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vehicle ELECTRIFICATION

2011 Chevrolet Volt Development Story

Inside GM's new extended-range electric car and its technologies

The leading-edge **lithium battery**

The new 4ET50 **electrified transaxle**

Body and chassis **engineering**

The "maniacal" engineering team

Volt supplier interviews

November 4, 2010

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Development of the 2011 Chevrolet Volt

System Architecture | Rapid Prototyping | ECU Autocoding | **HIL Testing** | ECU Calibration

Green Success

HIL Simulation Charged up and Ready to Go

Any new technology has to be sound and fail-safe . . . like the electronic control units (ECUs) for battery management in hybrid and electric vehicles. This is where dSPACE comes into play. As the experts in hardware-in-the-loop simulation, dSPACE offers special simulation models and real-time hardware to put the ECUs through the ultimate tests.

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Embedded Success dSPACE

On the critical path

Foreward

When veteran **General Motors** engineer Jon Lauckner sketched out his idea for a new type of electrified propulsion system for his boss, Bob Lutz, in 2006, he reckoned there were two major hurdles in the way of the idea actually reaching production.

The first hurdle was simply getting the idea for an "extended range" electric vehicle approved. But Lutz, then GM's Vice Chairman for Product Development, was immediately convinced this was something the automaker had to do. The second hurdle was far more daunting. For Lauckner's idea to work as conceived, it needed a high-power/high-energy automotive battery that did not exist.

Lutz likened the program to a "moon shot," because of the high level of invention and critical-path engineering required to meet the aggressive 2010 production target. Lauckner remained confident that the issue of developing a suitable battery would be solved.

"We have the best technical organization in the industry," he told me about a year into the Volt's development. "We're going to execute this program and deliver an exceptional new vehicle as planned."

With volume production of the 2011 **Chevrolet** Volt now under way, the development team and its strategic suppliers have delivered on Lauckner's promises. Volt's overall performance, battery range, NVH attenuation, driver interfaces, and build quality exceeded my high expectations during recent drives. Currently the car has no peer in its approach to "green" mobility.

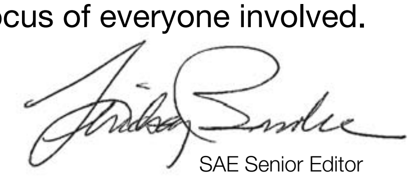
Competitors will find many things of interest when they tear down this vehicle for analysis. Among them are the liquid-cooled Li-ion battery pack; smart-phone driver interface for remote cabin conditioning and battery-charge control; a SAE J1772 charge coupler; and a novel "chiller" heat exchanger that uses both A/C refrigerant and glycol to help cool the battery in extreme operating conditions.

The various patents GM has netted in this program will prove useful as more competitors enter the electrified-vehicle space. Particularly vital is the intellectual property related to power controls and the new 4ET50 electrified transaxle.

My four years of reporting on this milestone vehicle inspired this special **SAE International** digital publication. My key takeaway about Volt is it represents the advent of the industry's turn toward vehicles that are primarily electronics platforms, rather than mechanical ones.

As of early October, the car had undergone 20 major vehicle control software calibrations (known as VESCOMs), plus many more v.1, v.2, etc., iterations. No wonder GM is investing so heavily in new resources in the rapidly growing electrical/electronics engineering arena.

But the highlight of covering Volt for me has been getting to know the high-caliber people that made it happen. Its execution reflects the dedication and focus of everyone involved.



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Lindsay Brooke

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Why Volt?

Engineers will debate whether Volt is technically a series-type hybrid or an extended-range EV (E-REV as GM prefers to call it). Lear Corp. helped develop the car's offboard 120-V and 240-V charging set. GM continues to evaluate charging technologies (Coulomb Technologies charging station shown).

After 48 months' development, the 2011 Chevrolet Volt has entered series production. The pioneering "E-REV" is as important to the mobility industry as it is to GM.

by **Lindsay Brooke**

Mention the words "fuel injector" to anyone who's reasonably savvy about vehicles, and they'll likely know something about the device that controls the metering of liquid fuel into an engine's cylinders and helps cause the vehicle to drive faster or slower.

But mention the term "IGBT" and the response may elicit a lot of blank stares. IGBTs, the acronym for insulated gate bipolar transistors, are the fuel injectors of electrically driven vehicles. They control the supply of battery electrical energy into the electric motors that drive the wheels. IGBTs are valves for electrons, much like a fuel injector is a valve for liquid fuels.

Comparing these two simple and essential components shows how fundamentally the auto industry is going to change, as it moves from the petroleum-based model that has sustained it for more than 100 years to the electrified model that many experts believe will literally propel it for the next 100 years.

Vehicle electrification—the industry's shift to hybrids, plug-in hybrids, and electric vehicles (EVs)—is bringing more than a different vocabulary. It is bringing new technologies, patents, core competencies, and skill sets for engineers.

Electrification is attracting investment capital that has helped create new companies aimed at disrupting the status quo. It has helped jump-start a U.S. battery industry (aided by billions in federal and state subsidies), invigorated development of more efficient electric motors, and forced traditional automakers and suppliers to rethink their own product-development strategies, R&D paths, and industry alliances. And it has prodded them toward new relationships with the energy sector and government.

Why Volt?

A production-spec Volt undergoes aerodynamic testing by technician Nina Tortosa at GM's Warren, MI, wind tunnel in 2009.

The 2011 **Chevrolet** Volt is in the vanguard of this shift. What literally began in 2006 as a napkin sketch by a **General Motors** executive engineer will soon be the world's first production extended-range electric passenger vehicle (E-REV).

The Volt's long-anticipated launch—the concept debuted at the 2007 North American International Auto Show in Detroit—kicks off a new age of vehicle propulsion offering significantly cleaner tailpipe emissions than the engines used in today's conventional cars and light trucks. Nearly 500 hybrid and EV programs of all types are in the works worldwide through 2015, according to forecaster **IHS Global Insight**.

Following Volt closely into showrooms are **Nissan**'s battery-electric Leaf, also slated for 2011, as well as Volt's European-market cousin, the 2012 **Opel** Ampera, and a flotilla of new hybrids and EVs from **Toyota**, **Honda**, **Ford**, **VW**, **BMW**, **Tesla**, **Fisker**, **Hyundai**, **Peugeot**, **Renault**, **BYD**, **Mercedes**, and others.

Many of the OEMs' technology roadmaps are linked to collaborative ventures with battery and power-electronics suppliers and systems integrators. They're teaming with university researchers and creating new EV-focused curricula with engineering schools. They're also supported by global engineering and testing specialists including **AVL**, **FEV**, **Ricardo**, and **IAV**. These companies have invested millions to develop their own hybrid and EV prototypes (including E-REVs) and related powertrain systems.

Even **Ferrari** and **Porsche** have committed to some degree of powertrain electrification. Company leaders say this will enable them to remain viable within the increasingly stringent global CO_2-emissions environment.

SAE International, too, is deeply involved in creating new standards, including the pioneer-

Lear Electrical Power Management Systems

Lear's expertise in high power Electrical Power Management Systems includes many of the critical hybrid and electric vehicle systems for a range of electrified vehicles, from micro hybrids to full electric vehicles. Lear's portfolio of products includes industry-leading Charging Systems required to plug in the vehicle to the electric grid, an assortment of optimized High Power Distribution Systems that connect and manage hybrid and electric vehicle electrical power, and Energy Management Systems that convert and control power to enable hybrid and electric drive.

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ing J1772 charge-coupler standard introduced earlier this year. More standards related to vehicle electrification are on the way. SAE also is working with a growing list of authors to publish technical papers covering all facets of hybrid and EV development. (See table, page 10.)

"With Volt and our next-gen programs that follow, we're talking about transforming the vehicle and the industry—and that's not just the auto industry because it includes fuels, the charging infrastructure, and energy producers as well," said Jon Lauckner, President of **GM Ventures**.

Lauckner is considered 'godfather' of the Volt. It was his napkin sketch over cocktails that convinced a skeptical GM Vice Chairman Bob Lutz of the E-REV concept.

"We can hypothesize whether E-REVs will be a permanent thing, or whether we all move toward pure electrics," he observed. "But the reason Volt is so significant is it represents the tipping point between the centrality of the internal-combustion engine (ICE) as the prime mover of vehicles, and electric propulsion systems. It's the tipping point between the petroleum and electric models."

Others agree on the vehicle's importance to its maker (which sees it as a new technical foundation for the company, rather than as a single model) and its significance to the industry. "Volt is perhaps the auto industry's most notable technological advancement of the past 50 years," said Dr. David Cole, Chairman Emeritus of the **Center of Automotive Research**.

Added the *Wall St. Journal*: "[Volt is] GM's most important model in decades—and possibly the key to its survival." Indeed, the program remained fully funded and supported by management, all through GM's financial turmoil and bankruptcy. It even outlasted four key engineers and three CEOs.

Jon Lauckner, President of the new GM Ventures group, is the "godfather" of Volt.

A "bridge" to an EV future

What makes the Volt different than the various hybrid vehicles currently on sale, and battery-electric cars like Leaf, is its "extended range" capability. This is made possible by a new type of powertrain developed by GM. The system, known as "Voltec," provides 25 to 50 mi (40 to 80 km) of zero emission electric-only operation, thanks to its fairly large 16 kW·h lithium-ion battery pack. When battery power is depleted, an onboard generator powered by a small gasoline engine engages automatically to provide up to 310 additional miles (500 km) of range.

The generator's role is to sustain a minimum state of battery charge while the car returns to a location where it can be charged via a 110/120-V or 220/240-V ac electrical outlet—the cleanest and most economical source of energy. Volt's regenerative braking system also provides a modest amount of energy back to the battery.

Volt Sparks SAE Technical Papers	
During the vehicle's development, GM engineers hinted to *AEI* that they would be chronicling Volt's development with a flurry of technical papers in 2011. The following titles and their code numbers were in development (not all were approved) at press time:	
Aerodynamic Development of the 2011 Chevrolet Volt	11B-0044
Chevrolet Volt Control Strategy for EV Range and Efficiency	11PFL-0136
Co-development of Chevy Volt Tire Properties for Electric Range and Performance Balance	11AC-0090
Chevy Volt Power Electronics	11PFL-0175
Developing a Portable Charge Cord for the Chevy Volt	11PFL-019
Selection and Development of the Engine for the Chevrolet Volt E-REV Application	11PFL-0900
The GM Voltec 4ET50 Multi-Mode Electric Transaxle	11PFL-0904
High Voltage Battery Tray Design Optimization	11PFL-0914
Design and Performance of the Voltec Drive Motors	11PFL-0948
Recyclability of the Chevy Volt Battery	11SDP-0016

Studies by GM and other automakers show that more than 70% of American and European car owners drive 40 mi (64 km) or less in their typical daily commuting. In such a duty cycle, Volt would never burn gasoline, making it essentially an electric car. Indeed, GM engineers expect Volt's 1.4-L gasoline engine will serve mainly in an occasional support role for many owners. (The engine is programmed to start every 45 days, regardless of use. The brief running time is designed to circulate lubricating oil, check the emissions-control system, and burn off some gasoline lest the unused fuel become stale.)

The gasoline-powered generator gives Volt a sort of umbilical cord to the existing liquid-fuel infrastructure. It also allowed the car's development team to balance battery size and capacity with the size and power of the ICE. This strategy produced a car with an attractive balance of efficiency and performance. It also kept systems cost down. And perhaps most importantly, it eliminated the dreaded "range anxiety" that will limit the appeal of pure electric vehicles until widespread public charging is available.

"In this role the ICE is the bridge to pure electrics, until we can get more capability from, and lower costs related to the batteries," Lauckner explained. "We realize that having two systems on board to create electricity is less efficient than settling on one. And we also know that sometime in the future we'll move away from petroleum as the centrality of our whole propulsion strategy."

At that point, would a piston engine even be necessary to generate electricity on board as efficiently as possible? Because it serves only as a stationary generator, the

Volt's 16-kW·h lithium-ion battery pack weighs 375 lb (170 kg) and serves as a structural member along the car's center line. The 1.4-L engine is designed to run on ethanol as well as gasoline and features sophisticated control algorithms for its starting regimen, including periodic starts to circulate fuel and oil when the car has been driven in EV mode for extended periods.

power unit wouldn't need to be capable of the high revs required by a conventional car. (Volt's engine is governed to 4800 rpm.) Nor would it need to run all the time. Indeed, engineers at GM and its competitors and suppliers are investigating super-optimized alternatives, opening up new avenues for mechanical systems and combustion science, and even bringing new life to proven engine types.

"People are talking about specialized twin- and three-cylinder engines, miniature gas turbines, Sterling cycle engines, Wankel rotaries, and fuel cells," Lauckner noted. "For future-generation E-REVs, we can consider a lot of things that can create electricity—including some we don't even understand at the moment. Because when we step across that line from petroleum centrality into where it's all about electricity, all of a sudden the game changes very quickly."

There has been much debate over exactly how to categorize the 2011 Volt, given its novel E-REV powertrain. It's not a classic EV. Neither is it technically a series-type hybrid, as defined by the traditional example of a diesel-electric locomotive. With the Voltec powertrain, GM has combined the operating characteristics of EV, series-HEV, and plug-in hybrid types to create a unique (and patented) propulsion system. It offers some unique attributes that are discussed elsewhere in this special digital SAE publication.

Why Volt?

Rather than base the new Volt on a unique platform, GM used the 2011 Chevrolet Cruze architecture to minimize complexity, reduce cost, and ensure a stiff, low-NVH foundation. The body-in-white contains a high percentage of high-strength and ultrahigh-strength steel alloys.

A "call to arms" for suppliers

Vehicle electrification skeptics often point out the industry's risk in investing billions in new technologies. Many of the technologies, like lithium-based batteries, are still unproven in mass automotive use and offer no certain return on investment in the short term. The skeptics also question a greater push toward vehicle electrification when U.S. gasoline prices remain relatively low. On these points the skeptics are correct, to a degree.

But industry leaders recognize that whether it's CAFE in the U.S. or all-encompassing CO_2 laws in Europe, the regulators are going to be "cranking it down in terms of CO_2 emissions and cranking it up in terms of higher mpg," as one engineer observed.

For the major global regions, including emergent China and India, it will be a slow-but-steady march to zero-emissions laws, experts believe.

"They're going to keep banging away and, despite all the creativity and cleverness we engineers can muster, we are not going to be able to keep the ICE as the prime mover. We just can't. The Second Law of Thermodynamics just grinds down on it," Lauckner asserted.

The advent of Volt/Ampera and their 2011-2015 hybrid and EV competitors is also a "call to arms" for suppliers who have entered this space.

"We need a supply base with both the product and process capability to design components and systems to be smaller, lighter, more efficient, reduced bill of materials—in quantity and with lower cost," noted Tony Posawatz, Volt's Vehicle Line Director. "This is where automotive experience can play a key role, because manufacturing critical propulsion-system items to automotive durability and reliability specs in 200,000-unit annual volumes is very different from making stuff for research."

Experts expect a steady global march to zero-emissions laws.

Skeptics point to the most expensive piece of the car—Volt's battery pack, a hefty 375-lb (170-kg) T-shaped module estimated to cost GM $10,000 per unit. (GM executives won't reveal actual cost but say it is lower.) Industry analysts reckon, however, that production scale and evolving technologies will steadily lower the break-even point. The experts note that the first commercial mobile phones were the size of bricks and cost $3000. Smart and steady engineering usually wins for the consumer.

"It's the typical case of having a pretty steep learning curve whenever you bring a new technology to the market," explained CAR's Dr. Cole. "It never happens immediately. No battery manufacturer is going to put up a facility to build a million lithium car batteries in the first year.

"Rather, they'll aim their first-year production volume at 20,000 to 40,000 units. They'll incorporate their learnings into the next-generation batteries," he said. "Pretty quickly, by perhaps the third generation, they'll begin to boost scale and become cost-competitive."

Cole believes by the third generation, GM and its battery-cell partner **LG Chem** will have reduced the cost of the Volt packs by about half.

In his new GM Ventures job, Lauckner is charged with sniffing out promising new-technology partners and sharing GM's home-grown technologies with promising collaborators. To him, the electrification journey started by the famous EV-1 in the early 1990s and re-ignited by Volt in 2011 is running faster than many observers believe.

"If you look back five years, the number of companies on the OEM and supplier level who had any level of competency in electrified vehicles would be close to zero. Count the number of companies who are on board today, and the number of battery companies. Not just U.S. or European companies; I'm talking about everybody everywhere. It's incredible growth," he said.

"Combine money and brainpower and you're very likely to get results. This thing is going to happen—it's not a question of 'if' but 'when.' The companies that step out and harness money and intellectual commitment are the companies that are going to win," he said.

And the entire auto industry will be chasing them.

