ELECTRICAL AND ELECTRONICS TECHNICAL TEAM ROADMAP

December 7, 2010

Executive Summary

Development of less-expensive, more-efficient, smaller, and lighter power electronics and electric machines for electric traction systems is necessary to achieve the widespread use of hybrid and electric vehicles, an essential part of the strategy to reduce the U.S. dependence on foreign oil. In spite of a rapid average growth rate between 2000 and 2008, hybrid vehicles still represent only about 2% of the vehicles sold in the U.S. The level of market penetration is expected to remain low—less than 5 to 15%—until hybrids are more cost competitive with conventional vehicles. Achieving a market share that is large enough to justify large-scale manufacturing will require reducing the cost to a level where vehicle purchases can be justified economically, reducing the size and weight, increasing efficiency, and ensuring reliability.

The R&D status and technical targets with respect to cost, specific power, power density, and efficiency are shown in the following table.

Status and Technical Targets for Electric Traction System

C	R&D Status	Targets	
	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

a. Based on a maximum coolant temperature of 90°C
b. Based on a maximum coolant temperature of 105°C or air

Production costs must be reduced by more than a factor of 2 compared to the most recent R&D prototype and by a factor of four compared to current commercial electric traction systems. Size must be reduced simultaneously by more than 20% compared to current commercial electric traction systems. This is in addition to past accomplishments in the Advanced Power Electronics and Electric Machines (APEEM) R&D, which have doubled power density while reducing the cost by about 65%. Also essential will be increased modularity to support multiple system configurations and economies of scale and system integration to reduce part count and to improve reliability, durability, and manufacturability.

Current and planned R&D focuses on the following areas:

- Power electronics
    - New topologies: to reduce size, weight, and cost and to improve reliability

    - Wide-band-gap semiconductors: to enable higher-temperature operation and greater efficiency
    - Improved packaging: to reduce size, cost, and weight while increasing reliability
    - Capacitors: to reduce volume and enable higher-temperature operation
    - Vehicle charging to minimize cost
- Motors
    - Permanent-magnet motors: to reduce cost and maintain performance
    - New magnet materials: to address the rapidly increasing cost of rare-earth magnets
    - Non-permanent magnet motors: to eliminate the cost of magnets
    - New materials for laminations, cores, etc: to reduce cost and size
- Thermal management
    - Thermal system integration: to enable technology integration at lower system cost
    - Heat-transfer technologies: to enable increased power density at lower cost
    - Thermal stress and reliability: to improve reliability of new technologies
- Traction drive systems
    - Integrated-system design: to meet future system targets
    - Benchmarking: to support program planning.

The major technical barriers to closing the gaps between the current status and the targets are the high cost of the materials and components, the weight and volume of the components, and the ability of the materials and components to withstand the temperatures that they will encounter. A major concern for motors is the rapidly increasing cost of rare-earth magnets along with questions about their future availability. Motors that do not contain rare-earth magnets tend to have much lower specific power. Other constraints include the maximum speed of the motor and temperature limits of the magnets and the insulation on the windings. Components of the power electronics such as semiconductor switches, diodes, packaging, and capacitors also are limited by the temperatures that they can tolerate. The size and cost of the capacitors also present significant challenges. Preventing overheating of the components of an electric traction system is a major design challenge, and developing more effective thermal management techniques offers important opportunities for decreasing size, weight, and cost while improving reliability. The need to decrease volume and the desire to eliminate the separate cooling system adds significantly to the thermal management challenges.

Key elements of the strategy to realize these aspirations include

- **Address multiple technologies**, because no single new technology will achieve of all of the targets. For the motor, it is necessary to consider issues such as new designs, magnet materials, and manufacturing methods. For the power electronics, it is necessary to consider semiconductor switches, capacitors, magnetics, packaging, and new topologies. Added to all of those issues is the challenge of thermally managing the modules.
- **Pursue parallel paths** to reduce the overall risk of technical failure. Multiple parallel paths also are more likely to produce technologies that meet the needs of more than one manufacturer.
- **Encourage technology transfer** to make sure that new technologies will be incorporated into commercial vehicles. Although the basic mission of DOE is long-term, high-risk R&D, the program needs to contain some short-term R&D to carry the technologies to the point where industry can adopt them. In many cases, this shorter-term R&D will be conducted in partnership with industry or by industry alone.

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Acronyms and Abbreviations

AC	alternating current
APEEM	Advanced Power Electronics and Electric Machines
BEV	battery electric vehicle
CPSR	constant power-speed ratio
DBC	direct bonded copper
DC	direct current
DoD	Department of Defense
DOE	U.S. Department of Energy
EEA	Energy and Environmental Associates
EETT	Electrical and Electronics Technical Team
EMF	electromagnetic field
EMI	electromagnetic interference
EREV	extended-range electric vehicle
ESR	equivalent series resistance
ETS	electric traction system
FAST	Functional Analysis Systems Technique
GaN	gallium nitride
HEV	hybrid electric vehicle
IAPG	Interagency Advanced Power Group
ICE	internal combustion engine
IGBT	insulated gate bipolar transistor
IPM	interior permanent magnet
ISG	integrated starter-generator
kg	kilogram
kHz	kilohertz
kW	kilowatt
L	liter
MOSFET	metal oxide semiconductor field effect transistor
NPT	non-punch-through
OEM	original equipment manufacturer
PEEM	Power Electronics and Electrical Machines
PHEV	plug-in electric vehicle
PM	permanent magnet
PNGV	Partnership for a New Generation of Vehicles
R&D	research and development
SBIR	Small Business Innovative Research
SiC	silicon carbide
SPM	surface mount permanent magnet
SR	switched reluctance

