	Moderate
Recyclability	Moderate	Moderate	Worst	Worst	Best
Weight	Worst	Worst	Best	Best	Best
Cost	Best	Best	Best	Best	Worst

Best
Moderate
Worst

Thermal Interface Material (TIM) between fin and cold plate was enabler for earlier GM solid fin concepts including the Wave-fin concept. However, TIM results in added cost, added weight and reduced thermal performance (relative to direct contact). Since split-fin concept does not utilize TIM whereby fins are mechanically bonded (brazed) to cold plate for metal-metal path for improved heat transfer. Split in fin along centerline of module provides allowance for component tolerances between cold plates within a minimum package space. Fin segments attached to a single cold plate provide ease of manufacturing for lower cost. Additionally, cells with foam layer load into module as a cassette and are not required to be processed sequentially reducing cycle time.

For these reasons, split fin concept was down-selected as the most promising one. Later design modifications allowed the team to address the initial concerns with mechanical reliability and recyclability.

Summary

In conclusion, a High Voltage battery module concept was designed developed and tested. The investigated split fin concept appears to be feasible from manufacturability, cost and performance standpoint. This project resulted in important technological learnings and advancement including multiple U.S. patent applications. The developed module design elements are being considered for future applications subject to vehicle packaging constraints and vehicle performance requirements.

Testing and Work Performed

Phase I and II – Engineering Development of Year 1 Mule Vehicles & Year 2 Integration Vehicles

Fuel Economy Development

Program objectives for utilizing Charge Sustaining Mode (CS) were consider program Fuel Economy (FE) enablers that could make vehicle competitive and utilize powertrain capability to emphasize a highway performance. The objective for Charge Depletion Mode (CD) was to generate clear FE enhancement associated with the use of plug-in capability vehicle for city operation, thereby providing the greatest FE benefit to short driving range customers for CD mode.

The development process for Fuel Economy utilized both analytical and tested results. Models were created to simulate and predict improvements to the different operational modes. Below is an example of this for the charge depleting mode.

The program goal was to focus on petroleum displacement and not EV range or EV performance for a blended PHEV. Determining charge depletion FE targets was difficult at the time due to emerging FE label definition and unknown customer expectations for a blended PHEV.

Fuel Economy Testing Results

Final fuel economy performance data taken at the 65% calibration development point was recorded through a collaborative testing effort at Argonne National Laboratories. GM's PHEV was able to demonstrate fuel economy double that of the conventional non-hybrid version for city type driving. Furthermore, a 50% fuel economy improvement was recognized on the highway schedule. This data clearly demonstrates the ability of PHEVs to reduce petroleum usage for customers who regularly plug-in charge. The data obtained also shows the fuel economy advantage over conventional non-hybrid vehicles of 75% fuel economy improvement in city driving and 16% fuel economy improvement on highway driving.

Hot Weather Development

Powertrain hybrid development and calibration required higher temperatures, long grades and altitudes in order to develop stability and capability in non-typical environments. Engine cold starts, powertrain calibrations, battery thermal calibrations and plug-in charging were all focused areas of development while in Death Valley, California and Phoenix, Arizona.

Hot weather development milestones:

- September 2009
- September 2010 – hot weather development
- March and April 2011 – high altitude development
- June – August 2011 – hot weather development

Hot Weather Testing Results

Powertrain hybrid development and calibrations met targets through extensive vehicle hot weather development. Verified analysis to use Rechargeable Energy Storage System (RESS) active cooling HEX discharge air to cool charger HEX intake air; results in approximately a 2-3 hour charge times @ 220V & 5-7 hours @ 110V with customers in hot climates seeing a $0.14 increase for 220V and $0.31 increase in cost to charge full state of charge. This meets compliance and customer charge time requirements/expectations.

Additional testing details have been supplied in a Protected Data attachment to the Department of Energy.

Cold Weather Development

General drive ability and diagnostics development required visits to a cold climate. General Motors used facilities located in Kapuskasing, Ontario Canada for this. Additional objectives included cold start development, voltage and state of charge control development and cabin comfort. In addition, both gasoline and alcohol fuels were used based on varying viscosity in lower temperatures.

Cold weather development milestones:

- January and February 2010
- January and February 2011

Cold Weather Testing Results

- Successful plug in engine starts down to -37 degree Celsius coolant
- Successful “unplugged” or “unassisted” starts down to -30 degree Celsius
- Li Ion battery is much more susceptible to under voltage and over voltage conditions than NiMH

Argonne National Lab

Our main objective working with Argonne National Lab (ANL) was to collaborate on a testing matrix that would provide charge depletion and charge sustaining data relating to vehicle performance to current fuel economy labeling strategies. This included collaborative testing of a General Motors supplied vehicle. The vehicle was instrumented to determine electrical energy distribution during drive cycles and total wall charging efficiency post charge depletion testing.

Argonne National Lab milestone:
October 2011 – 2 weeks of fuel economy and emissions testing

Phase III – Battery Thermal Development of Alpha Module

The project team also designed, developed and tested a high voltage battery module concept that appears to be feasible from a manufacturability, cost and performance standpoint. Module development included evaluations of thermal performance, vibration, and aging/sealing. The thermal performance analysis included evaluations of total module temperature, internal temperature variations within the module, maximum and minimum cell temperature, heat capacity of the battery coolant, and an evaluation of thermal effects on materials contained within the module. The vibration evaluation consisted of an evaluation of the structural integrity of the module to expected vibrations. The aging/sealing evaluation included a verification of seal integrity after thermal aging of the heater seal, hose interface and heat sink interface along with an evaluation of the heater seal, hose interface, and heat sink interface.

Module Development Testing Results

In conclusion, a High Voltage battery module concept was designed developed and tested. The investigated split fin concept appears to be feasible from manufacturability, cost and performance standpoint. This project resulted in important technological learnings and advancement including multiple U.S. patent applications. The developed module design elements are being considered for future applications subject to vehicle packaging constraints and vehicle performance requirements.

Overall Summary of Results

Technical Accomplishments

Two physical builds were completed producing vehicles for internal deployment at General Motors:

- 50+ vehicles built
- 180,000+ miles driven

Fuel Economy Improvements

	% Improvement over Baseline Hybrid
Charge Depletion Fuel Economy	City: 212% Hwy: 50%
Charge Sustaining Fuel Economy	City: 75% Hwy: 16%

Module improvement targets

	Target	**Achieved**
Mass Reduction	10% reduction	38% reduction
Cost Reduction	41% reduction in module cost per battery pack	34% reduction in module cost per battery pack

Publications and Collaborations Generated under the Cooperative Agreement

Publications

- Plug-In Charging Symposium (San Jose, CA) - July 22nd, 2008
- California Air Resources Board (CARB) vehicle demonstration (Milford, MI) - Sept 9, 2008
- EPA vehicle demonstration (Milford, MI) - Oct 30, 2008
- Hollywood Goes Green Event: - Dec 8, 2008
- North American International Auto Show (NAIAS) - Jan, 2009

Networks/Collaborations

- Michigan Economic Development Corporation (MEDC) - Funding
- University of Michigan Advanced Battery Coalition for Drivetrains – Research
- FEV - Collaboration of design and development of new module thermal management system

Intellectual Property

- 25 Invention Disclosures
- Patent applications filed on all inventions
- 6 Patents issued to date