2011 Chevrolet Volt Specifications

GM Vehicle Program Code: D1JCI

Vehicle Description

5-door hatchback, 4-passenger, front-wheel-drive, extended-range electric vehicle (E-REV)

Exterior Dimensions

Overall length (in/mm):	177/4498
Wheelbase (in/mm):	105.7/2685
Width (in/mm):	70.4/1788
Height (in/mm):	56.3/1430
Front overhang (in/mm):	39/993
Rear overhang (in/mm):	32.2/820
Front track (in/mm):	61.2/1556
Rear track (in/mm):	62.1/1578

Interior Dimensions

Headroom (in/mm)	
Front:	37.8/960
Rear:	36.0/915
Shoulder room (in/mm)	
Front:	56.5/1436
Rear:	53.9/1369
Hip room (in/mm)	
Front:	53.7/1365
Rear:	51.2/1301
Leg room (in/mm)	
Front:	42/1068
Rear:	31/787
Cargo volume (ft^3/L):	10.6/301

Capacities

Curb weight (lb/kg):	3781/1715
GVWR (lb/kg):	4583/2079
Fuel tank (gal/L):	9.3/35.2
Generator cooling (qt/L):	7.7/7.3
Battery pack cooling (qt/L):	7.4/7.0
Power electronics cooling (qt/L):	3.1/2.9
Engine oil w/filter (qt/L):	3.7/3.5
Drive unit fluid (qt/L):	8.9/8.45

Powertrain

GM Voltec rechargeable electric propulsion system with integral ICE powered generator

Combustion Engine

Architecture:	GM "Family Zero" inline 4-cylinder; cast-iron block, aluminum head
Bore x stroke (mm):	73.4 x 82.6
Displacement (in^3/cm^3):	85.3/1398
Compression ratio:	10.5:1
Valvetrain:	DOHC, 4 valves per cylinder; variable intake and exhaust valve timing
Throttle control:	Electronic
Rated power (hp/kW, SAE net):	84/63 (est.)
Max. rpm:	4800
Required fuel:	Premium gasoline; E85-capable from MY2012
Fuel delivery:	Electronic sequential-port, returnless fuel rail

Battery Pack

Configuration:	T-shaped module with integrated thermal management
Case construction:	Glass-filled polyester composite
Total rated energy (kW·h/MJ):	16/58
Total usable energy (kW·h/MJ):	9.4/34
Total pack volume (L):	100
Pack length (ft/m):	5.5/1.67
Total pack mass (lb/kg):	375/170
Total number of cells:	288
Cooling medium:	Electrolyte-based liquid
Minimum operating temperature:	0-10°C (32-50°F)

Battery Pack cont'd

Maximum/minimum state of charge (%):	85/30
Max. state-of-charge utilization (%):	65
Pack warranty:	8 yrs/100,000 mi (160,000 km)

Battery Cells

Manufacturer:	LG Chem/Compact Power Inc.
Chemistry:	Lithium-ion manganese-spinel (LiMn2O4)
Architecture:	Prismatic with proprietary ceramic-coated Safety Reinforced Separator (SRS)
Cooling medium:	Liquid

Electric Transaxle

Traction motor:	3-phase ac induction type, air cooled
Rated peak output (kW/hp):	111/149
Rated peak torque (lb·ft/N·m):	273/370
dc generator:	High-flux permanent-magnet type, liquid cooled
Rated peak output (kW/hp):	55/74
Final drive ratio:	2.16
Hydraulic clutches:	3
Driver-controlled operating modes:	Normal, Sport, and Mountain

Off-car Charging System

Standard voltage:	110/120 V, 15 A, ac (U.S.); 220/240 V ac (Europe) Optional "quick-charge" voltage, SAE Level 2: 240 V ac
Charge coupler:	SAE J1772-compliant standard connector with cord

Emissions Rating

U.S. EPA:	NA at time of publication
CARB:	Super-Low Emissions Vehicle (SULEV)

Body & Chassis

GM body architecture: Delta II

Vehicle classification: SAE midsize J1100 EPA class

Body structure: Steel; 80% high-strength alloys

Weight distribution unladen, front/rear (%): 51/49

Coefficient of drag (Cd): 0.281

Chassis control: All-speed traction control, StabiliTrak; drag control

Suspension

Front: Independent MacPherson struts, coil springs, anti-roll bar; hydraulic ride bushings

Rear: Compound-crank torsion-beam with semi-trailing arms, coil springs, tubular shocks, hydraulic ride bushings

Power Brakes/ABS

Front rotors (in/mm): 11.8/300, vented

Rear rotors (in/mm): 11.5/292, solid

Front calipers: Sliding type with two 60-mm opposed pistons

Rear calipers: Sliding type with single 38-mm piston

Assist type: Electrohydraulic, 4-channel ABS

Friction/regen blending: TRW Slip Control Boost

Steering

Type: Rack-mounted ZF electric power steering (EPS), variable assist

Turning circle, curb-to-curb (ft/m): 36/11

Ratio: 15.36

Tires: Goodyear Assurance Fuel Max, all-season, low-rolling-resistance

Front: P215/55R17

Rear: P215/55R17

Spare tire: Standard tire inflation kit

Production

Assembly plant: GM Detroit-Hamtramck, Hamtramck, MI

Planned volume (units): CY2011 = 10,000; CY2012 = approx. 45,000

Fuel Efficiency & Performance

EPA city/highway:	NA at time of publication
***AEI* tested fuel economy,** mpg**, 150-mi loop**:	51
Claimed range, EV mode (mi/km):	25-50/40-80
***AEI* tested range, EV mode** (mi/km)**, 150-mi loop**:	44.5/71.6
Claimed range with range-extender (mi/km):	+350/483
Est. average annual electric energy useage:	2520 kW·h
Top speed (mph/km·h):	101/161

Safety Engineering (std.)

Dual-stage frontal airbags; side-impact and knee bags for driver and front passenger; roof-rail (side curtain) side-impact bags for front and rear outboard seating positions. Front airbags include Passenger Sensing System. Front seatbelt dual pretensioners and force limiters. Pedestrian alert (horn chirp) for use in EV mode, driver activated by turn signal lever. StabiliTrak stability control system with brake assist and traction control. Optional: Rearview camera and front/rear park-assist package.

Navigation/Information System

GM OnStar: Standard – 5 years of Directions and Connections plan includes automatic crash response; emergency services, crisis assist, stolen vehicle assistance including stolen vehicle slowdown and remote ignition block; remote door unlock; turn-by-turn navigation with destination download and OnStar eNav (where available), OnStar vehicle diagnostics, roadside assistance, remote horn and lights, hands-free calling.

Pricing (U.S.)

2011 MSRP: $40,280 (base); Volt qualifies for the maximum $7500 federal tax credit ($33,500 with the credit)

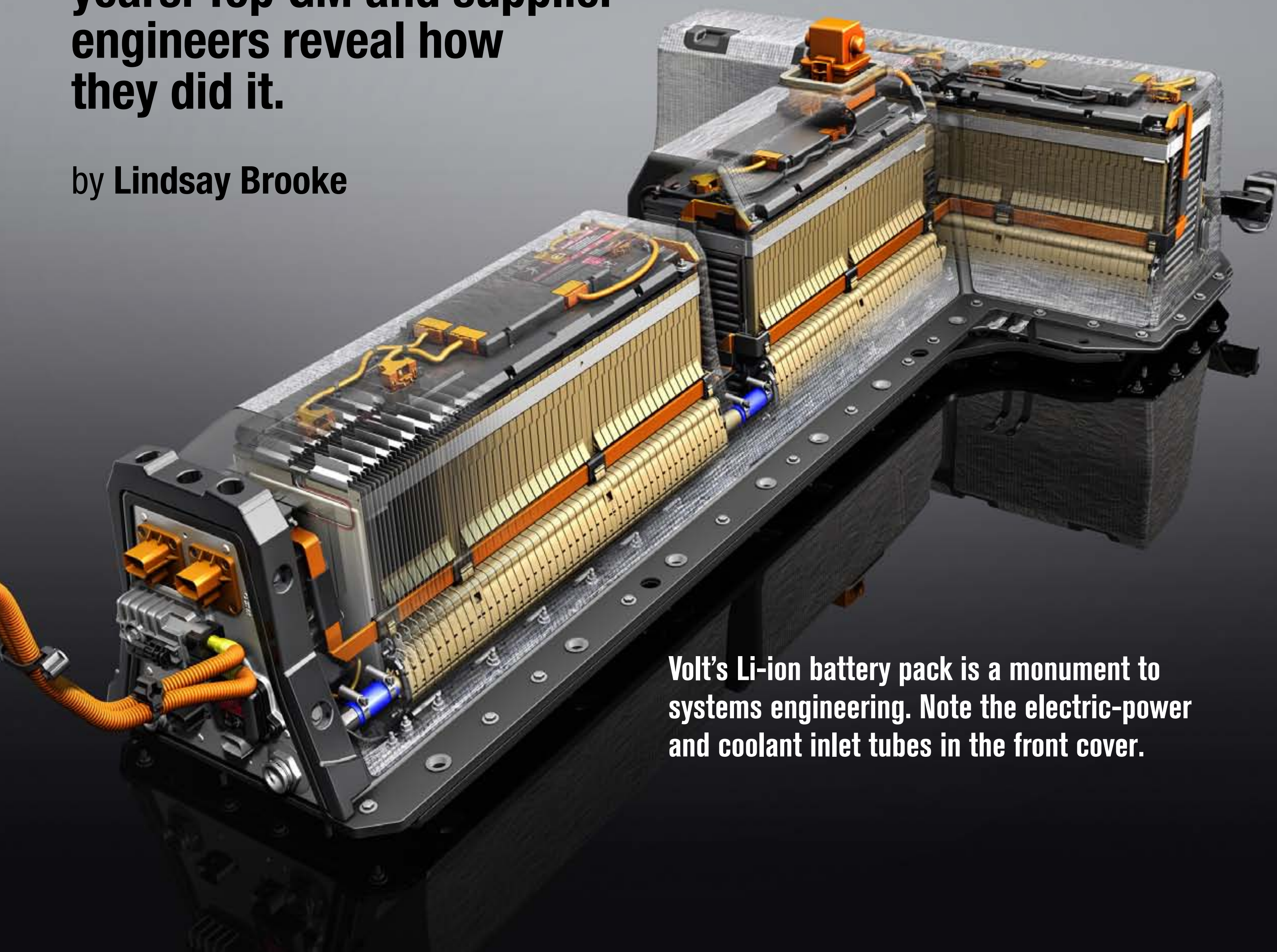
Standard features: 17-in alloy wheels; automatic headlights; heated mirrors; keyless ignition; remote ignition; automatic climate control; cruise control; auto-dimming rearview mirror; six-way manual front seats; tilt-and-telescoping steering wheel; cloth upholstery; Bluetooth; OnStar; touchscreen navigation system with voice controls and real-time traffic; 6-speaker Bose audio with CD/DVD player, auxiliary audio jack, iPod/USB interface and 30 GB of storage.

Optional features: Premium Trim package adds leather upholstery, leather-wrapped steering wheel, and heated front seats. Rear Camera and Park Assist package adds a rearview camera and front/rear parking sensors.

Creating the heart of Volt

GM's battery requirements meant creating new state-of-the-art in-vehicle energy storage—and doing it in less than four years. Top GM and supplier engineers reveal how they did it.

by **Lindsay Brooke**



Volt's Li-ion battery pack is a monument to systems engineering. Note the electric-power and coolant inlet tubes in the front cover.

The lack of a suitable battery made electric vehicles niche players for most of the last century. For **General Motors**' Volt team, finding a battery with the energy capacity, performance, durability, reliability, and package density needed for use in a high-volume passenger car with the range-extender powertrain presented a significant challenge.

"In April 2007 when GM put out its solicitation and requirements for Volt, nobody had a battery that would meet the requirements—including us," said Prabhakar Patil, CEO of **Compact Power** Inc. (CPI), which supplies Volt's battery cells.

Patil recalled that CPI's parent company **LG Chem**, the South Korean lithium-battery giant, had a cell that could meet GM's power requirements or energy requirements—but not both.

"Typically lithium-ion's performance characteristics are kind of a trade-off between power and energy. GM's battery requirement for Volt meant raising the state of the art of the entire power/energy envelope," he said.

Volt's technology linchpin, and its biggest chunk of supplier involvement based on cost, is its lithium-ion battery pack. CPI's development bogey was to achieve long life, super-robust thermal stability, and high energy density.

"The challenge for advanced automotive batteries is the superb energy content of liquid-petroleum motor fuels. The standards for energy and power density set by the ICE are very tough to beat," observed Dr. Ann Marie Sastry, a **University of Michigan** engineering professor and expert on advanced battery technologies.

Regarding reliability, GM needed to warranty the pack for the life of the vehicle. The aim was to validate Volt's technology with consumers and also to meet the **California Air Resources Board**'s Advanced Technology Partial Zero Emissions Vehicle (AT-PZEV) standards—an early strategic goal that did not pan out.

The car carries a Super-Low Emissions (SULEV) certification at launch, and GM plans to add emissions equipment to meet AT-PZEV. Its 8-year/100,000-mi (161,000-km) powertrain warranty is equal to **Toyota**'s Prius warranty and is three years longer than GM's standard powertrain warranty.

The battery cell "bake off"

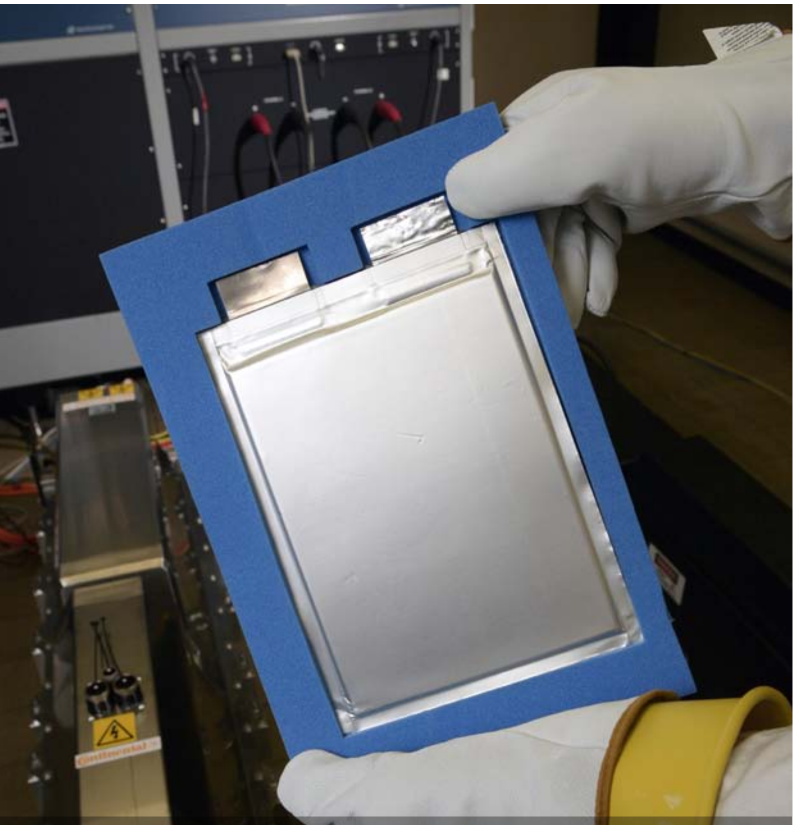
To establish Volt's battery-cell chemistry, and to select the program's cell supplier, GM began with deep-dive investigations into more than 25 different lithium-based battery chemistries, according to Andy Leutheuser, Lead Battery Systems Engineer on Volt.

He described the lengthy evaluation as "a rigorous, multi-phase process." Phase Zero involved pre-screening more than 155 chemistries submitted in reports from makers and technologists across the advanced-battery spectrum. In Phase 2, that universe of candidates was reduced to 60 potential cell chemistries GM's experts felt were promising for automotive use. Cell qualification followed in Phase 3, which left CPI and **A123 Systems** as finalists.

Compared with nickel-metal hydride (NiMH), the incumbent chemistry long proven in hybrid-vehicle use, lithium-ion cells pack up to three times as much power (110-130 W·h/kg) in a much smaller package. Lithium cells are also more configurable, according to experts, and are prone to less discharge when not in use. They're also 50% lighter and potentially less expensive.

Electric-powertrain engineers appreciate lithium's ability to be "tuned" to increase cell

Creating the heart of Volt



The CPI prismatic cells are protected by aluminum cases. Volt's pack comprises 288 cells.

power or energy densities, depending on the vehicle application. Leutheuser said the Volt's 288 cells have been tuned to deliver a balance of power and energy.

The LG Chem prismatic (flat package) cells use a carbon-graphite anode and manganese cathode, separated for protection against thermal "runaways" by the company's proprietary separator within the cell. GM battery engineers said this combination of chemistry and architecture provides a very stable, robust cell. The Volt cells are encased in polymer-coated aluminum housings and are stacked vertically within the pack.

"Lithium is unquestionably where the industry's going," said Mark Verbrugge, Director of the Chemical Sciences and Materials Systems Lab at GM R&D. He explained that finding ways to reduce cell and pack cost through engineering and manufacturing is an ongoing priority.