SUV	sport utility vehicle
UL	Underwriters Laboratories
USCAR	U.S. Council for Automotive Research
V	volt
V2B	vehicle to building
V2G	vehicle to grid
VDC	volts direct current
WBG	wide band gap
WEG	water plus ethylene glycol

Introduction

The unstable and generally increasing cost of oil and its escalating use in highway vehicles—the U.S. transportation system is currently 98% dependent on oil—are accelerating the need for more fuel-efficient automobiles. With guidance from the Electrical and Electronics Tech Team (EETT), the Vehicle Technologies Program of DOE supports long-term, high-risk research to advance new and improved technologies that improve vehicle fuel efficiency in the midterm and facilitate the transition to more electrically dominant hybrid vehicles and electric vehicles.

Substituting electric propulsion for petroleum-fueled engines, either completely in all-electric vehicles (EVs), or partially in hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) is one important approach to the large-scale reduction of automobile oil use. Although advanced EVs, HEVs, and PHEVs are produced commercially today, their widespread adoption is inhibited by high costs compared to conventional petroleum-fueled vehicles. The higher costs are directly related to the need for more energy-storage capacity, power electronics, electrical machines (motors and generators), and in some cases fuel cells. In addition to cost, these components, which are unique to hybrid and electric vehicles, also add weight and volume and represent potential efficiency and reliability problems. Therefore, research is needed to develop technologies that are less expensive and, at the same time, smaller, lighter, more efficient, and equally reliable as conventional automotive technologies.

DOE's Advanced Power Electronics and Electrical Machines **(**APEEM**)** activity seeks to reduce the $33/kW cost of currently available electric propulsion systems to $12/kW peak by 2015 and to $8/kW peak by 2020, thereby enabling large-scale application of advanced, energy efficient vehicles. Thus, the total cost of a 55 kW system will be reduced to $660 by 2015 and to $440 by 2020. Furthermore, there is a trend toward higher power levels, but the total system cost target is not expected to increase despite the increase in power level.[1*]

Mission/Vision

Achieving energy independence demands hybrid electric and fuel cell vehicles that are economically justifiable for the average consumer. Essential to this effort is the development of advanced power electronics and electrical machines, as key enabling technologies for propulsion systems. For the successful adoption of the technology, system integration will be essential to reduce part count and to improve reliability,

[*] All costs are in 2006 dollars.

durability, and manufacturability. This first requires reducing the production cost of current automotive electric traction systems by a factor of four. Improved cost and ease of integrating electric traction systems into vehicle platforms in turn dictates reducing size by more than 20% with increased modularity to support multiple system configurations and economies of scale.

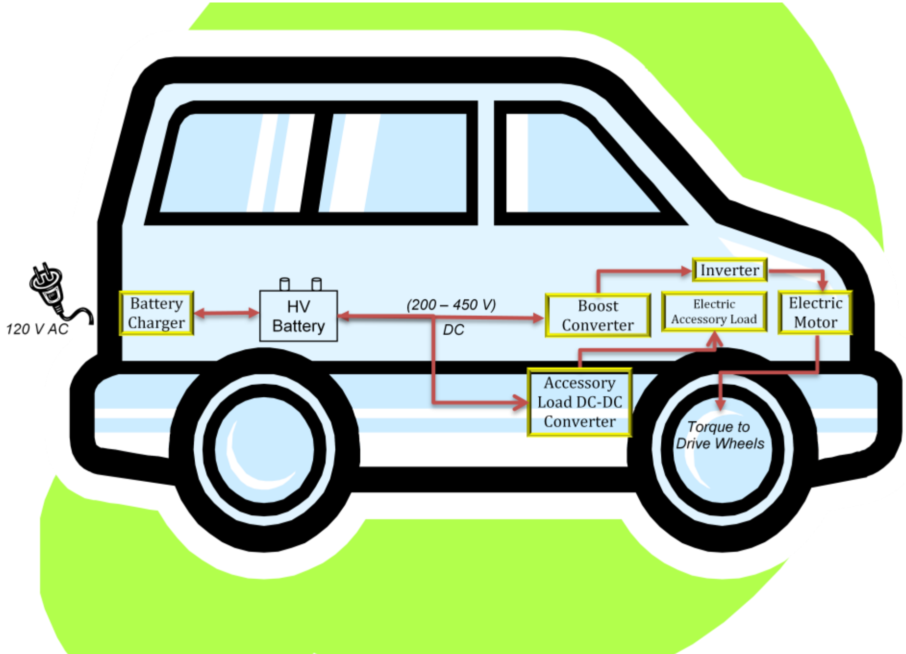
As technology moves from HEVs to PHEVs and then to battery electric vehicles (BEVs) and fuel cell electric vehicles (FCVs), the Electrical and Electronics Technical Team (EETT) is charged with advancing the technologies required to make electrically driven transportation preferred to today's petroleum-fueled vehicles. The team will encourage the national research community and industry to focus on developing technologies that will lead to the commercial viability of electric propulsion in the future.

Objective

APEEM research is developing cost-effective technologies to produce electric traction systems, accessory-power converters, and on-board chargers that are significantly smaller, lighter, and more reliable than existing systems. To ensure a reasonable pay-back period, the cost of the electric traction system (motor, inverter, and, if needed, DC/DC boost converter) should be no greater than $12/kW peak by 2015 and $8/kW peak by 2020. For example, as is shown in Figure 1, a 55 kW electric traction system should cost no more than $660 by 2015. A cost target for a charger will be developed in concert with the new partnership and is expected to be available in 2011.

Context: Historical Perspective and Future Outlook

The EETT consists of scientists and engineers with technology-specific expertise from the U.S. Council for Automotive Research (USCAR) member companies (Chrysler, Ford, and General Motors), National Laboratories, and U.S. Department of Energy (DOE) technology-development programs. The team is responsible for constructing research and development plans and roadmaps, identifying data gaps and research and development needs, reviewing research results, and evaluating the technical progress toward meeting the established research goals.



2015 Cost Target

$12/kW x 55 kW = $660

Including electric traction motor, inverter, and, if needed, gearbox, DC/DC boost converter, and any additional cooling system necessary to facilitate an electric drive

Figure 1. Components of Generic Electric Propulsion System

The Electrical and Electronics Technical Team's emphasis is on developing economically viable electric traction systems. Advancement of power electronics and electric machines for automotive traction has been the charter of the tech team over the years, but the method of achieving viability of electric traction systems in vehicles has evolved over time.

Initially, in the 1990s, the R&D focus was on individual technologies and the development of basic specifications for major components. This work provided EETT with an understanding of the state of the technology and the capabilities of national labs, universities, and industry. Early work included switch technology, inverter topologies, and induction and permanent magnet motors.

In the late 1990s and early 2000s, the increased knowledge base highlighted the need to develop complete components and, if the technology was to be commercialized, the supplier industry needed to be engaged. DOE offered solicitations to develop inverters, motors, and DC/DC converters, but gaining the involvement of viable automotive suppliers proved to be difficult. Almost all large suppliers of power electronics or electric machines were industrial-equipment suppliers, had no automotive experience, and had little interest in the price-sensitive automotive market. Many small companies were interested and did engage in addressing the automotive needs, but they lacked the resources to place a developed component or technology into production. Significant work by the tech team resulted in further accomplishments at a component level; inverters and motors were developed that reduced cost, mass, and volume 30 to 50%.

While this progress increased the viability of electric traction, by the mid 2000s, the tech team and the National Academy of Sciences both recognized that more emphasis needed to be placed on the electric traction system as a whole in order to adequately address the cost, weight, and production volume. Another gap identified was the lack of transition of new technologies developed in the program to implementation in advanced vehicles. This knowledge led the tech team to identify and update technical targets and requirements leading to the next generation of competitive solicitations from DOE for industry-led R&D activities with national labs and universities to develop components and complete electric traction systems.

The EETT has adapted its technology-development strategy through planning and lessons learned from previous years of work. Initial work had a more fundamental focus, but, over time, the EETT built on its growing knowledge and will soon be producing complete systems. More recently, the coordination of activity among the original equipment manufacturers (OEMs) and the DOE with its National Labs has greatly enhanced the potential for innovative technology to move from the Labs to the electric traction systems and for making these systems economically viable.

Recent projects have demonstrated innovations that are helping to achieve the performance and cost targets. A summary of a few of the projects is given below.

- **Sintered Die Attachment to Direct Bonded Copper:** For the power electronics to meet the lifetime and reliability targets, new innovations are necessary to replace traditional solder bonds from the die to the substrate and overcome the temperature extremes, rapid temperature changes, high humidity, exposure to salt and chemicals, and the combined effects of high temperature, shock, and vibrations within the automobile. This project demonstrated a new sintering process to attach the die to the substrate for a more reliable connection. The tests conducted showed that the thermal resistance of the sintered die did not increase throughout the rigorous power cycling test, even up to 60,000 cycles, whereas the traditional soldered die showed a significant increase in thermal resistance at 30,000 cycles with ultimate failure before 45,000 cycles.
- **Advanced Bidirectional DC/DC Converter:** The DC/DC converter is needed to step down high voltage to supply traditional 12V loads and also to step up the voltage for the traction motor. The ability to provide that function within the performance and cost targets is a challenging task. This project demonstrated the ability to achieve high efficiency and multiple voltage levels in high-temperature environments for automobile applications through the use of a novel magnetic-less topology and several innovative technologies. The efficiency of the step-

down converter exceeded 97%, and the efficiency of the step-up converter exceeded 98%.

- **High-Speed Interior Permanent Magnet (IPM) Machine with Brushless Field Excitation:** IPM machines traditionally suffer high core losses at the higher speeds due to the large back EMF and require flux-weakening controls and higher voltages through the use of a DC/DC boost converter. To overcome the high flux at high speeds, the development of a novel IPM motor design that uses brushless field excitation to control the flux density across the air gap overcomes this limitation. Testing demonstrated that the higher excitation increased the torque 24% at low speeds and increased efficiency at high speeds.
- **Direct Backside Cooling of Power Electronics:** Developing reliable and cost-effective power electronics modules that do not require a dedicated cooling system demands innovative thermal management. The efficient rejection of the heat generated was analyzed using computational fluid dynamics and experimental tests to identify and overcome the key barriers with traditional designs. A novel heat exchanger was developed that combined jet-impingement cooling with a significant reduction in the thermal resistance from the die to the cooling structure. Testing confirmed a 37% reduction in the thermal resistance when compared to the baseline heat exchanger. Temperature variation between the dies was also reduced, resulting in more uniform distribution and less mechanical stress from differences in the coefficient of thermal expansion of the materials.