The final evaluation phase for Volt's cells was Pack Qualification, where LG Chem's manganese-spinel cells were pitted against those from Massachusetts-based A123 working in partnership with **Continental Automotive** (serving as pack integrator).

"In selecting our battery partner, we had to consider many factors," Verbrugge told *AEI*. They included having significant R&D depth in materials, design, and process; understanding battery life, failure modes, and abuse tolerance; endurance for long development periods; relationship to raw materials suppliers; and high-volume cell manufacturing experience.

He noted that a cell supplier's overall quality and process control must be near-perfect because failure of a single cell in use can cause failure of the entire pack.

When GM announced the results of its "battery bake-off" in January 2009, *AEI* talked with Denise Gray, Director of Hybrid Energy Storage Systems, about her company's decision.

"It was pretty close between the two candidates, and there wasn't a single 'standout' element for CPI," she said. "Their cell design works really well with our pack design, and LG Chem has a lot of experience in the battery business. We also were a bit more familiar with their cells because we'd used them in most of our early testing."

GM's pack-assembly secrets

GM originally planned to have CPI manufacture the Volt's 5.5-ft-long (1.7-m) battery pack as well as supply the cells. That strat-

Battery development: "not much room for error"

A robust, reliable, high-performance Li-ion battery was critical for the Volt program's success. **General Motors** engineers say they could not have done it without their partnership with **Compact Power** Inc. (CPI), part of South Korean battery giant **LG Chem**. CPI's CEO, Prabhakar Patil, is no stranger to electrified vehicles, having led the Escape Hybrid program while an engineer at **Ford**. Here he recalls challenges of developing the "heart" of Volt.

Q: What was the Volt program's key technology takeaway for CPI?

Patil: Systems engineering. Often you cannot predict the level of interaction of subsystems until you put them together—putting the cells into modules and the modules into a pack, for example. So we had to rely quite a bit on analytical models, many of which we developed for this program. They were also critical for developing the liquid-cooled thermal management system. There simply wasn't enough time to do a build-and-test kind of approach.

The battery's calendar life had to be modeled, because we couldn't wait for 10 years of actual testing, over the required miles. We had to have 'acceleration factors' that gave us confidence that we could warranty the packs for 150,000 miles.

Analytical modeling of vehicle batteries is still evolving. The USABC [**U.S. Automotive Battery Consortium**, an industry group] played an important role with us because they have the benefit of looking across different manufacturers and technologies, and identifying common factors.

Q: What are the CPI cells' competitive advantages that clinched the Volt supply contract?

Patil: Ours was the only technology GM evaluated that has two layers of protection inside the cell. One layer is the manganese-spinel-based chemistry, which **A123** also has. The other is the internal separator [between the anode and cathode], which is our innovation. Our other strong point is the flat-format prismatic cell architecture, whose failure mode is naturally benign. Its robustness from a manufacturability standpoint is inherently good. Another asset was LG Chem's experience in making these cells in high volume. That's a track record you need when you have over 200 cells per pack. A pack is only as good as its weakest cell, so the OEM needs proof that you can deliver cells with extremely high consistency. Being part of LG Chem, our intimate knowledge of the cell characteristics allowed us to do the module and pack development quickly.

Q: What has the Volt program meant to you as an engineer?

Patil: It's been very challenging and gratifying at the same time. The program really pushed technology from many sides—at the cell level, getting power and energy together. It pushed packaging technologies. It pushed development of liquid cooling in an EV pack of this complexity. It pushed our use of analytical methods.

With so much riding on the Volt program, there was not much room for error. We delivered the first pack to GM on Halloween, 2007. It was developed in six months, and that same pack is still running in GM's battery lab.

In the early tests that battery's performance came in line-on-line to what GM predicted. Such longevity and performance are very gratifying for me as an engineer.

egy changed in order to give the automaker more design latitude in terms of integrating the pack with the vehicle, as well as greater control over intellectual property.

"We were developing some thermal management and power control solutions that we thought were pretty slick," explained Volt's Vehicle Line Executive, Tony Posawatz. "Pack management and integration are critical for us, as we look to apply the Voltec powertrain to other programs."

Posawatz noted that keeping pack engineering in-house enabled GM to develop some automated pack-assembly processes at its Brownstown Township plant near Detroit that he believes will help save manufacturing costs and help improve the design of future battery packs.

Within the T-shaped pack are nine interlinked, liquid-cooled battery modules, each containing 32 prismatic cells. The cells themselves are less than 0.25 in (6.35 mm) thick, measure approximately 5 x 7 in (127 x 178 mm), and weigh about 1 lb (0.45 kg).

The Volt's battery pack is a very sophisticated piece of systems engineering. It includes integrated thermal management and power control, and its design enables it to fit longitudinally along the Volt's high-strength-steel central tunnel and under the rear seats. Besides storing electrical energy, the battery pack serves as a semi-structural element of the vehicle structure, contributing to the body's claimed 25-Hz bending stiffness.

Volt's energy management system is designed so the battery does not have to endure the deep-cycling that shortens life. Control algorithms allow the pack to operate within a conservative 65% state-of-charge (SOC) window. In more extreme vehicle duty cycles, such as driving in Mountain mode, the SOC will raise the lower limit to ensure there is adequate power when needed. The battery's upper and lower "buffer zones" help ensure long life.

To keep its cool, and warmth, GM engineers opted for a liquid-cooled pack rather than air cooling for durability, thermal stability, and packaging benefits. Li-ion automotive batteries must endure very high dynamics. Momentary peak loads, such as created dur-

Lithium-ion manganese spinel prismatic cells make the Volt's pack (shown at right) 75% lighter and 40% smaller than the 2nd-gen NiMH pack used in EV-1 (shown at left), with the same energy capacity.

GM battery systems engineer Bill Wallace has seen the size of GM's battery-development group grow from less than 30 to more than 200.

ing brake-energy regeneration and acceleration, generate powerful electrical currents. The currents create internal resistance, which causes significant warming of the cells.

Temperature extremes can diminish a battery's efficiency and rapidly accelerate battery aging, noted Frank Weber, Volt's enthusiastic and laser-focused Global Chief Engineer who departed the program last year for **Opel**.

"For example, the delta between 70°F (21°C) and 90°F (32°C) can be critical to battery life," he asserted. The battery is designed to work while plugged in, at temperatures from -13°F (-25°C) to +122°F (+50°C). The permitted temperature gradient within a battery cell, and from cell to cell, is 5 to 10 K.

A 50:50 glycol mixture is actively circulated through 144 metal "fins" between each of the Volt's 288 cells. The fins are 1-mm-thick (0.04-in) stamped aluminum plates that conduct heat. The Volt's pack has five thermal management circuits to handle the multiple subsystems. The system uses multiple electric coolant pumps (12- and 50-W) supplied by **Buehler Motor** of Germany. The pumps feature brushless dc motors and integrated electronics, and are designed to run extremely quietly, explained Robert Riedford, President of Buehler Motor Inc.

In cold weather, the battery is preheated during charging. Inputs from 16 temperature sensors are sent to a heating coil that warms the coolant, regulating individual cells' temperature, said Bill Wallace, GM's Director of Global Battery Systems.

GM engineers worked with heat-transfer-systems expert **Behr America** to develop Volt's front-end cooling module (FECM) as well as to introduce the industry's first use of "chiller" technology in a production electrified vehicle. (See sidebar, page 33.)

Volt's battery management system runs more than 500 diagnostics at 10 times per second, continuously monitoring the battery in real time. GM engineers said 85% of the diagnostics ensure the pack is operating safely, while the remaining 15% track battery performance and life.

GM engineers have performed more than 1 million mi (1.6 million km) and 4 million hours of validation testing on Volt's battery packs since 2007.

For the engineers, scientists, and chemists who developed Volt's battery pack, the project "was a giant leap of faith for everybody involved," said CPI's Patil. He said the key to the program meeting its November 1, 2010, start-of-production date—effectively launching a battery that didn't exist in 2007—was the teamwork among his company and GM.

"A window of 3½ years is tough enough to meet on a conventional vehicle program," he noted. "But trying to develop new technology and put it in a production vehicle…there were a lot of skeptics who said it would never work."

Engineering with a maniacal focus

Chief Engineer Andrew Farah, an EV-1 veteran, kept the program on schedule while managing to keep his sanity intact.

Volt's many learnings are now part of GM's "tool kit" for electrified vehicle development, said VLE Tony Posawatz.

Former Global Chief Engineer Frank Weber directed the program's critical early development before leaving to join Opel.

A dedicated, cohesive team and a conservative engineering approach put this innovative vehicle into production at moon-shot speed.

by **Lindsay Brooke**

Not long after he became **General Motors** Vice Chairman for Product Development, Bob Lutz spoke with *AEI* about what he called "decoupled development." By disconnecting development of the most engineering-intense subsystems (*i.e.*, a new powertrain) from a vehicle program's critical path, overall efficiencies can be realized and a higher-quality end product can result.

Interior Design Manager Tim Grieg's group worked with the body and powertrain development teams to wrap the four-seat cabin around the large battery pack.

GM Director of Global Battery Systems Engineering Ronn Jamieson worked closely with his counterparts at LG Chem's Compact Power group in tuning, testing, and validating the new prismatic Li-ion cells.

But Lutz gave us his dissertation before the Volt program began. Few vehicle development efforts in modern times have required such an intense engineering effort, not to mention inventions, on the critical path. Before he retired, Lutz called Volt a "moon shot" and equated it to that mother of all critical-path projects, NASA's space program of the 1960s.

Reflecting on the four years of Volt development during the car's media launch in early October, Vehicle Line Executive Tony Posawatz said the program's success was due to one critical element.

"It really came down to how well the overall team—from those dedicated to the Volt program, to the engineers and scientists in GM R&D, to our key supplier partners—worked together. Looking back, the team made many, many smart decisions and maintained a maniacal focus on developing this vehicle."

Chevrolet Volt
Development Timeline

January 2007 – GM reveals the Volt concept car at the North American International Auto Show.

June 2007 – Advanced Li-ion battery-development contracts awarded to LG Chem and Continental Automotive Systems.

August 2007 – GM and A123 Systems announce partnership to co-develop battery cells with A123 Systems' nanophosphate battery chemistry.

November 2007 – "Decoupled development" phase including proof of concepts, engineering development vehicles, and mules begins. Design of Volt's electric drive system incorporates elements of the Two Mode hybrid transmission. First mules use Malibu bodies (called MaliVolts).

May 2008 – GM Vice Chairman Bob Lutz test-drives the first pre-production Volt at the Milford Proving Grounds. "Decoupled development" phase for subsystems ends.

June 2008 – GM's Board of Directors approves the Chevrolet Volt and "Voltec" electric propulsion system for production starting in late 2010.

Sept. 2008 – Many aerodynamic changes to the Volt body are revealed at GM's Centennial celebration. Second-gen mules using Cruze bodies arrive.

November 2008 – Product development phase begins.

January 2009 – GM announces it will develop and manufacture Volt's battery pack in the U.S. It also selects LG Chem as the Li-ion battery cell supplier for production.

March 2009 – Volt's European cousin, the 2012 Opel Ampera, is revealed at the Geneva Motor Show.

June 2009 – GM opens its new Global Battery Systems Lab at the Warren Technical Center. The facility is four times larger than GM's previous battery lab. It employs >1000 engineers.

August 2009 – As part of the U.S. Recovery Act, the DoE awards GM over $240 million for the high-volume assembly of battery packs and electric motors, and for testing hundreds of Volts.

October 2009 – Volt road testing moves to Pikes Peak, where the car's performance on long grades and at high altitudes, plus brake regeneration and other aspects, are evaluated.

November 2009 – 80-car PPV (prototype production vehicle) build completed. 300 Volt battery packs under test. PPV mules have racked up 250,000 mi in all conditions. Systems calibration is 65% complete.

December 2009 – Full-vehicle simulation tests (300,000-mi. equivalent) completed. The Detroit/Hamtramck plant begins building Volt parts using production tools and processes.

January 2010 – Chevrolet and OnStar unveil the industry's first working smartphone application. The Volt mobile app works on the Apple iPhone and Motorola Droid. It allows 24/7 remote connection and control of various vehicle functions and OnStar features.

February 2010 – GM's new Brownstown Twp. (MI) Battery Plant builds the first Volt pre-production battery pack.

March 2010 – The first production-spec Volts are built on the Detroit-Hamtramck assembly line. These vehicles are used for final validation and testing prior to on-sale.

November 2010 – Volt series production begins.

October 2010 – The global automotive media drives production Volts in Michigan. GM reveals hybrid-drive elements of Volt's electric propulsion system.

August 2010 – First production battery packs are built at the Brownstown Twp. plant. President Barack Obama drives the Volt at Detroit-Hamtramck. Chevrolet ups its planned Volt production capacity in 2012 to 45,000 units.

July 2010 – Chevrolet announces Volt's MSRP: $41,000. Buyers are eligible for U.S. income tax credits up to $7500. A $350/month 36-month leasing scheme also debuts.

May 2010 – Final major calibration test drives are under way in the western U.S. Systems calibration is 99% complete. GM unveils Volt's "Mountain" driving mode for extreme duty cycles.

April 2010 – GM announces $8 million expansion of the Global Battery Systems Lab, doubling the facility's size to 63,000 ft^2. The first pre-production 2012 Opel Ampera is built at the pilot plant in Warren. GM unveils Volt MPV5 crossover concept at Bejing Show.

Engineering
with a maniacal focus

Posawatz joined Volt from the start. A superb communicator with a comprehensive understanding of the vehicle, its subsystems, engineering challenges, regulatory issues, and the charging environment, he played a key role in connecting key constituent groups and keeping them informed on Volt's progress.

When a reporter noted that GM kept the Volt program alive throughout its financial meltdown, bankruptcy, and government-funded resurrection, Posawatz joked that "regardless of which CEO had recently fallen, the next one always seemed to say he liked Volt more than the previous guy!"

> *"There were many heroic efforts by team members to accomplish this project."*
>
> **—Volt VLE Tony Posawatz**

The team's strength also proved itself after losing a few key engineering executives—including Global Chief Engineer Frank Weber (now at **Opel**); Director of Energy Storage Systems Denise Gray (at a California battery start-up); Executive Director of Global Hybrid and Electric Vehicle Engineering Bob Kruse (now at battery R&D company **Sakti3**), and Assistant Powertrain Chief Engineer Alex Cattelan, who left to join **AVL** North America.

By making "smart decisions," Posawatz refers to not reinventing technology wherever possible and always erring conservatively on the side of robustness, reliability, operating safety, and customer delight.

"There are many, many examples of our team doing things intelligently," he noted. "Instead of developing a new blended braking system, we leveraged what we had done on the hybrid trucks (T900) and **Saturn** Vue Hybrid. We used the same suppliers, same everything, but with a few subtle enhancements." (See sidebar interview with **TRW**'s Dan Milot, page 45.)

Volt's electric power steering system is very similar to what GM is applying across its global portfolio of conventional vehicles, he added. But the battery, its controls and management, and the car's super-efficient HVAC system required "enormous effort" to develop, test, and validate.

"We opted to over-engineer everything—to make all subsystems so safe. We lavished loving care on the battery and its thermal management, and on the charger and power electronics. They're all liquid-cooled, so we can keep them in a bandwidth that's easily controlled, and maintain behaviors that we fully understand," said Posawatz.

The team "engineered-in multiple [coolant and control] loops" to manage the battery and electric powertrain, a strategy that ended up costing more than if GM had chosen air cooling or a less conservative design approach, Posawatz explained. He added, however, that being "too conservative" in the early stages of vehicle electrification will pay off as GM Powertrain continues to refine and optimize the Voltec system.

"I believe the one that's the fastest learner in this game has the greatest advantage," he said. "The regulatory requirements, the customer-delight issues, the warranty-cost issues, all had to be managed. But basically we had a great team and we were on a mission."

Was there ever a point in the program where the team faced hurdles that appeared insurmountable—that may have caused them to question the effort's chance of success?

"There was never a point where we went back to senior leadership and said, 'We're stumped.' There was never a point of anyone even considering that," Posawatz stated. "But there were many heroic efforts by team members to accomplish this project. We didn't hit a single huge pothole or sinkhole in the road, but we hit a lot of little ones. And the team responded incredibly well and kept moving forward."

Solving the BSE riddle

One of the program's most daunting technical challenges, one whose solution caused a "hurrah" moment, was developing the car's BSE (battery-state estimator) program. The BSE is an enormously complex control algorithm on which each powertrain subsystem's operation and performance is dependent.

A BSE that's not properly developed, whose calculations are off by mere percentage points, can cause the ICE to engage at inopportune times and decrease the car's EV operating range. NVH and driveability also can suffer.

"Talk about an algorithm that's really, really hard to develop and get absolutely right, the BSE was a big one for us," Posawatz recalled. "But now that our guys know how to do it, we have a major competitive advantage that opens the door in a lot of technology areas going forward." Volt's BSE is key intellectual property for the company, he added.

The engineers who found the BSE solution worked for Scott Miller, the Vehicle Performance Manager at the Milford Proving Ground, in charge of controls. He told *AEI* there were times where it seemed the team had run up against a wall.