Although technological developments from the APEEM R&D have resulted in a doubling of power density while reducing the cost by about 65%, considerably more progress is necessary to achieve economic viability. Future efforts will need to continue to emphasize developing a supply base with suitable manufacturing processes.

1. Scope

Types of Vehicles

The Advanced Power Electronics and Electrical Machines R&D activities are directed at full hybrids, including HEVs and PHEVs, and all-electric vehicles, including BEVs and FCVs. Extended-range PHEVs (EREVs), PHEVs with a significant all-electric range, will have requirements similar to those for BEVs and FCEVs. PHEVs that are designed for blended operation—operating for only brief periods without the internal combustion engine (ICE)—will have requirements similar to those for HEVs.

The emphasis in this program will be on EREVs, but any new technology (except, of course, charging technologies) should be applicable to the other types of HEVs and EVs. Mild hybrids with an integrated starter-generator (ISG) system are not considered because they have limited or no electric traction and they use a non-hybrid transmission. Important features of the electric traction system (ETS) of each type of vehicle are summarized in Table 1. Ideally, each technology will be scalable to cover a wide range of vehicle sizes, from a small two-seater to a large SUV and even to heavy-duty vehicles such as buses and trucks.

Types of Modules and Research Focus Areas

At a minimum, the electric traction system must include a **motor** to drive the wheels and an **inverter** to convert the direct current from the batteries or fuel cell to alternating current for the motor. A power-conditioning **DC/DC converter** to step down the bus voltage to a suitable level (e.g., 14 volts) for electric accessories also is an essential part of the power electronics. Many vehicle designs also may include a boost DC/DC converter and, for PHEVs, possibly an on-board **charger**. Preventing overheating of the components of an electric traction system is a major design challenge, and developing more effective **thermal management** techniques offers important opportunities for decreasing size, weight, and cost while improving reliability.

Table 1. Important Features of Various Types of Vehicles

++ Critical   + Desirable   - Not a key consideration

ETS Key Parameters	ISG-Type HEV	Hybrid Electric Vehicle (HEV) and Blended PHEV	Plug-In Hybrid Electric Vehicle (PHEV), EREV Type	Electric Vehicle (BEV or FCV)
ETS Usage	Limited or no electric traction. Utilizes non hybrid trans.	Hybrid 2-motor transmission. Multiple modes of operation for each motor through transmissions, clutches, and planetary gear sets. Variable gear ratios	EREV Motor A- generator to charge battery; Motor B- full range electric traction.	Full speed range electric traction. Fixed gear ratio
Number of Electric Motors and PIMs Required	1	2	2, traction and generator	1
Peak Mechanical Output Power , kW (Min., Typ., Max.)	10 – 30 - 40	60 generator 85 motor	70-110 (traction) 45-55 (generator)	110
Continuous Mechanical Output Power, kW (Min., Typ., Max.)	6 – 10 -14	20 (each motor)	35-85 (traction) 20-40 (generator)	65
High Torque Density and Power Density (Volume)	++	++ (package in hybrid transmission)	+	+
Weight	++	+	++	++

ETS Key Parameters	ISG-Type HEV	Hybrid Electric Vehicle (HEV) and Blended PHEV	Plug-In Hybrid Electric Vehicle (PHEV), EREV Type	Electric Vehicle (BEV or FCV)
ETS Wide High-Efficiency Area Around Maximum Continuous Power	+	+	++	++
ETS High Efficiency @ Maximum Peak Power Levels	+	+	++	++
ETS Efficiency over Wide Input Voltage Ranges	++	+ (narrower voltage range)	+ (depends on battery control strategy)	++
Motor Cooling- Current Options	Ethylene Glycol water jacket	Transmission Oil Spray	Transmission Oil Spray	Ethylene Glycol water jacket
Inverter Cooling- Current Options	Ethylene Glycol	Ethylene Glycol (High Temp loop 105°C or low temp loop 75°C)	Ethylene Glycol (High Temp loop 105°C or low temp loop 75°C)	Ethylene Glycol (Low Temp loop 75°C)
Inverter Ambient Air Environment	-40°C to 105°C (remote) -40°C to 125°C (on trans)	-40°C to 105°C (remote) -40°C to 125°C (on trans)	-40°C to 105°C (remote) -40°C to 125°C (on trans)	-40°C to 85°C
Difficulty of Integration	High	High	Medium High	Medium High
Cost	++	++	+	+

Motors

Motor R&D will address the following design and development topics:

- Permanent-magnet (PM) motors that require smaller magnets or less-costly magnets to avoid the rapidly escalating cost and declining supply of rare-earth magnets
- Motor concepts that do not require magnets
- New magnet materials that will be less expensive than rare earth magnets but still attain the desired power density
- Less expensive materials for other parts of a motor such as laminations and cores

Inverters

System-level R&D will address both modular and integrated solutions to meet the size, weight, and cost targets for 2015 and 2020. It also will include benchmarking of commercial systems to provide awareness of the state of the art and guidance for program planning. Inverter R&D will address the following topics:

- New topologies that will decrease size and cost and increase reliability by
    - Reducing the capacitance needs
    - Reducing the part count by integrating functionality
    - Reducing inductance, EMI, ripple, and current through the switches
    - Eliminating the need for a boost converter
- Wide band gap (WBG) semiconductors to enable higher-temperature operation, greater system efficiency, and reduced size of passive components, such as capacitors
- New packaging concepts to reduce cost, size, and weight
- Capacitors that can tolerate higher temperatures and are smaller than commercially available capacitors

DC/DC Converters

Issues related to power-conditioning DC/DC converters and boost DC/DC converter are similar to those for inverters.

Chargers

The EE Tech Team will collaborate with the Grid Interaction Tech Team, the Vehicle Systems Tech Team, and the Energy Storage Tech Team to

- Determine the requirements for an on-board charger
- Improved hardware where needs are identified.

Thermal Management

The need to decrease volume and the desire to eliminate the separate cooling system add significantly to the thermal management challenges. Therefore, a critical part of the APEEM portfolio includes the following thermal management research:

- Characterize and develop advanced heat-transfer technologies to increase power density and lower system cost
- Integrate thermal technologies into power electronics and electric machines
- Mitigate thermal stress to improve reliability and ensure that new technologies meet the requirements for life and reliability.

2. Key Drivers and Issues

Desirable Features

In order to achieve the vision for the electric propulsion system, a number of features related to manufacturing and vehicle integration are important:

- *Scalable and flexible*. Designing components with standardized dimensions will facilitate easy assembly, repair, and flexibility in arrangement.
- *Affordable*. The ability to interchange parts among manufacturers' vehicle models, as well as among manufacturers, will create a greater range of applications for each component. The supplier base will grow as demand for components grows, subsequently leading to large-scale production and lower per-unit production costs.
- *Easy to manufacture*. In order to assure multiple sources of components, the component design should be simple enough to allow for its manufacture by several suppliers.
- *Small and compact*. Significant reductions in the volume and weight of components will allow for ease of integration within current vehicle architectures.
- *Easy to install*: Reduced complexity of putting into the vehicle.
- *Reduced cooling burden*. Several options for cooling systems may be considered. They may be different in the near term and far term. Depending on system requirements and overall system cost, the following may be considered:
    - Separate cooling system
    - Engine (or fuel cell) coolant
    - Transmission fluid
    - Air

Challenges

The automobile manufacturers, with support from the federal government, are being challenged to design and install power electronics and electrical machines that perform better and can be integrated more easily into the next generation of highway vehicles. In order to accomplish this, a number of technical, market, and societal challenges need to be addressed. These include

- High cost of power electronics, motors, and batteries
- System requirements such as the need for components to operate at higher temperatures, improved materials, and better facilitation of components into vehicles
- Low level of interest and involvement from most power electronics manufacturers in related research and development (R&D)

- Environmental regulations that are applied at both the federal and state levels

Market Challenges

As shown in Figure 2, hybrid vehicle sales in the United States increased steadily from 1999 through 2007 and decreased slightly in 2008, reflecting the decrease in total automobile sales that year[2]. In spite of the rapid average growth rate, hybrid vehicles still represent only about 2% of the vehicles sold in the U.S. The level of market penetration is expected to remain low—less than 5 to 15%—until hybrids are more cost competitive with conventional vehicles. Achieving a market fraction that is large enough to justify large-scale manufacturing will require reducing the cost to a level where vehicle purchases can be justified economically; current customers typically do not consider the fact that fuel savings are insufficient to offset the higher initial cost of a hybrid vehicle.