"This is the first production extended-range electric vehicle with a lithium-ion battery that does plug-in charging," Miller explained. "Monitoring what's going on in the battery when it's in charge-sustaining mode, with the engine running, is different than when the car's charging plugged in. The BSE predicts this activity. It's a major algorithm and it has to consider a lot of variables. A small error in monitoring any one of the 288 battery cells can create a performance issue."

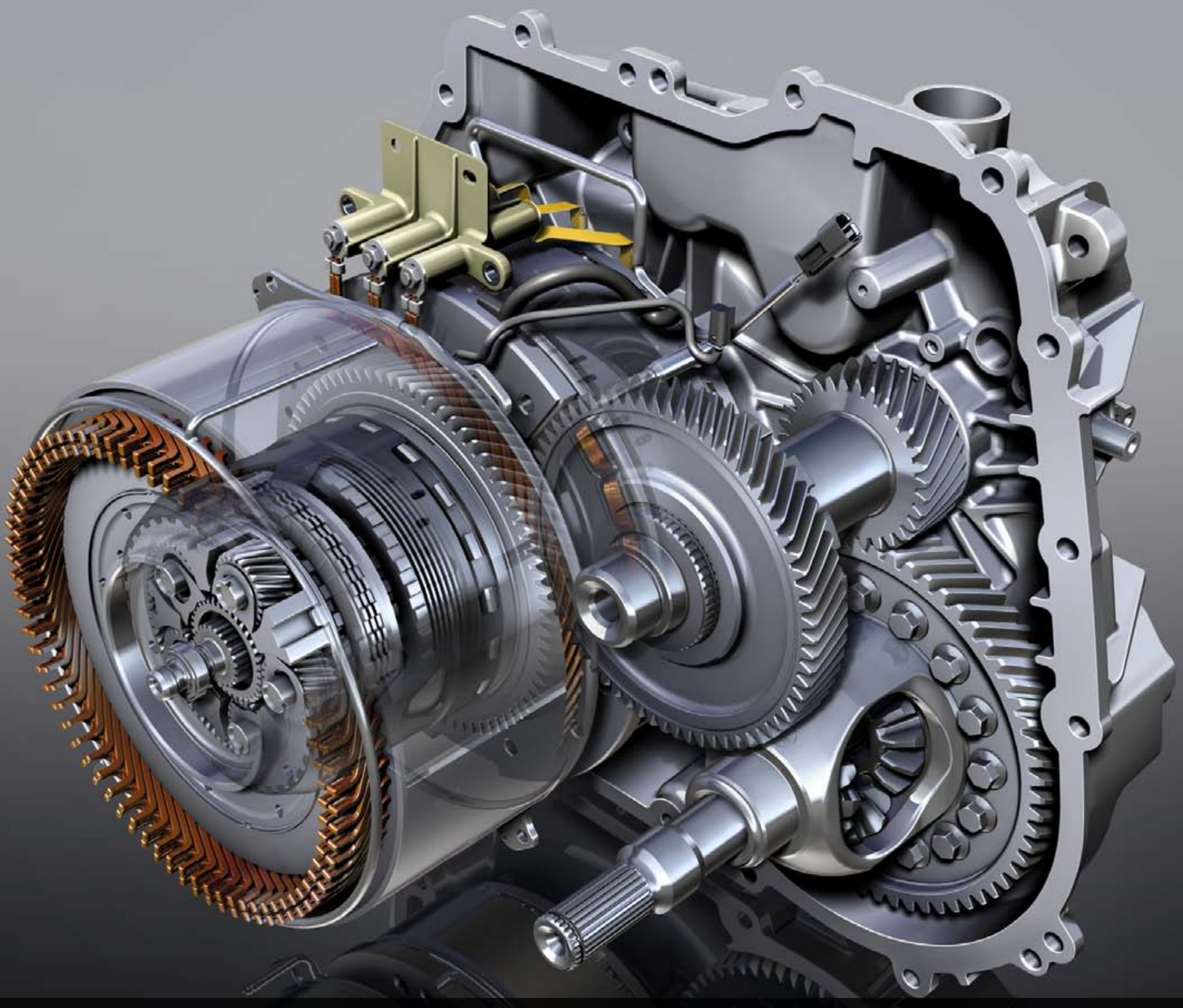
The team "significantly beat" its extremely aggressive original target for error, he noted.

Developing the architecture, the hardware, and the propulsion modes put a lot on each engineer's platter. As Volt's launch arrives, Posawatz and Miller quipped that most of GM's engineering staff will be putting in for the vacations they missed during the crushing 40-month program.

"Volt is all about balanced operation—delivering an efficient point of running the engine, staying within the bandwidth that the regulators like, and making the car pleasing to the customer," acknowledged Posawatz. "There were a lot of struggles in solving this three-legged stool.

"But now it's all part of our 'tool kit.' We plan to do a few more electrically powered vehicles, so we think our learnings may come in handy!"

A unique electrified transaxle



Hybrid or not? Definitions aside, what really matters is GM wisely leveraged its next-generation Two Mode propulsion technology to give Volt greater overall efficiency.

by **Lindsay Brooke**

Leave it to the Volt to cause the telephones at **SAE International** to ring almost nonstop. Since the car's media launch in early October, reporters have been looking for answers as they try to apply a standard technical description to the Volt's cleverly engineered powertrain.

GM has called it an "E-REV" (extended-range electric vehicle) ever since the concept was unveiled in January 2007. Over the course of the next 40 months, simply mentioning the word "hybrid" around any of Volt's senior development team members netted plenty of discourse as to why their baby is a new breed of propulsion system. Indeed, *AEI*'s first story covering the original show car described Volt as a series-type plug-in hybrid, drawing fire from two ranking executives on the program.

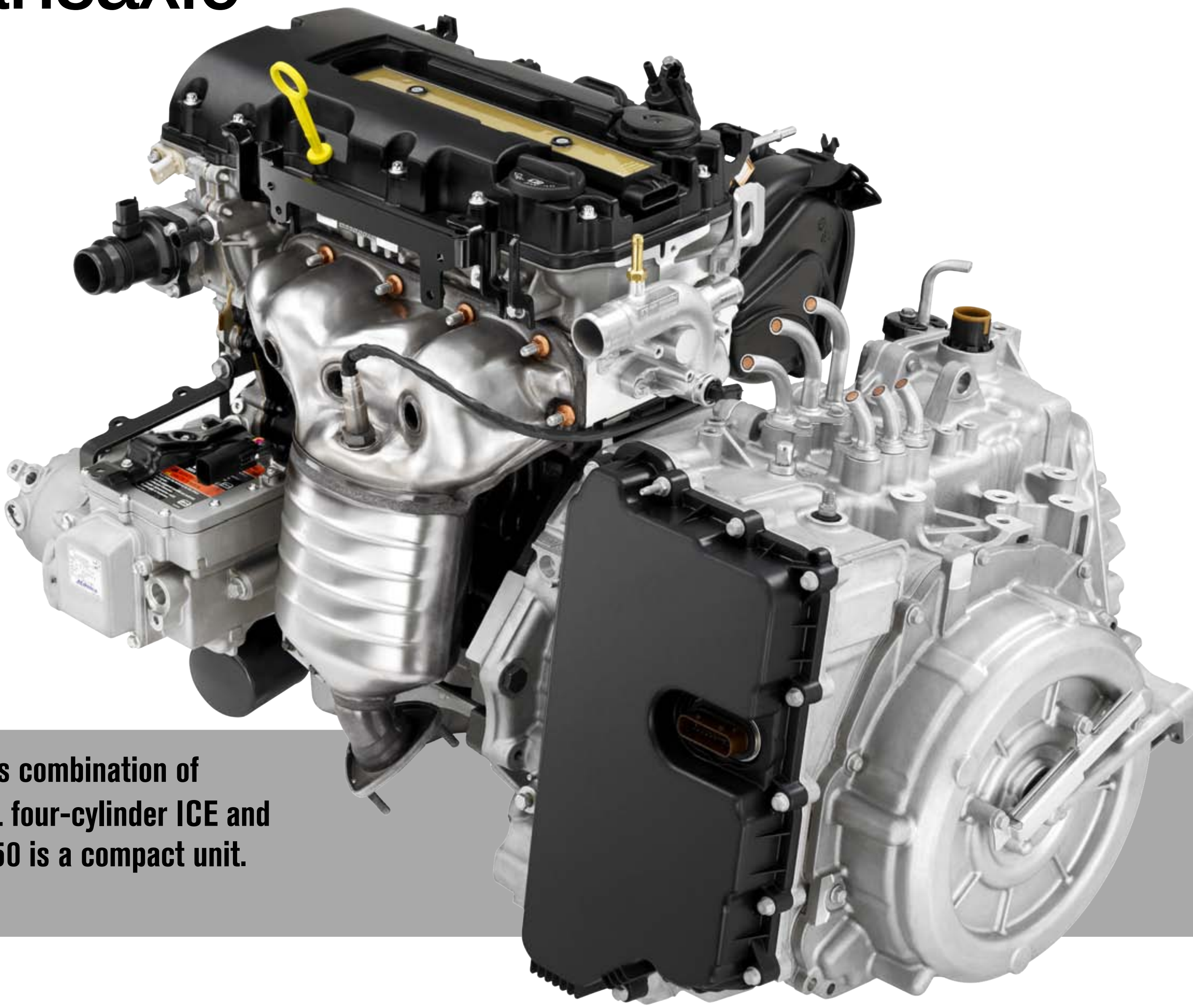
So what type of powertrain is Volt's? SAE's definitions for the main types of hybrid vehicles define "hybrid" as "a vehicle with two or more energy storage systems, both of which must provide propulsion power—either together or independently."

We describe a series-type hybrid as a vehicle "in which both sources of energy go through a single propulsion device." And a plug-in hybrid (PHEV) is defined as "a hybrid vehicle with the ability to store and use off-board electrical energy in the RESS (rechargeable energy storage system).

Currently there is no standard definition for an E-REV, but *AEI* continues to see Volt as primarily hybrid. It combines series and PHEV capabilities, and delivers battery-EV performance for those owners who travel less than 40 mi in their daily driving cycles. It can't deliver an EV's zero tailpipe emissions,

The view inside GM's new 4ET50 electrified transaxle (at left) shows the dc generator motor, ac traction motor, a trio of hydraulic clutches, and the planetary gearset. The control module is integrated into the main case.

A unique electrified transaxle



Volt's combination of 1.4-L four-cylinder ICE and 4ET50 is a compact unit.

however, because as explained in Chapter 8 the 1.4-L internal combustion engine (ICE) is calibrated to start up every 45 days, regardless of whether it's called on for generator duty, and run for about 10 min for various checks and maintenance.

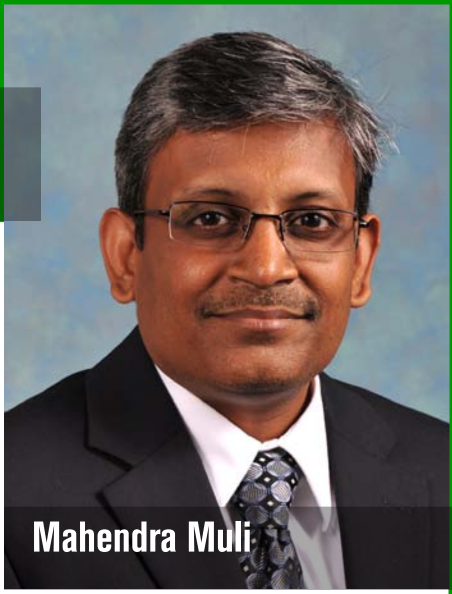
Battery EVs, however, are currently incapable of matching Volt's go-anywhere, anytime, capability, made possible by its liquid-fueled generator in the powertrain support role.

As a relevant aside, the car's customers won't care about technology labels. They'll only care that Volt delivers as promised—as it did during *AEI*'s recent 150-mi (241-km) test drive of a production-spec Volt in southeastern Michigan. Under 70°F (21°C) ambient conditions our car with driver and two passengers netted 44.5 mi (71.6 km) of EV range in varied traffic conditions and terrain.

The four-cylinder engine engaged remarkably quietly and seamlessly, chiming in at its governed 4800-rpm maximum but effectively muffled through great attention to NVH details.

The car had no trouble accelerating up to

Providing the tools for fast, accurate simulations and testing



Speed, efficiency, and engineering precision were critical to all aspects of Volt's development. **General Motors** engineers explained that only with the latest simulation and testing tools were they able to bring the car to market in such a compressed timetable, given the high level of electrical and electronic systems developed on the critical path. *AEI* asked Mahendra Muli, Manager of New Business Development for **dSpace**, about his company's involvement.

Q: What specifically did dSpace contribute to the 2011 Volt program?

Muli: We provided rapid controls prototyping and hardware-in-the-loop systems for electronic control unit software development, validation, and verification for technology development of powertrain, vehicle dynamics, body electronics, safety, and, finally, integration testing.

Q: How did dSpace collaborate with the Volt/GM engineers?

Muli: We provided engineering support for our products for various product development and testing departments at GM. Our engineers helped ensure that the development and testing platforms performed to the satisfaction of GM engineering teams involved in meeting complex challenges of the technology development under tighter timelines.

Q: What challenges did the Volt program present in terms of technology development/systems integration?

Muli: In general, vehicle electrification has posed challenges to the simulation systems required for development and testing of these complex vehicle architectures. The fast dynamics of the electrified vehicle powertrain systems require high computational power. dSpace responded by providing test systems based on the latest processor and FPGA technology and high-speed interconnection between processor boards. This resulted in powerful multicore, highly scalable simulation platforms used for component and integration testing of vehicle systems.

Q: What learnings did your team take away from your company's involvement with the Volt program?

Muli: Automotive engineering is taking a huge leap in evolution with electrification, led by automotive OEMs such as GM. The tasks and challenges are enormous both at the OEM level and at supplier levels. The challenges demand every player to put their best foot forward and more. Individuals and companies have to be highly adaptive in learning newer technologies, and to respond with solutions to various problems that arise. In summary, we learned that it takes the entire community to collaborate and move at a rapid pace in this evolution of vehicle propulsion.

Q: What opportunities does vehicle electrification present to your company?

Muli: It has expanded the industry's scope in both energy storage systems such as batteries and ultracapacitors, as well as semiconductors, battery management systems, and components for electric drives and related electronics. Also, it has increased the complexity of the overall vehicle electronics, resulting in the need for extensive validation and verification of software in production programs.

A unique electrified transaxle

and sustaining its 101 km/h (63-mph) governed maximum speed. The average "fuel economy" in electric and extended range (with generator) modes combined was 51 mpg. It will be interesting to observe the vehicle's performance in daily use under thermal extremes. Your mileage, as they say, may vary.

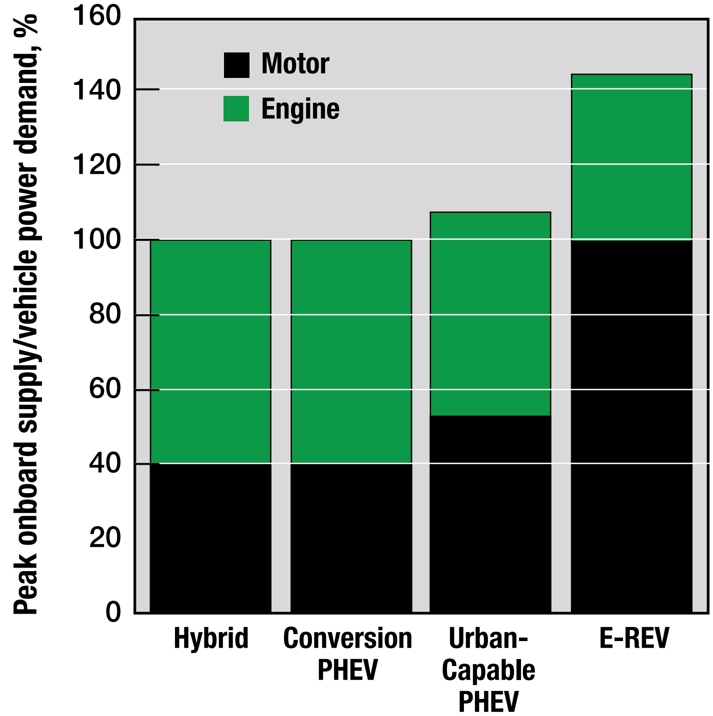
GM Powertrain engineers draw distinctions between Volt and a classic PHEV, noting their decision to equip the car with a relatively large battery (compared with plug-in hybrids) for greater EV-mode range. This allowed them to downsize the combustion engine, although not to the extent originally envisioned. First, they admit Volt resembles a series hybrid in its basic configuration. They acknowledge its operating characteristics are similar to those of a PHEV in Initial EV drive mode.

However, they also note an E-REV must maintain this mode of operation during all operating schedules when energy is available from the battery. Unlike the PHEV, it doesn't need to transition to a blended-operation strategy when battery energy is available.