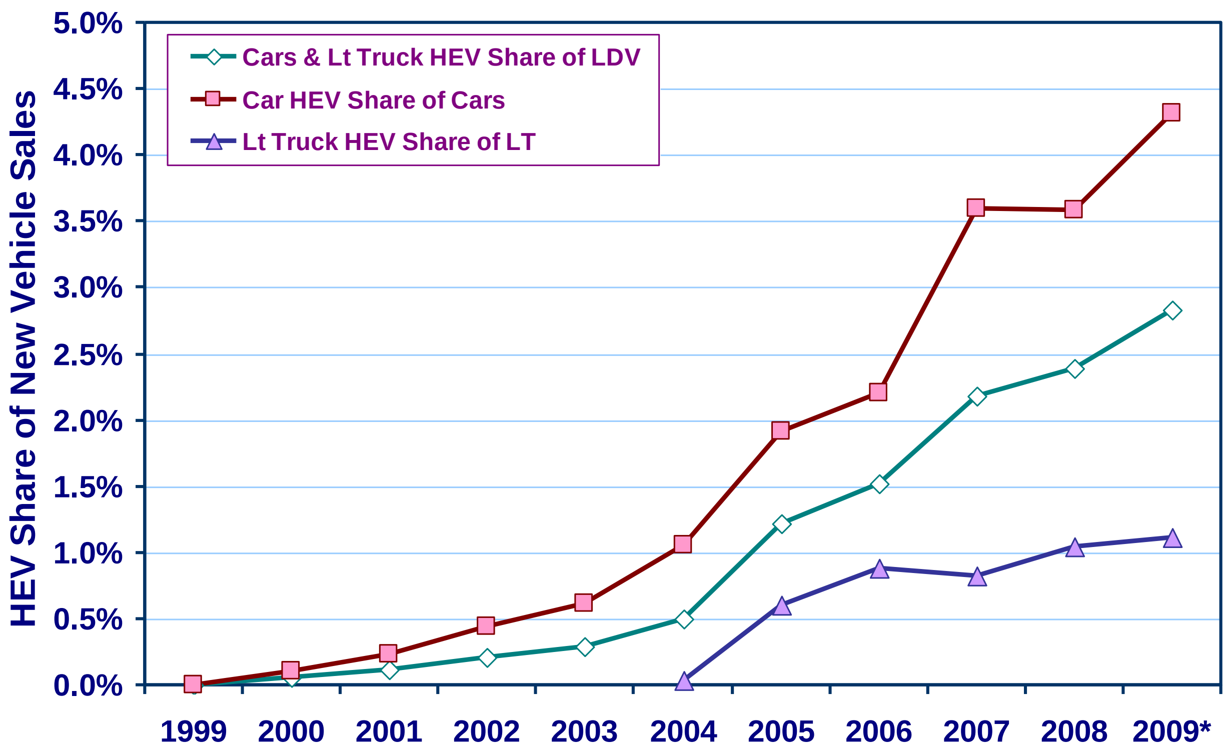


Figure 2. History of HEV Sales in the United States

[2] Based on data from http://www.afdc.energy.gov/afdc/data/vehicles.html

Although some reduction in price can be expected as production volumes grow, significant technological advancements also will be needed to achieve the necessary cost reductions. Empirical cost data collected from numerous industries have shown that unit costs of developing technologies typically follow a curve such as the ones shown in Figure 3. The curves relate unit costs to cumulative production volume and are defined by cost entry points and progress ratios. A progress ratio of 90% describes a product or technology that experiences a 10% reduction in cost for every doubling of cumulative production. Studies have shown that progress ratios for repetitive electronics manufacturing are typically 90% to 95% with similar rates for repetitive machining operations.[3,4]

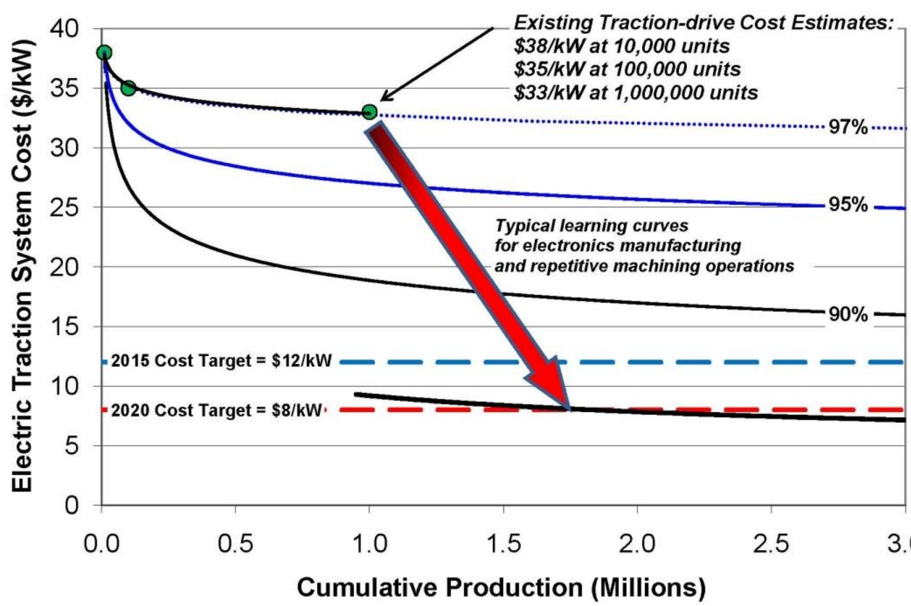


Figure 3. Required Technology Shift to Achieve Cost Target for Electric Propulsion System

The existing traction-drive cost estimates in Figure 3 were derived from three cost assessments conducted on the Gen I Toyota Prius[5], the Gen II Toyota Prius, and the MY2007 Toyota Camry.[6] The projected progress ratio for these data points is

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[3] Delionback, L.M. "Learning Curves and Progress Functions," Chapter 5. Stewart, R. et al., ed. *Cost Estimators Reference Manual.* John Wiley and Sons, 1995.

[4] *Experience Curves for Energy Technology Policy.*, International Energy Agency 2000, online http://iea.org/textbase/nppdf/free/2000/curve2000.pdf.

[5] K.G. Duleep, Technology and Cost of MY 2004 Toyota Prius, ORNL/TM-2007/132, 2006.

[6] K.G. Duleep, Technology and Cost of MY 2007 Toyota Camry HEV, ORNL/TM-2007/132, 2007.

approximately 97% (or 3% cost reduction for every doubling of cumulative production), a lower rate of cost reduction compared to the referenced values. While there is some uncertainty of the exact progress ratio, the ultimate cost target of $8/kW for the electric propulsion system will not likely be reached through production volume alone or incremental technology advances. Substantial investment in R&D is typically required to achieve the type of technology breakthroughs that enable the cost targets to be reached.