The Volt's battery and electric drive system are sized so that the ICE never is required for vehicle operation when battery energy is available. This configuration doesn't require a specified operating cycle, while PHEVs require discussion of the urban schedule, the engineers argue.

The accompanying bar graph from GM shows that as greater electric-only operation is required, motor size and overall electric-propulsion capability must be increased. Hybrids and PHEVs are able to blend electric and ICE power to propel the vehicle, so they require less total onboard power than Volt.

HEV and E-REV peak motor and engine power as a percentage of peak vehicle power demand



GM bar graph shows that as greater electric-only operation is required, motor size and overall electric-propulsion capability must be increased. Hybrids and PHEVs are able to blend electric and ICE power to propel the vehicle, so they require less total onboard power than Volt, which offers full-electric-propulsion capability.

"Unlike any hybrid, Volt delivers full performance on electric power alone," said the car's "godfather," **GM Ventures** President Jon Lauckner. "It only draws energy from the liquid fuel in the tank after the initial battery SOC is depleted. This is an electric vehicle with full vehicle performance available as an EV, but with the onboard electric generator to extend driving range and take advantage of the liquid-fuel infrastructure that will be in place for many years globally."

Three operating modes

Volt's drive system can be operated in three distinct driving modes, via the center console mounted selection lever. Normal Mode is what most owners will likely use for their daily commutes. It biases a moderate energy draw from the battery to the traction motor for maximum range. Sport Mode changes the accelerator map to increase torque response.

Mountain Mode helps optimize the car's performance under long, steep-grade conditions. According to Larry Nitz, GM Executive Director of Hybrid and Electrical Powertrain Engineering, Mountain mode enables the power controllers to "dip deeper into battery" while under range-extended operation.

When the driver selects Mountain Mode, the controllers place more of the battery's

"Chilling out" Volt's battery pack


Uwe Krueger

Behr America engineers collaborated with their **General Motors** counterparts to create an extremely sophisticated thermal management system for Volt. Behr's Vice President of Engineering, Dr. Uwe Krueger, talked about his company's technical contributions.

Q: What did Behr contribute to the Volt program?

Krueger: We contributed two major parts. One is we're doing the full front-end cooling module. The second is what we call the 'chiller.' [This is a highly compact, purpose-built heat exchanger designed to efficiently transfer waste heat from the secondary battery-cooling loop to evaporated refrigerant from the car's A/C circuit. The evaporated refrigerant is used to re-cool the secondary loop in extreme-temperature conditions.] In designing the chiller we also had discussions with **CPI** so that we understood each other and to ensure the systems integration works well.

Q: How far up front did Behr work with the GM Volt engineering team?

Krueger: We've been involved since the very early stage of the project. We were part of a concept consortium which brought together the basic concept of how the thermal management system of this very unique range-extended car could work. We started obviously with a lot of design studies and thermal analyses. Then we got the production contract. We also helped optimize the thermal management technologies when GM revised the car's aerodynamics during body development.

Q: What learnings did you and your team take away from the Volt program?

Krueger: First, that early involvement is key to the program's success. If we had not been involved with the program from the beginning, it would have been difficult to pull it together in the end. Cooling of the electric drivetrain is in some ways more challenging than cooling conventional IC vehicles. By working with GM on Volt we learned a lot about the needs of advanced Li-ion batteries and how to optimize the next generation of EV thermal systems. We have great ideas on how to make them even more robust and help to lower costs.

A unique electrified transaxle

Micky Bly, GM's Executive Director, Electrical Systems, Hybrid & Electric Vehicles and Batteries, said future generations of the Voltec propulsion system are well into development.

energy capacity in reserve than during Normal Mode operation. This causes the ICE's revs to rise a few hundred rpm, providing supplemental power and boosting the charge-sustaining capability of the ICE.

"When you have a substantially downsized engine as we do—we call it "half-sized" in terms of its power-delivery capability of the electric side of the vehicle—you need to be able to reach into the battery and pull that extra performance," Nitz said during a Western states test session last May.

The Specifications section in this publication provides details of Volt's powertrain component set. But it wasn't until the car's media launch that GM officially revealed the internal workings of the new 4ET50 electrified transaxle. Various mechanical and electronic-control aspects of this cleverly designed, slick-operating device were first implemented in GM's Two Mode drive developed for C/D-segment front-drive applications. Its initial application was to be the 2010 **Saturn** Vue Green Line prior to Saturn's closing.

The Two Mode Vue, a PHEV, was configured for EV-only range of more than 10 mi (16 km). Higher speed and load demands would engage the vehicle's ICE and/or electric power to propel the vehicle.

4ET50 trickery yields benefits

GM's recent surprise revelation with Volt is the capability to clutch-in the 55-kW generator motor and connect it to the ring gear of the planetary gearset for greater operating

Battery Use	2010	Around 2015	Around 2020
HEV-focused batteries	>32 kW	>32 kW	>32 kW
	260-300 V	260-300 V	260-300 V
	$45-60/kW	$30-40/kW	$20-30/kW
E-REV-focused batteries	>120 kW	>100 kW	>100 kW
	>8 kW•h usable	>8 kW•h usable	>8 kW•h usable
	$500-2000/kW•h	$300-400/kW•h	$200-300/kW•h
Data derived from industry targets. Source: GM			

GM and other OEMs expect advanced lithium battery costs for automotive use to fall while battery performance rises—but neither will likely happen as quickly as product planners would prefer.

efficiency. Under most road speeds and loads, the engine/generator is waiting to be deployed when battery state-of-charge drops below 35-30%. It's basically along for the ride unless the ride is longer than Volt's 25-50 mi (40-80 km) of battery range.

When the battery is depleted, the generator engages to maintain minimum SOC until the car can be plugged in for cheaper and more efficient static charging. Torque to the drive wheels is provided by the 111-kW traction motor coupled to the planetary's sun gear.

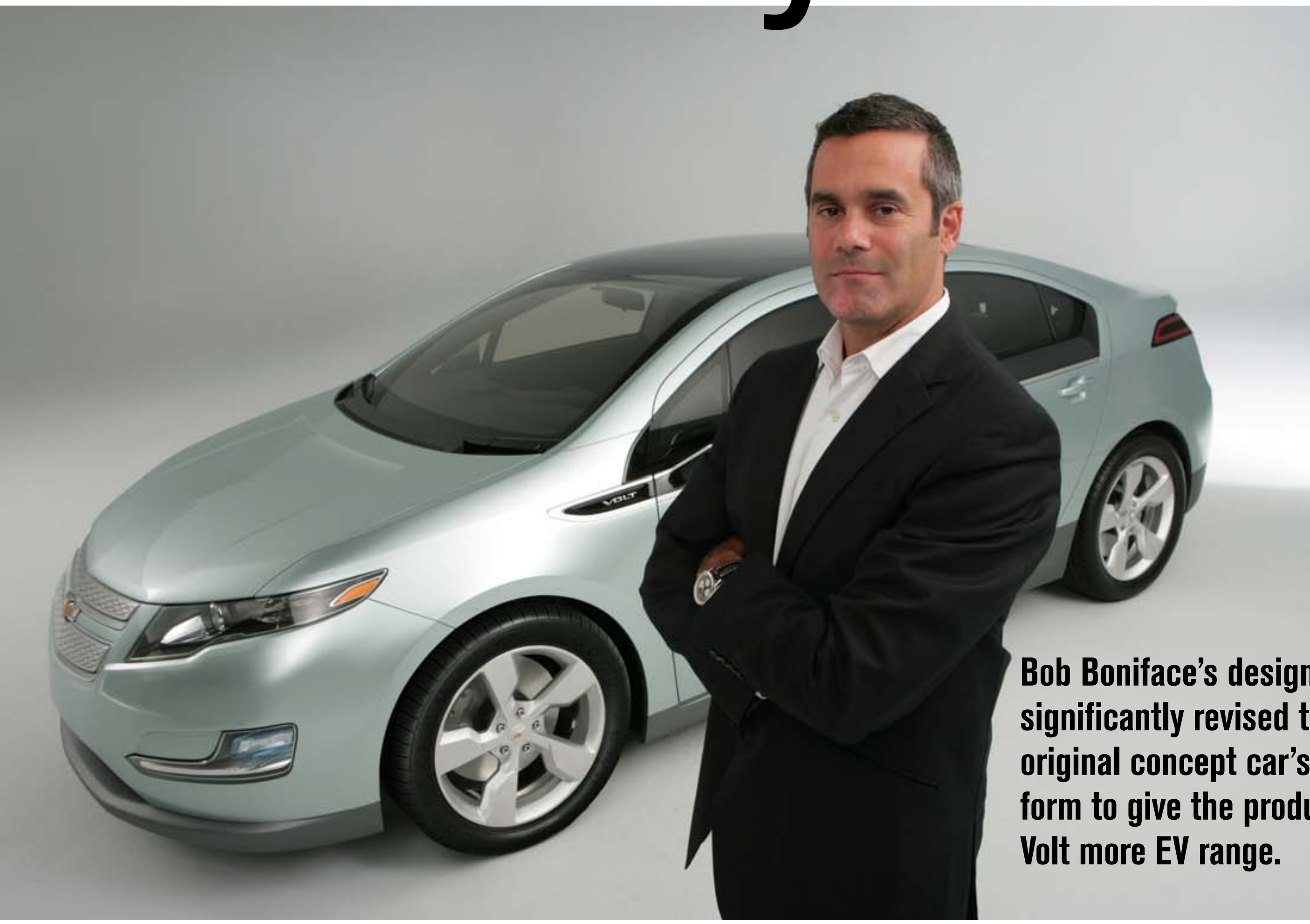
But in a few narrow operating conditions, typically accelerating from 70 mph (113 km/h) while in extended-range mode, the shaft speed of the 111-kW traction motor begins to exceed its peak efficiency. So the system's designers took advantage of the more direct and efficient mechanical connection to the car's wheels offered by coupling the generator and ring gear. In doing so, the generator brings the traction motor's shaft speed down to a more optimum rpm.

GM engineers claim the resulting power flow provides a 10-15% improvement in highway fuel economy.

The engineers set up this subtle technique because the 4ET50's three hydraulic clutches, two electric motors, planetary gearset, and ample control software gave them the right stuff to do it. "If the hardware and controls are there, why not use them," commented Volt VLE Tony Posawatz.

So is the Voltec drive system a hybrid or something else? The car simply cannot move without power from the electric motors. Remove the traction motor from the equation and the ICE generator cannot propel the vehicle alone. Remove the ICE, and Volt remains an EV.

Sweating the body details



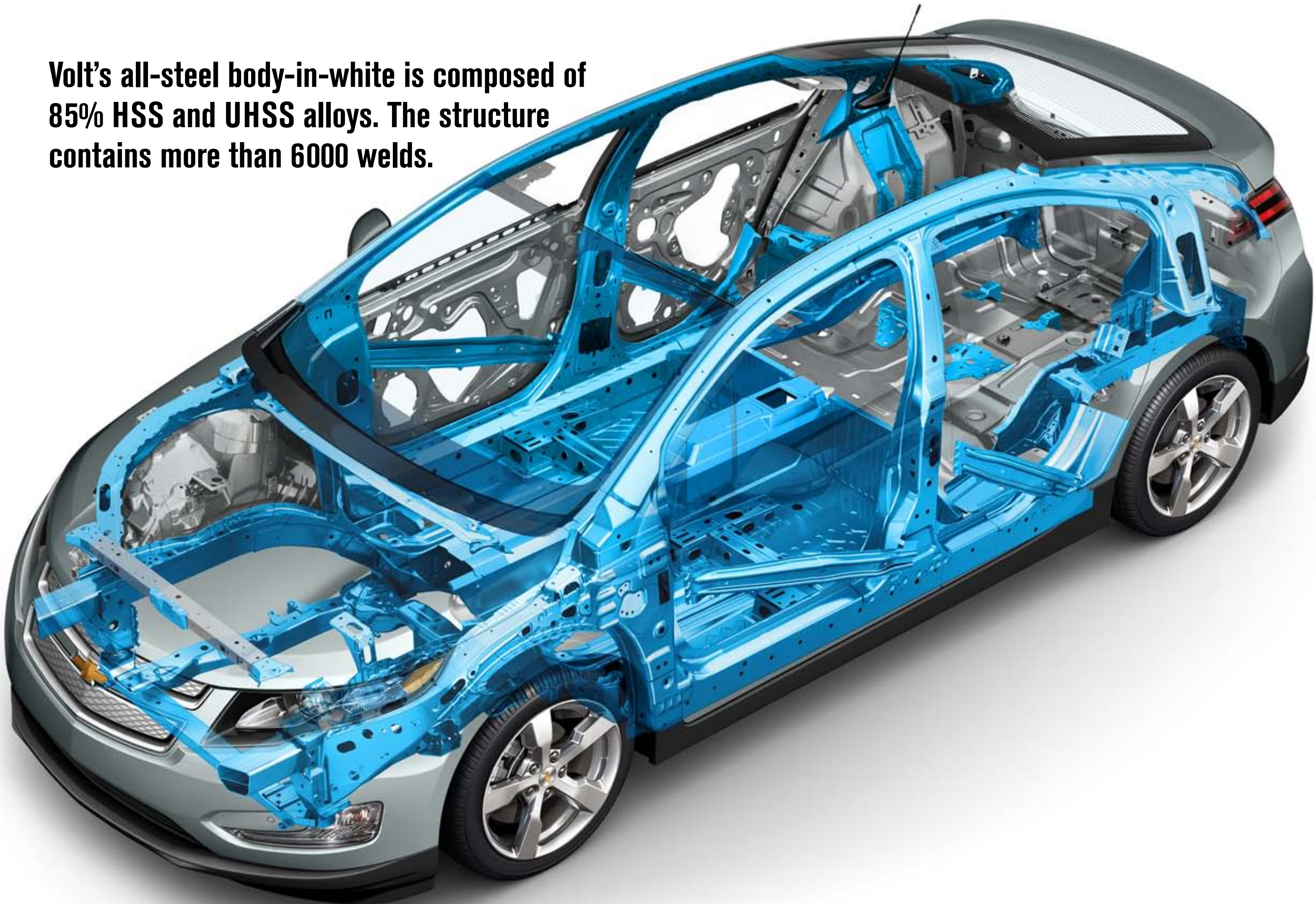
Bob Boniface's design team significantly revised the original concept car's exterior form to give the production Volt more EV range.

Extensive wind-tunnel work gave Volt a shape that's slicker than it looks. But engineers aren't happy with the curb weight.

by **Lindsay Brooke**

Advanced powertrain engineers and eco-enthusiasts argue convincingly that Volt's technology crown jewel is its electrified propulsion system. And they're right. But the car's overall efficiency, and success in the marketplace, also hinges on its aerodynamics, styling, package efficiency, and occupant protection.

The body form and construction count as much for electrified vehicles as it does for conventionally powered ones, perhaps even more. Witness **Toyota**'s Prius, whose overall wedge shape and tall greenhouse make it far from a handsome car. But that look struck a



Volt's all-steel body-in-white is composed of 85% HSS and UHSS alloys. The structure contains more than 6000 welds.

major chord with hybrid early adopters and cemented it to the point that Honda paid homage with the current-generation Insight.

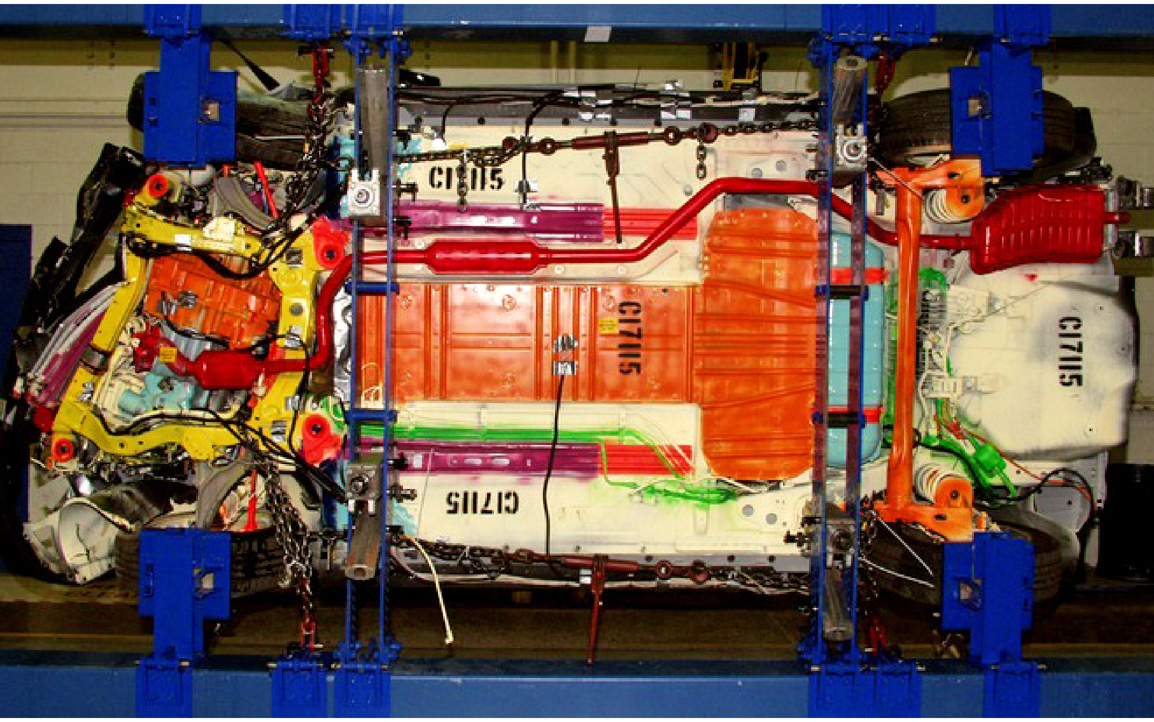
The "Prius look," often satirized by editorial cartoonists, became the face of the hybrid movement.

But when **General Motors** began developing Volt as a concept car for the 2007 Detroit auto show, Vice President of Global Design Ed Welburn's team had no intention of following the crowd. Nor did they simply stuff the E-REV powertrain into a mildly restyled existing body.

"The challenge to the designers wasn't to design the most beautiful car imaginable and accept the compromises you have to make to do so," explained former GM Vice Chairman Bob Lutz on GM's Fastlane blog. "It was, make no compromise to fuel efficiency and electric range, and then do the most beautiful design possible around those aerodynamic dictates."

The task of directing Volt's four-seat body design was given to Bob Boniface, a graduate of Detroit's **College for Creative Studies** who had worked in **Chrysler**'s styling studio before joining GM in 2003. Boniface had worked on the Corvette and Camaro design teams prior to being assigned to a new group dedicated to hybrid,

Sweating the body details



Post-test image showing the result of a 30° frontal impact conducted at 40 mph (64 km/h). The test rig has been rotated up, showing that the T-shaped battery pack (painted orange) was not affected by the impact. Chief Engineer Andrew Farah expects Volt will achieve 5-star ratings for both front and side impact.

EV, and fuel-cell vehicle design based at GM's Advanced Design Center.

Their sporty Volt concept car, with its extremely squat greenhouse, tall beltline, and big-shouldered stance, echoed the new Camaro and helped make Volt an immediate sensation. But soon after, in early 2007, reality struck when GM put the concept car into the wind tunnel.

"Our early tunnel work showed we had some work to do to improve the car's aerodynamics," Welburn told *AEI*. He said everyone involved recognized the car's drag had to be reduced significantly for it to deliver 40-mi (64-km) battery range. An E-Flex Systems Design Studio with Boniface at its helm was established to prioritize Volt's body development while developing styling proposals for future electrified vehicles.

"When Volt was approved for production, I decided we needed a dedicated mix of designers and engineers from the show-car team, working together with people from vehicle aerodynamics and the production side, and they needed their own creative space," Welburn said. The E-Flex design group grew to 50, and more than a year of aerodynamic development followed.

The evolved Volt was revealed in September 2008 during GM's centennial celebration in Detroit. This was essentially the production body form, the result of approximately 500 h of wind-tunnel development, according to Boniface. At the GM 100 event, he walked around the improved Volt detailing the changes to *AEI* and other media. At first glance the car looked more conventional, with a taller greenhouse, and less Camaro.

But the real aero gains were found at the corners. The leading edges of the front fenders were rounded and refined to create consistent laminar airflow down the body sides. The car's front fascia was made flush and the frontal air intake was now handled by a horizontal opening below the grille rather than by the grille itself, which became ornamental. The rear corners were resculpted, their edges sharpened.

Boniface said much attention was given to the rear spoiler, rocker panels, and the "speed" (rake) of the A- and C-pillars to minimize turbulence over the roof, and reduce drag overall.

"We sweated the details in so many areas," he recalled, "and gained many counts of aero in the end."

Boniface eventually revealed that the production Volt's coefficient of drag (Cd) would be 0.28. This was significantly less "slippery" than the EV1's groundbreaking 0.19 Cd, which was achieved with the help of partially faired rear wheelhouses. The Volt team wanted to avoid fender skirts.

Volt's new lower-drag shape achieved a lower Cd number than that of GM's reigning aero king, the Corvette (0.29 Cd). It also beat **Honda**'s Insight (0.32 Cd) and Toyota's Prius.

"We tested both a 2010 Prius with 17-in wheels as well as the new Insight," he noted. The Prius came in at 0.30 Cd, and that number was also verified in the tunnels of both **Ford** and Chrysler." Toyota officially claimed 0.25 Cd for Prius.

Curb-weight compromises

As a concept vehicle, Volt suggested GM would deploy significant lightweight-material content if a production version was approved. The extended-range powertrain was designed to be plugged in for charging, thus mandating a relatively large and heavy battery pack. Mass-reduction countermeasures on the concept were led by various thermoplastic body elements developed by the former **GE Plastics** (now part of Saudi-owned **SABIC Innovations**).

"We were able to take mass out of the Volt in order to optimize its overall efficiency," commented Jon Lauckner, who brainstormed the Volt concept and was GM's Vice President of Global Program Management at its debut. Lauckner strategized that high composites content, some of it using recyclate, would also help boost the car's eco-cred. GM consulted **GreenOrder**, an independent auditor on all things environmental, regarding the benefits of using certain materials.

When the concept rolled out in Detroit wearing Noryl GTX front fenders, veteran autowriters recalled GM's past quality issues due to use of composite fenders on various models. Volt's door panels were molded in Xenoy iQ resin (a collaboration of GE Plastics and **Azdel**), and its roof panel and decklid made with Lexan GLX and coated in Exatec.

These and composites applications, including plastics window glazing, offered a 30-50% mass reduction per part, according to Amanda Roble, Executive Director of the former GE Plastics' Automotive business. Even the car's low-voltage wire harness was made from GE's nonhalogenated plastics, which Roble estimated was worth a 25% weight reduction compared to traditional wire.

But the dream of diverse exterior-body panel materials evaporated almost immediately when Volt was green-lighted for production, according to Vehicle Line Executive Tony Posawatz. "Incorporating a lot of new materials ideas into concept vehicles is part of the reason we do concepts," he said.

The decision to base Volt on the global Delta II's 100% steel architecture offered scale, cost savings, and proven assembly quality, Posawatz noted. The body is commendably stiff in torsion, at 24-25 Hz. That's due to extensive finite-element modeling, a

An interior **trendsetter**

Paul Haelterman

Volt is in the vanguard of vehicle cabins that are stylish and also energy-efficient, says automotive interiors expert Paul Haelterman, Managing Director of Global Automotive Consulting at **IHS Automotive**.

Q: What interests you most about Volt from an interior-sourcing perspective?

Haelterman: That **Lear** Corp. is the second-largest supplier on Volt, based on dollar value. The battery cell supplier **LG Chem** is the top content supplier. Lear supplies the Volt seats but they also have the charging hardware sets. They picked up the electronic technology when they purchased **United Technologies Automotive** a while back. Volt's seating configuration is unique—four buckets. You get a manual height adjuster for driver and passenger, and a leather option. That's about it.

Q: Volt's interior team chose to use the car's seats to heat and cool the occupants directly, rather than conditioning the cabin air which gobbles electricity. Will we see more of this strategy?

Haelterman: Yes. Reducing energy consumption of key components such as the HVAC and other electronic devices is a smart strategy that's gaining a lot of attention. So are EPS [electric power steering] and electric coolant pumps. Everybody needs to reduce parasitics across the vehicle. The problem with EVs is there's no heat engine—or in the case of stop-start hybrids when the IC engine shuts off at a stop you no longer have thermal capability.

Q: With more EVs coming into the market, do you expect more use of seats as primary heaters?

Haelterman: Yes. It's the easiest, lowest-tech solution. With seat heaters you're not talking that much expense. Currently the technology costs around $10 per seat. If you install them as standard equipment, it makes everybody's life easier.

Q: When will electric HVAC become more viable?

Haelterman: As the number of EV and high-voltage hybrid programs increase. In many cases the OEMs are jumping to this seat-based cabin heating solution as a temporary step until the really good electric HVAC solutions are ready.

Q: When will electric HVAC hit the market in volume?

Haelterman: I believe it will be the middle of the decade before electric HVAC starts to show up in any appreciable numbers, maybe 1-2% of the HVAC systems market. And it will be the end of this decade before we see real volume—perhaps 10-15% penetration by 2020.

Sweating the bo

ody details

The centerpieces of Volt's cockpit are the multiconfigurable instrument cluster and center stack, the latter styled to resemble an iPod or similar portable device.

The Volt MPV5 is the most recent Volt spinoff. The Delta II-based concept was revealed at the 2010 Beijing auto show and points to GM's intent to proliferate EREV iterations.

commitment to high-strength and ultra-high-strength steel alloys (comprising 85% of the overall structure, according to Posawatz), more than 6000 welds, and using the battery pack as a semistructural member.

Chief Engineer Andrew Farah and other engineers on the Volt team are on record as not being happy about Volt's 3781 lb (1715 kg) curb weight. This is perhaps the car's major engineering compromise due to the need to carry a 16 kW·h battery, use the relatively large iron-block 1.4-L ICE, and get the car into production on an extremely aggressive timetable with high build quality.

"Looking ahead, we can optimize many of the technologies as aspects of the car that are somewhat suboptimized on Volt, due to the program timing and our focus on getting the battery absolutely right," Farah explained.

Examples of GM's plans for future E-REVs include the **Cadillac** Converj coupe, which was mothballed during the automaker's financial crisis prior to bankruptcy, and the **Chevrolet** MPV5, an E-REV-powered crossover-type people mover concept shown at the 2010 Beijing Auto Show.

The six-passenger MPV5's design and aero details are based on the production Volt, and showcase the architectural stretch of the Delta II-derived platform. MPV5's 108.6-in (2758-mm) wheelbase is 0.6 in (15 mm) longer than Volt's. Its body measures 180.5 in (4585 mm) overall, 7 in (178 mm) longer than Volt. It's also 2.9 in (74 mm) wider and 7.1 in (180 mm) taller.

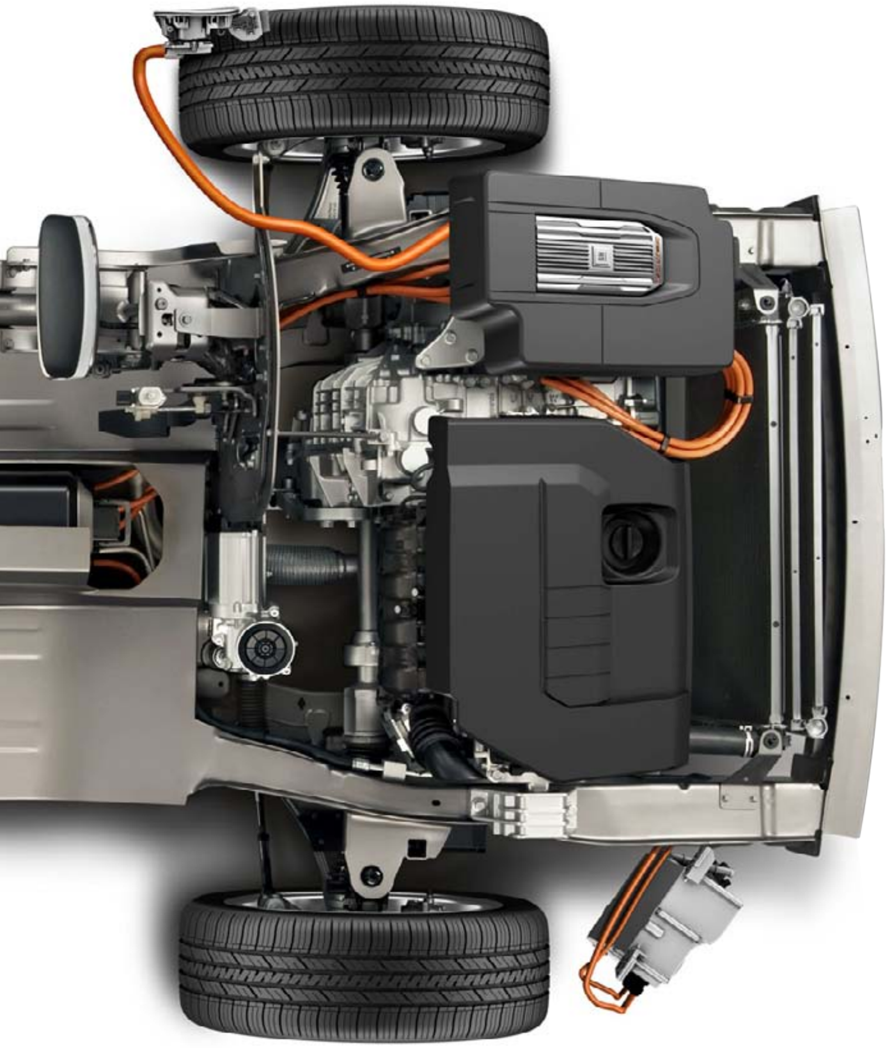
MPV5 was created by GM's North America Crossover Exterior Design team, noncoincidentally headed by Bob Boniface, with input from GM's **Holden** studio. The concept is a good indicator of how GM aims to leverage Volt learnings to spin many new E-REV body styles and vehicles.

A chassis that Cruzes

To speed development and minimize cost, Volt shares key underpinnings with its high-volume cousin.

by **Lindsay Brooke**

Bringing an all-new advanced battery and electrified powertrain to market in less than four years required a significant investment in engineering resources for **General Motors**, including hiring hundreds of electrical engineers and battery technologists. So when it came to deciding on the car's body structure and chassis systems, Volt's strategic planners wisely chose not to give the vehicle an all-new chassis and suspension system to go with the high-tech drivetrain.



Volt's underbody structure (concept shown) has some unique features. Its deep center tunnel accommodates the large, T-shaped battery, which helps the body achieve a claimed 24-25 Hz bending frequency. The structure contains a high content of high- and ultra-high-strength steel alloys.

"We had a lot of stuff on the critical path with this new powertrain. Leveraging the Delta II architecture for the body and suspension made sense in terms of keeping the program on target," former GM Vice Chairman Bob Lutz told *AEI* in early 2009.

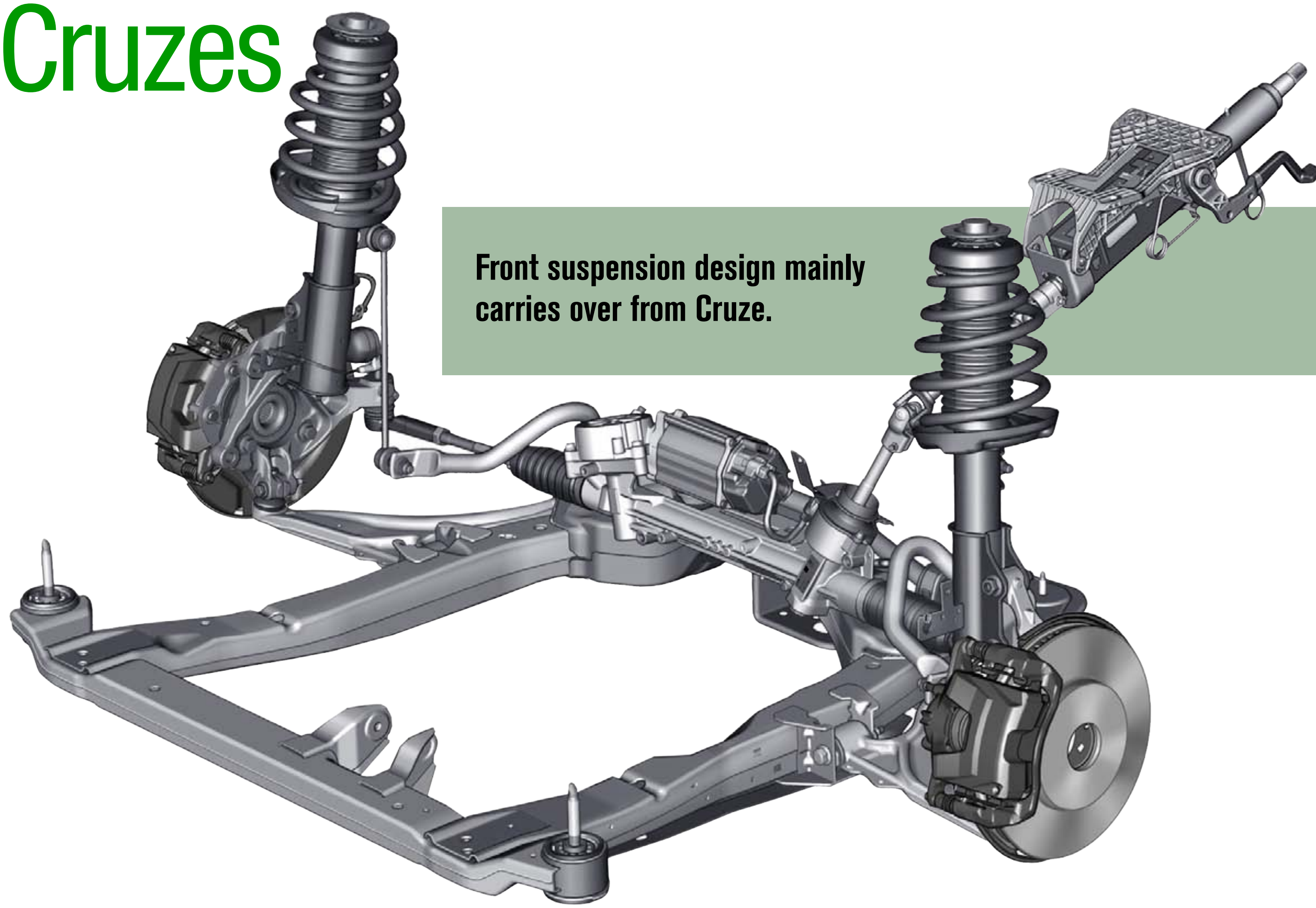
That doesn't mean Volt is merely a **Chevrolet** Cruze in disguise. The two vehicles share some of their bills-of-material, but Volt's underbody stampings and assembly are significantly different. In particular, the geometry of its deep center tunnel is designed to accommodate the 5.5-ft-long (1.7-m-long) T-shaped battery pack and its attendant electrical and coolant-pipe connections.