System Requirement Challenges

Successful integration of power electronics and electric machines into an electric traction drive requires achieving various thermal characteristics and performance targets while reducing the cost, volume, and weight of power electronic components. System components must be durable and able to function reliably at high operating temperatures and in adverse conditions that include vibrations, dirt, and humidity. Air-cooled systems need to be developed that circumvent the cost and complexity of integrating power electronic components with the existing or additional cooling system.

Research and Development Challenges

Meeting the integrated electric traction system requirements for power electronics and electric machines will require substantial R&D. R&D faces many non-technical challenges, such as the limited number of suppliers and the reluctance of OEMs and their suppliers to risk investing in new technologies. Therefore, R&D depends on a collaborative effort focused on lowering the cost of components and proving the viability of technologies that are designed to meet system requirements.

As advanced components are developed, the gap between R&D and industry adoption must be narrowed. Since hybrid vehicles are only a small portion of the vehicle market, and FCVs are not yet ready for the market, the lack of predictable demand for power electronics and motors has made OEMs and their suppliers uncertain about investing in them. Comprehensive component packaging, testing, and documentation with results that establish the function, reliability, and integration of the component into a vehicle will aid manufacturers in understanding the potential and applicability of these products and will give them confidence to stimulate their investment in the technology.

Societal Challenges

The United States imported 50% of its net oil requirement in 2010[7], with projections that the nation will need to import as much as 8.3 million barrels per day by 2030[8]. The

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[7] http://www.eia.doe.gov/emeu/mer/pdf/pages/sec3_7.pdf
[8] http://www.eia.gov/forecasts/aeo/excel/aeotab_11.xls

transportation sector is projected to account for 72.3 percent of total liquid fuel consumption in 2030, up from 70.6 percent in 2010.[9]. As the future supply of fossil fuels remains uncertain and fuel costs and pollution remediation costs escalate, increasing fuel efficiency is becoming a necessity.

In addition to concerns about oil imports, environmental considerations weigh heavily in future choices. Many regions of the United States are designated as nonattainment areas by the Clean Air Act; and, therefore, have been required to establish limits on pollution from vehicle emissions. Addressing air quality is an important aspect of improving public health, and consumers have become more aware that air pollution directly harms humans and the environment. Potentially of much more concern than air quality is global warming; if government agencies begin to regulate greenhouse gases, pressures to increase fuel efficiency will dwarf current ones.

Federal and state agencies and vehicle manufacturers understand the challenge of creating a transportation sector that consumes less oil and emits less pollution. Higher oil prices are leading consumers to purchase more fuel-efficient cars, as can be seen by the continuing increase in hybrid sales. If energy costs continue to rise, consumer demand for higher fuel efficiency and alternative fuel options also will continue to rise.

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[9] http://www.eia.doe.gov/emeu/mer/pdf/pages/sec3_21.pdf and http://www.eia.gov/forecasts/aeo/excel/aeotab_11.xls).

3. Technical Targets

Targets for the electric propulsion system were developed to measure technical progress through defined test criteria or data collection points. A wide variety of vehicle applications exist, each with different requirements. The electric propulsion system includes all necessary components to add an electric traction function to the vehicle, including, at a minimum, one traction motor and an inverter (including a controller). Additionally, the system may include a DC/DC boost converter, any necessary additional gears, and a dedicated coolant system. The scope of the APEEM research does not include the battery, DC cables from the battery, or gearbox.

The technical targets were last visited by the EETT in 2001, and it is important to understand how these were set. Mass and volume targets were set by auto industry technical experts to meet vehicle needs for packaging. The ability to package power electronics and electric motors across the range of vehicle types is essential to achieving scale of production and program objectives of reducing U.S. energy consumption. Cost targets were determined by cost/benefit analysis with the objective of providing a consumer payback for their hybrid investment within three years from fuel savings. The assumptions that were made for the cost/benefit analysis are a fuel cost of $2.60 per gallon and 12,000 miles driven annually. Since these technical targets were set for the program, substantial progress has been made. Mass and volume seem to be on track to achieving the targets. Cost targets though are at risk of not being met because several factors such as rare earth magnets and wide band gap switches play such a significant role in whether the cost targets can be met. The EETT has determined that an assessment of risk needs to be made in order to determine if the cost targets are achievable. This risk assessment will be worked on as an ongoing activity.

Electric Traction System

The technical targets for 2015 and 2020 that are shown in Table 2 are appropriate for an HEV application[10]. For other applications, the targets may be adjusted on a case-by-case basis. Selecting the HEV application, which has a power level near the low end of the range, is appropriate for this program because that is where the challenge of meeting the specific power and power density targets would be greatest. Meeting the targets for more powerful systems should be somewhat easier because some of the “overhead” items (e.g., connectors) would not have to be entirely proportional to the power.

[10] Technical targets for 2010 are listed in Appendix A.