Various underbody members are dedicated to supporting the 375-lb (170-kg) battery pack.

GM engineers also note that Volt's underbody contains greater content of high-strength and ultra-high-strength steel than its conventional cousin.

Volt and Cruze are built in different assembly plants, but they could easily be processed

A chassis that Cruzes



Front suspension design mainly carries over from Cruze.

on the same line without any tooling changes. Key dimensions are very close—they share a 105.7-in (2685-mm) wheelbase—but Volt's front and rear tracks (61.2 in/1554 mm and 62.1 in/1577 mm, respectively) are slightly wider and thus more muscular-looking than Cruze's.

Volt's front MacPherson-strut-type suspension hardware and geometries are virtually identical to those of Cruze. Same goes for their rack-mounted electric power steering system with **ZF** steering gear. It's a dual-pinion system (one pinion is used for steering, the other to add assist) with variable assist.

A combined electric motor and sensing unit monitors steering angle, and delivers appropriate assist to the steering gear in all scenarios. The system draws its power from a 12-V battery in the rear of the vehicle.

Volt's semi-independent rear suspension geometry is based on the standard Delta II with subtle unique changes to compensate for Volt's different center of gravity, heavier curb weight (3781 lb/1715 kg vs. Cruze's 2900 lb/1315 kg), and resulting different handling characteristics.

The compound-crank torsion beam features a double-walled, U-shaped profile at the rear. Volt's system adds a variable-section cross-car beam, to which the control arms are attached with a patented "magnetic-arc" welding process.

Front and rear hydraulic ride bushings help eliminate road harshness.

Helping GM put the **brakes on Volt**


Dan Milot

General Motors tapped **TRW**'s experience in developing electrohydraulic brake-control technologies for the 2006 T900 hybrid trucks and the **Saturn** Vue Hybrid and Vue Fuel Cell Vehicle for the Volt program. Dan Milot, Chief Engineer for TRW's North American Advanced Control Systems group, explains.

Q: What specifically did TRW contribute to the 2011 Volt program?

Milot: TRW supplies the braking systems actuation and slip controller, the ABS/ESC functionality, to the vehicle. This also encompasses the regenerative braking. It required us to begin working with GM very early in the program.

Q: What did your team learn from this program?

Milot: Volt's type of powertrain is different from the GM Two Mode hybrid. The Two Mode has a transmission that's mated with the two electric motors, but the ICE is the primary engine. Volt is primarily an electric-motor-driven vehicle. Its electric drive mode produces scenarios where the vehicle NVH is significantly different than any other car.

With Volt's configuration, the effects of wheel inertia from the traction motor are different than in a vehicle with a conventional powertrain. That includes during ABS and traction control activation, and even the interface with the powertrain for developing torque. We did a lot of work around that to ensure our ABS, ESC, and even the regen blending will quickly generate the actual braking torque for us. Then we determined the friction braking response time to make it all seamless to the driver.

Q: What was GM's brief to TRW for tuning the 'feel' of Volt's braking?

Milot: Putting 'drag torque' into the regen system is meant to replicate the deceleration feel of a manual transmission. Compared with some electric vehicles that have fairly aggressive regen 'feel' due to a high calibration, Volt's braking is tuned to feel more like a conventional vehicle. Lifting off the throttle is not intended to be the primary means of braking; that's for the brake pedal.

The GM engineers provided their own level of what we call 'base brake' software, which we integrated into our control module. That had to interface with the powertrain that's doing the actual brake blending. There was a lot of work to achieve this. We had the powertrain guys and the braking guys working closely together every day to make sure it is a seamless experience for the driver.

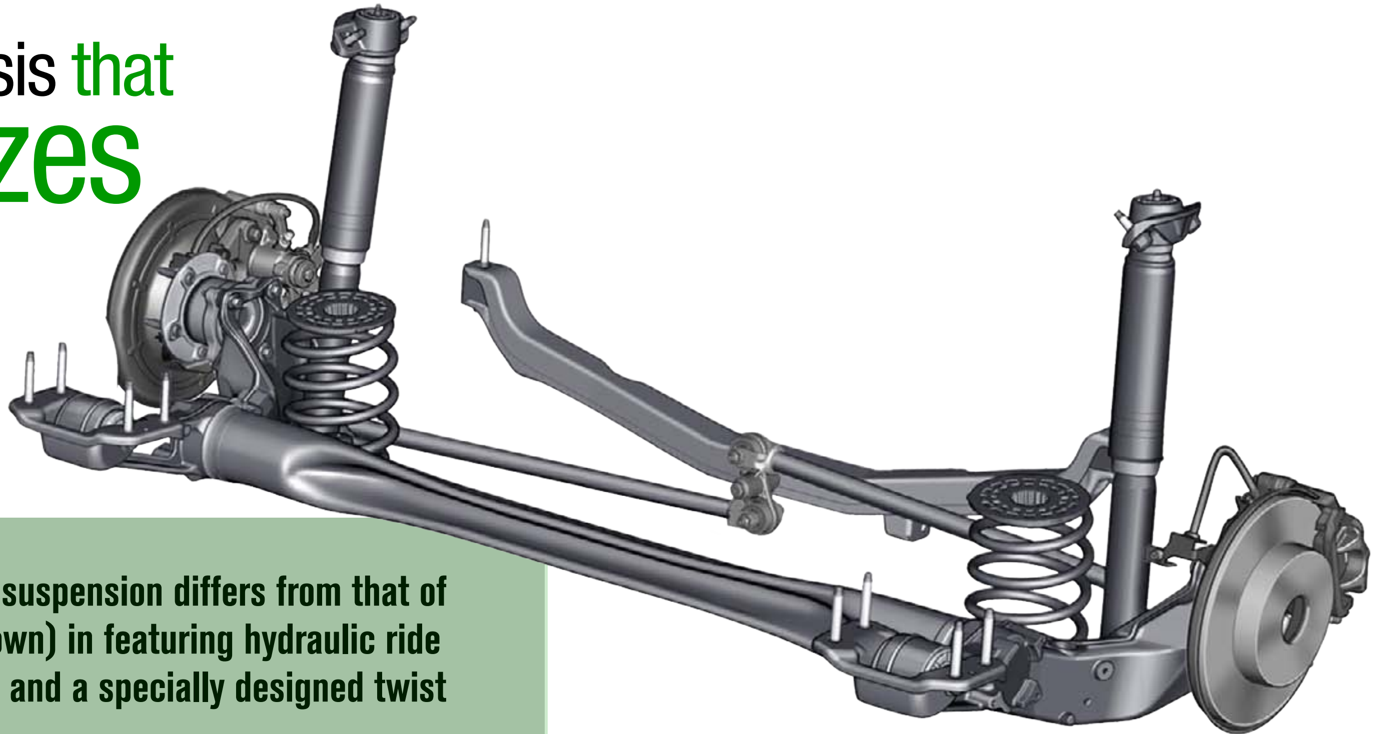
Q: As an engineer, what did you learn from working with GM on Volt?

Milot: A big learning was the car's NVH, or lack of it. With an EV when you come to a stop, it's dead silent. If your braking system has to turn a motor on, or if anything comes on, you can hear it.

You have to be careful how you control your motors and do your mounting, and pay attention to many other details in these vehicles.

We spent a lot of time with GM, including directly with their NVH team, to find solutions to make the system quieter and quieter.

A chassis that Cruzes



Volt's rear suspension differs from that of Cruze (shown) in featuring hydraulic ride mountings and a specially designed twist beam.

Volt's electrohydraulic regenerative braking system is, of course, different from Cruze's conventional hydraulic brakes. It is calibrated to capture energy up to 0.2 g for transfer back to the battery. The friction braking system features large rotors with a GM-patented coating known as FNC that is impregnated into the rotors. According to Volt Chief Engineer Andrew Farah, the new coating protects against corrosion and promotes longer life.

The brake system's careful blending algorithms provide 100% regen, 100% friction braking, or any combination of the two. (See sidebar).

Rolling assurance

Farah's vehicle-dynamics team aimed to ensure Volt did not sacrifice rolling-resistance efficiencies for good handling performance. From the earliest days of the program, GM worked closely with **Goodyear** to develop a tire that helped save propulsion energy without sacrificing ride quality and grip.

The resulting Goodyear Fuel Max tires are standard on Volt, as well as the Cruze Eco model. GM tests showed they help Volt achieve 1 additional mile of range on electric-only mode, said Farah.

The main challenge in developing tires for EVs is balancing ride quality, grip, and low-noise operation, noted Chad Melvin, Goodyear's Project Manager for the Volt and Cruze programs. His company's engineers refer to balancing tread wear, traction, and rolling resistance as "the performance triangle." Melvin recalled the tire's development path.

"At the same time GM was developing the Volt, we were in development of our Assurance Fuel Max line. The tread pattern for the Volt came concurrently with our replacement Fuel Max tire, so it seemed like a perfect fit."

He said engineers in Goodyear's Replacement Tire group developed the pattern in collaboration with GM, the two teams working in what he described as "excellent synergy."

"We were able to use the low-rolling-resistance technology that we were developing for the replacement market for the Volt as well. There were some caveats, because the Volt tires were developed specifically for it. But, visually, the tread patterns of the Volt and Cruze Eco tires are visually the same."

During the tire's development, Goodyear used its advanced modeling techniques to develop a tread cavity and mold shape that would allow both fun-to-drive and reduced rolling resistance qualities. Melvin's team worked closely with GM, whose engineering team provided kinematics and compliance data to go with Goodyear's rolling-resistance modeling work.

Goodyear's new Assurance Fuel Max tire was designed for Volt and the Cruze Eco. GM tests show the tires give the car an extra mile range in EV mode.

"The parallel development allowed us to model how the Volt was going to handle on the road," Melvin said. Optimization of that process created the mold shape.

The new tires also feature the latest iteration of Goodyear's advanced compound technology, which incorporates what Melvin calls "functional polymers." The Volt tire has a "dual-cap" tread—it has two compounds.

"This allowed us to provide a bit more traction than our replacement line of Fuel Max tires, which has a functional polymer as well," Melvin noted. "The Volt is just a slight tweak of that, because GM wanted to get a sportier feel with better stopping distance as well. We were able to achieve that through the modeling and compounding."

He said the Assurance tire's low-rolling resistance is achieved through design and not by using higher pressures than conventional tires.

In terms of 'hurrah' moments in his team's effort, Melvin cited creating the mold shape using advanced tooling, then finding the tire achieved the level of performance that the tire maker's model had predicted.

"That's always a good feeling," he said, adding that the advent of electrified vehicles has Goodyear dialing up its game in designing quieter-running tires that don't sacrifice safety and fun-to-drive qualities.

"We didn't go into this program thinking we're going to design an ultimate low-rolling-resistance tire for GM and the Volt," Melvin noted. "We also needed to make the vehicle fun to drive, with good traction, and best-in-class stopping distance.

"Achieving the overall balance was a challenge, and the results are something that will impact our future developments for these types of vehicles," he said.

A new role for the ICE

Volt's modified Family Zero inline four is along for the ride—until it's needed.

by **Lindsay Brooke**

Judged by its individual components, Volt's 1.4-L four-cylinder combustion engine resembles its nearly identical cousin in the **Chevrolet** Cruze. It has got an aluminum DOHC head with four valves per cylinder. Its hollow-frame iron cylinder block is a thin-wall casting, making it nearly as light as a comparable aluminum block while retaining iron's inherent strength and noise-damping qualities.

Derived from GM's global Family Zero of small-displacement gasoline inline triples and fours, the Volt engine was designed for efficient operation. Its hollow camshafts are manipulated with two-step variable electrohydraulic phasers. Its lubricant is distributed through a variable-displacement flow-control oil pump to reduce parasitics under light load conditions. The thermostat is map-controlled.

There is no starter motor; the car's generator motor handles that task. And the engine's undersquare bore/stroke promotes good low-and mid-range combustion efficiency, particularly in turbo versions.

But a closer look, and a drive in the Volt, show this is not a typical Family Zero unit (nor is it turbocharged). It is governed to 4800 rpm, the speed at which the engine typically runs when the Volt's powertrain management controller calls for the generator to engage.

There are unique control algorithms (Engine Maintenance and Fuel Modes) that start the engine every 45 days and run it for up to 10 min, in case the owner has been driving solely on battery power, to lube the internal surfaces and run the diagnostics.

It's an off-the-shelf engine almost invisibly modified to serve the Volt's series-hybrid operating mode.

"With our propulsion architecture, the role of this engine is completely different from any other car in the marketplace today, or from what we currently know is coming," said Pam Fletcher, GM's Global Chief Engineer, Hybrid and Electric Engineering.

She noted that the engine is calibrated to operate "completely differently" than engines in the Cruze or other conventional powertrains.

The 2007 Volt concept used a three-cylinder engine, but engineers opted for a modified four-cylinder 1.4 L from the same Family Zero portfolio for the production car. It was the smallest engine in GM's global portfolio capable of delivering the necessary output for Volt. It is shown here with the new 4ET50 electrified transaxle attached.

A new role for the ICE


Veteran GM Powertrain engineer Pam Fletcher considers the Volt program to be a career highlight.

"We did all of our development around maximum efficiency," noted Fletcher, who also serves as the chief engineer of GM's plug-in-hybrid program. "It was a different game than the one we usually play in balancing power and efficiency, because this engine's really set up to run like a generator."

The engine's role in Volt allowed the powertrain development team many degrees of freedom for calibration, as the car's electric generator and traction motors deliver positive and negative torque at a wide speed range. The engine thus does not respond directly to demand from the driver's right foot as in a conventional vehicle, because you are effectively driving the traction motor, not the ICE.

GM has yet to receive an official **SAE** output rating for it, but the engine produces approximately 63 kW (84 hp) at 4800 rpm. Combined with the full electric drivetrain, total output is 150 hp (112 kW).

"The engine's output numbers are all we need to maintain a minimum battery SOC [state of charge] when the car is cruising at highway speed," Fletcher asserted.

She explained that ideally a purpose-built power unit would optimize the Voltec propulsion system, and likely be more compact and lighter in the car. But opting for the available Family Zero four saved development time, vs. developing a clean-sheet engine to meet the aggressive production timetable.

This was the smallest engine in GM's global portfolio capable of delivering the necessary horsepower for Volt, she said. The engine's 10.5:1 compression ratio was designed to cope with the premium gasoline GM specifies for Volt, due to how the Voltec system is calibrated to handle multiple driving modes in various conditions. Fletcher and other GM engineers are not particularly happy about the premium-fuel spec. They note that an E85-capable version is scheduled for MY2012.

WOT nearly all the time

Integrating the ICE with the car's electric drivetrain consumed much development time, Fletcher said, with multiple iterations of control code developed and tested.

"We put an enormous effort into making the ICE pleasant and unannoying to the customer when it comes on," she said. "We could have chosen to operate it at one fixed speed and load, or perhaps a couple fixed speeds and loads, where you have the balance of maintaining battery charge and not always dissipate charge of the battery, and pick a point that's very efficient—a very specific BSFC [brake-specific fuel consumption] 'island.' But such a powertrain would be very awkward to drive.

"We could still make the propulsion system smooth and responsive to driver input, but from all the driver's sensory perceptions it would be terribly awkward," she said. "We recognized that as being very important. So we made a lot of choices and spent a lot of development to make it a comfortable, smooth, quiet, pleasant-driving vehicle as well as making efficiency a big priority."

Algorithm and control development was a main focus of Fletcher's team, as was working with its colleagues developing the clever new 4ET50 transaxle, based on GM's Two Mode hybrid technology.

"The engine operates at or near WOT [wide-open throttle] pretty much all the time that it's on," she said. "There are a few unique conditions where it doesn't. One of those cases is we do have an 'idle' condition, where we run the engine at less than WOT. To do this, we had to find an rpm point that's pleasing from an NVH standpoint."

The notion of "idle" regarding Volt's operating protocol seems unusual. But Fletcher explained there are times ICE operation is needed when the vehicle is not moving. It may be in the middle of a catalyst light-off, for example. Or it may be in a condition of low battery SOC, where it is necessary to put a little bit of charge back in the battery.

Then there is the aforementioned Engine Maintenance Mode, and Fuel Maintenance Mode. The former is for those drivers who mainly drive electrically and the ICE does not have to come on. GM wants the ICE to be ready for when it is needed, so every 45 days or so if the ICE hasn't come on, the controller starts the ICE in Engine Maintenance Mode and runs it for up to 10 min.

"We actually have a model such that we'll run it so that we get temperature in the oil, to get any accumulated moisture out of it, to basically keep good lubrication in the bearings and keep the gaskets and seals moist and sealing properly. Keep the oil conditioned," Fletcher explained.

The Fuel Maintenance Mode story is a bit different. Volt uses a completely sealed fuel system, its 9.3-gal (35-L) steel fuel tank slightly pressurized, so oxidation really does not come into play. But fuel is blended seasonally, so once every year if a Volt customer has not burned a tank of fuel, the controller will start the engine. This is to combust the fuel in the tank down to the point where the customer will have to add enough fresh fuel to blend it up to an appropriate volatility for the next time it is called to duty.

"In reality, people can be 'all-electric, all the time' with this car," Fletcher said. "But you buy a Volt to have peace of mind, to not have range anxiety if you want to travel more than 40 mi.

"We've built in these protection measures just for that. They'll burn a little bit of fuel, but the trade-off is considerable peace of mind."

Charging and connectivity

GM engineers designed in maximum flexibility for keeping the Volt juiced up and connected —to the grid and to the Internet.

by **Lindsay Brooke**

To know Volt, you must learn a new language. Vehicle electrification brings with it almost Defense Department levels of arcane terms and acronyms, particularly those related to vehicle charging and telematics. PEV (plug-in electric vehicle) and PHEV (plug-in hybrid) engineers have a head start with the new lexicon. For others, it is time to get smart.

GM's OnStar telematics offer almost unlimited opportunities to create value with Volt and its progeny, according to experts.

EVSE is electric vehicle supply equipment—the off-board hardware needed to supply charge energy to the vehicle. Volt's EVSE includes the vehicle's charging cord, residential or public charging stands, attachment plugs, power outlets, and the vehicle connector.

Charging with ac Level 1 uses 110/120 V ac from standard 15 A or 20 A household outlets. Charging with ac Level 2 takes 208/240 V ac up to 80 A. Level 1 is the standard charging used in Volt and the 2011 **Nissan** Leaf, with a Level 2 option available for both cars. Level 1 and 2 equipment is expected to serve as the workhorse of EV charging for the near-term future, according to experts.

Volt is equipped with an onboard 3.3-kW powered charger supplied by **Delta Electronics**. According to **General Motors** Engineering Specialist Gery Kissel, the unit is sized to the recharge requirements GM engineers set for Volt—to replenish the 16-kW·h battery to half its total energy capacity (8 kW·h) within 10 h using the Level 1 power supply. For Level 2, the requirement is a 4-h recharge, depending on efficiencies.

Many safety and durability requirements had to be met in developing Volt's Level 1 and 2 charging sets, explained Vehicle Line Executive Doug Parks. The design had to endure a 10,000-cycle life with exposure to dust, corrosion, and water. Besides complying with **SAE International**'s pioneering J1772 charge-connector standard published in early 2010, it also had to meet various **IEC** and **Underwriters Laboratories** standards. The durability tests for Volt's standard 120-V, 20-ft-long (6.1-m-long) charge cord include being driven over repeatedly by the vehicle.

The optional (left) and standard charging sets in Volt's EVSE. The standard 120-V set is stowed in the rear luggage area.

Volt's charging sets were developed by **Lear** Corp., whose engineers began working with the Volt team in 2008. Best known as an interior systems Tier 1, Lear has steadily expanded its focus on electrified vehicle technology since it acquired **UT Automotive** in 1999. Last year, more than 60% of Lear's patents were related to EV and hybrid technologies. The shift in R&D investment indicates where the supplier is placing its bets for the future.

Connecting Volt and OnStar

AEI's experience with Volt showed it to be as simple to recharge as a mobile phone. The car is also about as easy and intuitive to operate overall. "It's not a spaceship, and that's by design," explained Dave Lyon, who oversaw Volt's interior design and development as GM's Executive Design Director for North American Interiors.

Indeed, the Volt team leveraged its OnStar telematics technologies and organization to make the ownership experience convenient and seamless. On- or off-board charge programming, for example, can be done via smartphone when the vehicle is plugged in by going through the dedicated MyVolt.com website or through Chevrolet's Volt mobile application powered by OnStar Mylink.

Volt mobile apps offer owners the ability to use grid energy to pre-condition the car's battery before driving, depending on ambient temperatures. It can also remotely control cabin pre-cooling and heating, the latter via a new electric cabin warmer that operates when the combustion engine is not engaged.

"Early in development we realized that OnStar offers endless possibilities for connecting Volt and its owners to the energy infrastructure," noted Micky Bly, GM Executive Director, Electrical Systems, Hybrid &

Telematics and the Volt

Electrified vehicles offer unlimited technology and business opportunities to link the vehicle, customers, and the energy and communications infrastructures. **OnStar** CEO Chris Preuss recently spoke with *AEI* about his company's developments in this fast-growing sector.

Chris Preuss

Q: What's the level of importance of the **Chevrolet** Volt as it relates to the development of OnStar?

Preuss: It's huge. Because as much as Volt is a demonstration platform for the best of what propulsion technologies can do, it's also an example of the best of what telematics can do. That's how OnStar sees it. We believe 'smart grid,' and being present in the smart-grid area, is an enormous business opportunity for us.

Secondly, it's going to be a demand from consumers as they use these technologies to manage their lives. Nobody has really gotten into this space substantially, so a lot of our IT infrastructure development right now around the Web-based applications, and around how we're aggregating data from the vehicle, is focused on interacting with smart grid. We're on the forefront of this. And we're working with a lot of outside companies to tap that potential.

Q: GM engineers involved with vehicle electrification are spending greater amounts of time working with their counterparts at the energy utilities and with those developing charging hardware. How do you expect OnStar will leverage these activities?

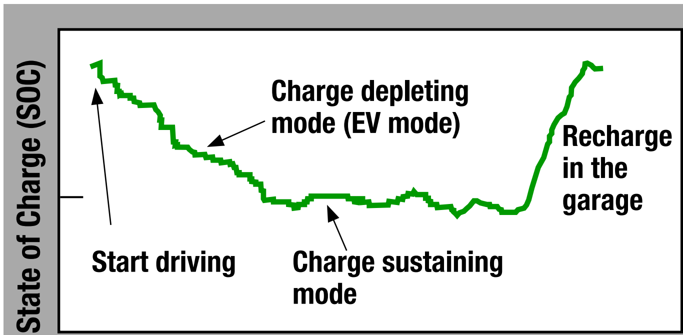
Preuss: As we talk about future business opportunities for OnStar, we might want to acquire technologies or companies that are in that [charging technology] space. It would be of key interest to us because we think Smart Grid is the future. It will be a big differentiator, and we've been involved from the ground floor.

Q: Is OnStar working with Jon Lauckner's GM Ventures group to seek acquisitions, as well as possibly sell IP or rights to GM and OnStar IP?

Preuss: Without being specific, we are very aggressively looking in this space—both in terms of what we possess and what we want to create. We're seeing more and more of our IT capability as 'core' technology—it defines the value in our products. From my perspective, it's our 'secret sauce' and it's a place where GM and OnStar lead. When I joined OnStar [spring 2010], I did not appreciate the level of development that was already resident in this space.

Verizon Chief Technology Officer Dick Lynch is the architect of LTE—the next-generation 4G cellular Verizon is launching this year. Dick is one of the biggest evangelists for OnStar—not just because he thinks it's a great service, but he knows what we've been able to figure out, how to move massive amounts of data, how to translate and analyze and make it consumer-usable. We do better than anybody out there.

The automotive telematics space is vast. I've spent two-thirds of my time working to understand it. Volt and its successors are just the beginning of what's possible in terms of vehicle-to-grid technologies, and telematics overall. There's some amazing stuff coming.



A simplified plot showing Volt's drive modes as related to battery SOC. The point is to rely on grid energy for power.

Electric Vehicles and Batteries. He believes Volt and other early EVs will require owners to learn new behaviors regarding both the human-machine interface (HMI) and the human-vehicle interface (HVI)—how we react to the vehicle.

"We're accustomed to charge our cell phones at night, and plug our laptops into docking stations, so having charging devices around us is a natural thing today," he said. "But we're not yet used to doing that with vehicles," he said.

"Early on, you'll want to check to see that the car's plugged in at night—maybe your kids took the car out, brought it back and didn't plug it in," Bly said. "One of our mobile-app features provides notifications around a variety of events, including battery state of charge. But seemingly more trivial but no less important is, 'Is the car plugged in at night?'"

He said the OnStar mobile apps allow Volt owners to communicate directly with their car, requesting and receiving text notices about charging status.

OnStar's almost unlimited upside, as it relates to keeping Volt owners connected to their vehicles, will come increasingly from remote-server-based tools and information. This technology trend is known as "cloud computing," and Bly believes it will help bring GM's PEVs into the mainstream by making them more user-friendly, capable, and, perhaps most importantly, rapidly upgradable.

Automotive electronics analyst Paul Hansen, publisher of the respected *Hansen Report on Automotive Electronics* agrees. He predicts "a wonderful convergence of 4G connectivity—zero latency, wide-wide bandwidth communications"—being linked to Internet cloud computing. Hansen reckons PEVs like Volt with sophisticated electronics architectures will serve as excellent platforms for this trend.

The physical act of charging Volt goes like this: Pop the hatch to the charge port on the left front fender. The standard 120-V portable charge-cord pack stowed in the rear cargo area enables Normal charging for most situations, and Reduced charging for when electrical current is limited.

Plug the charge cord's coupler into the receptacle until it clicks. The cord's LED charge-status indicators glow green to identify the vehicle can be charged. The LEDs flash red if the cord will not permit vehicle charging due to incorrect voltage or if the electrical outlet lacks a proper safety ground.

The process is basically similar with 240-V charging, a technology space that is already flush with suppliers. **Chevrolet** collaborated with **SPX Service Solutions** to offer the latter's 240-V home charging set priced at $490. That is before installation, of course, which must be handled by a certified electrician.

Chief Engineer Andrew Farah reckons a typical garage installation including local permits might cost $1500 to $2000, depending on location and codes. For that amount you could buy a lot of gasoline, EV skeptics argue.

As champion of GM's Plug-in Cities plan, Britta Gross sees progress in making electric energy a ubiquitous 'fuel' for vehicles.

But for most homeowners, the first charger installation will be the only one needed.

Setting standards critical to the EV future

The challenge of implementing Volt, **Opel** Ampera, and their progeny becomes evident when one considers the diversity of electric-energy providers worldwide. There are more than 3000 electric utilities in the U.S., and scores in Europe, making the many standards efforts currently under way key to documenting and getting the widespread consensus OEMs need if electrified vehicles are to move beyond their current niche.

"We have to get the technical interface between vehicles today and in the future on the same page as the grid today and in the future—and we've seen some recent progress on this," said Britta Gross, GM's Director of Hybrid and Electric Infrastructure Strategy.

Since the advent of Volt, she has helped build dialogue between GM, policy makers, energy utilities, and various industry stakeholders regarding the emergent EV-charging base. The "Plug-In Cities" plan she spearheaded is a simple one-page outline of the critical steps cities and states should put in place to make vehicle charging possible. "It's a starting point for what these communities should do to make cities plug-in-ready," she said.

Volt's engineering leadership believes home charging will be the most popular means to juice up the car for the foreseeable future. Lack of public charging won't be a problem due to the car's petroleum-fueled range extender, they noted.

Gross agrees. "All the advancements that must be made on the grid side—how to plug in a car; how to communicate between the vehicle and the grid (V2G) or between the utilities and the car; how we will one day work billing issues—don't have to be figured out on day one," she said. "That's because most of it becomes an issue only when you're talking about large volumes of vehicles. That's when we start to care that they're not all charging at the same time."

Setting expectations correctly is critical, she explained. For example, Gross noted that a few years ago utilities and automakers (including GM) were "not on the same page" in how they were answering PEV-related questions from consumers. "Utilities were talking about secondary use of batteries; they were talking about V2G and V2H [vehicle to home]. We said, 'Wait a second, guys! We've got to get the car right first.'"

Standardizing the EV charge-connectors' dimensions and function through the SAE J1772 standard (along with the wide-ranging

SAE International's J1772 charge-coupler standard will greatly simplify consumers' transition to PEVs.

J2836 communications standard) was a pioneering step toward getting the industry on the same page. J1772 will help minimize cost for automakers, charge-station suppliers, and energy utilities. It also greatly simplifies consumers' transition to EVs. With the J1772 hardware ready to go for Volt and other makers' PEVs in the pipeline, EV charging locations are expected to proliferate in the U.S. and in other regions.

SAE is developing a new version of J1772 that includes a standard for dc charging (also known as "fast charging"). Gery Kissel, who chaired the J1772 task force, said dc charging is still under development. He explained that the technology uses an off-board charger to connect directly to the vehicle's onboard high-voltage battery bus. Charging via dc allows for extremely high power (>100 kW) transfer and thus promises recharge times in minutes rather than hours.

Interest in faster charging times has sparked investigation of a vehicle charge connector that combines ac and dc capabilities in a single unit. But keeping the size of an integrated ac/dc connector small and lightweight is a technical challenge, Kissel said. Approval for SAE's dc charging standard is anticipated in the late 2011 time frame.

Meantime, Volt will be in the vanguard of what some experts see as a new era of vehicle propulsion and mobility technologies in general. The change from petroleum to electricity is not unlike moving from coal to oil—or shifting from the hay that "fueled" genuine horse power when the automobile era dawned, to gasoline.

"With an E-REV, there's a whole bunch of 'handshaking' between the vehicle and the utility," explained Britta Gross. "It's a new relationship, and we need to make sure it's a smooth experience for consumers."

In the past decade, "vehicle electrification" has rapidly evolved from a mere buzzword to a key element in every global OEM's product-development plans.

For the engineers charged with developing the technology solutions that will drive electrification, **SAE International** has created an exclusive new source of information. It's a new Vehicle Electrification Web portal at evsae.com created to be the "go-to" source for engineering professionals looking for the latest technical information on technology advances, product solutions, supplier news, and vehicle-development trends from the most plugged-in experts in the electrified-vehicle field. You'll also be able to find information on the latest SAE books, events, technical papers, standards, and training—as well as content from an increasing number of SAE partners. The site is being updated and upgraded continually, so check it out and come back often.

In addition, this SAE Vehicle Electrification digital magazine is the first in a series devoted to the most significant hybrid and electric vehicles and the current and future technologies being developed for them.

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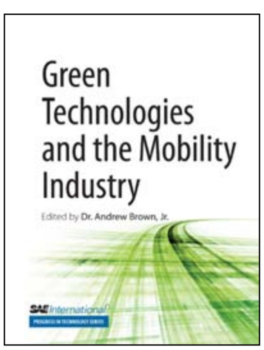
What's on evsae.com

Toyota takes hybrids off-highway

Evidence of automotive technology being used beyond the highway comes from **Toyota**. Using Hybrid Synergy Drive technology, subsidiary **Toyota Industries** Corp. (TICO) has launched the world's first internal-combustion hybrid lift truck in Japan.

Green Technologies and the Mobility Industry

This special Progress in Technology book, created with Dr. Andrew Brown Jr., **SAE International**'s 2010 President, features an overview of the state of green technologies today, select SAE technical papers, and a Worldwide Emissions Standards booklet developed by **Delphi**. A downloadable presentation as well as a streaming video interview with Brown complement the title.



Electric Motor Symposium

The **SAE International** 2010 Powertrain Electric Motor Symposium for Hybrid and Electric Vehicles will be held Dec. 1 in Stuttgart, Germany. The program will address technical issues as well as market growth projections, requirements and cost structures for three varieties of electric traction motors: permanent magnet, induction, and switch-reluctance

Hybrid power and energy for UGVs

"A Scalable Hybrid Power and Energy Architecture for Unmanned Ground Vehicles," an **SAE** technical paper published in November by researchers at **Penn State** Applied Research Lab and the **University of Michigan**, proposes a Hybrid Power and Energy for Robots (HyPER) system architecture that is easily scalable and facilitates the use of a wide variety of energy storage and conversion devices.

Hybrid and EV Academy

From Nov. 15-19, **SAE International** will offer its first Hybrid and Electric Vehicle Engineering Academy at SAE Automotive Headquarters in Troy, MI. The course covers vehicle engineering concepts, theory, principles, and practices necessary to understand electrified vehicle powertrains, and it will provide a collaborative, immersive learning experience comprised of lectures as well as structured practical sessions including case studies.