Table 2. Technical Targets for Electric Traction System

	2015[a]	2020[a]
Cost, $/kW	<12	<8
Specific power, kW/kg	>1.2	>1.4
Power density, kW/L	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>93%	>94%

a. Based on a maximum coolant temperature of 105°C or air

The targets are very aggressive but necessary if the electric traction system is going to be affordable and package friendly to enable large-scale reduction of oil and CO_2 in the future. Current HEV solutions primarily rely on a dedicated cooling system for the electric traction system; however this approach adds cost, weight, and volume and would not offer a path to achieving the targets. For example, the separate cooling system today represents 28% of the cost target for 2015 and 43% of the cost target for 2020. To achieve those aggressive targets, a strategic decision was made to emphasize solutions in which the electric traction system cooling function is integrated with an existing onboard cooling system such as for the engine or transmission.

The desire to eliminate the separate PEEM cooling system by integrating with an existing vehicle cooling system results in a range of possible coolant temperatures for the PEEM system. When considered across the range of vehicle platforms (HEV, PEV, FCV, BEV, etc.) being addressed, this leads to the potential need for both high- and low-temperature PEEM solutions.

In an HEV or PEV platform that uses an engine cooling system, integration is likely to result in the engine coolant being used for the power electronics. This leads to the need for high-temperature (inlet coolant temperature peak of 105C) solutions. In a fuel cell vehicle the fuel cell stack coolant is likely to be used. With current technology, the coolant temperature entering the PEEM system is somewhere in the 85C to 95C range. Newer, more efficient stacks may have coolant outlet temperatures in the 100°C to 110°C range. This again points to the need for high-temperature PEEM solutions. In a BEV application, the battery coolant appears to be the prime candidate for integration. Coolant from this system could range from air cooling to water-ethylene glycol (WEG) liquid coolant to even refrigerant. For a WEG loop, coolant temperatures would probably be in the 30 to 40 C range after cooling the battery. For this application the low-temperature PEEM solutions are applicable. Thus, when considered across the range of vehicle platforms, the desire to reduce cost by eliminating the separate PEEM cooling system results in the need for high- and low-temperature solutions.

Operating with higher coolant temperatures will place greater demands on the components by raising operating temperatures. Although a significant challenge, the requirement for higher temperature components is desirable because it will enable higher power densities.

For research and development projects that are not able to integrate the cooling function with an onboard cooling system and will require a dedicated cooling system for the electric traction system, that separate cooling system's cost, mass, volume and efficiency must be accounted for in the targets.

The long-term (2020) technical targets for the electric traction system are based upon what is needed for an HEV, BEV, PHEV, or FCV to be competitive in performance and economics. To achieve these aggressive targets will require major technological breakthroughs from the R&D program. and intermediate technical targets have been established that represent optimistic but reasonable expectations for what can be achieved by 2015.

Cost

Ultimately, hybrid and fuel cell vehicles should cost no more than comparable ICE vehicles. The cost targets allow for a small price premium, but the cost difference should be no greater than that which could be recovered from the fuel savings in three years. The effect of fuel price on allowable extra vehicle cost is shown in Table 3. These data were generated assuming that the fuel efficiency doubles from 27 mpg to 54 mpg, and a vehicle that travels 12,000 miles per year will recover the extra cost of the vehicle in three years. Thus, the 2015 target of $12/kW peak would be compatible with a gasoline price of about $4 per gallon, and the 2020 target is compatible with a gasoline price of about $2.60 per gallon.

Table 3. Effect of Fuel Price on Cost of Electronic Propulsion System Allowing Three-Year Payback

Gasoline Price, $/gal	PEEM Cost Target $/kW peak
2.00	6.00
2.50	7.50
3.00	9.00
3.50	10.50
4.00	12.00
4.50	13.50
5.00	15.00

While the cost targets in Table 3 were developed for an HEV application, consideration was given to other applications. For FCVs, the cost target is similar to that established above for HEVs and depends upon success in fuel cell stacks and hydrogen storage meeting cost targets.

For PHEV applications, the allowable PEEM cost will be established once the EPA has established its method for calculating fuel consumption and electrical energy usage, which is expected to be in 2nd half of 2010.

Power Density

Power density is an extremely important target because of limited space "under the hood" and in the vehicle. Packaging constraints vary with the different types of electric drive applications (see Table 1) but can become greatest in vehicle types that have the most potential for reducing the U.S. vehicle fleets fuel usage.

Specific Power

Vehicle mass directly affects overall fuel efficiency, and the benefits of the additional electric traction systems can be greatly reduced if the mass is not carefully managed. Additionally, increasing vehicle mass complicates and may even prevent integrating electric traction systems into vehicles.

Efficiency

System efficiency is important, not only for the direct effect on fuel consumption, but equally important is that the losses (inefficiencies) are converted to heat, which must be removed with a thermal management system that carries added cost, weight, volume, and system complexity.

DC/DC Converters

In addition to running accessories from the high-voltage bus, HEVs, PHEVs, BEVs and FCVs also will require up to 3kW of 14V DC; the power level will depend upon the vehicle architecture and the features content. At a minimum, a buck DC/DC converter will be required to reduce the nominal 325V battery voltage to 14 V for the accessories. Although not a part of the propulsion system, a DC/DC converter is an important power electronics module and, therefore, is included in the scope of this program. In addition, some of the technical developments for DC/DC converters may be transferable to inverter designs. Table 4 shows technical targets for a 3 kW DC/DC converter to reduce the battery or fuel cell voltage from a nominal input voltage of 350 VDC to 14 V. The cost target for 2020 is such that it will cost no more than the alternator that it replaces.

Table 4. Technical Targets for 3 kW DC/DC Converter

	2015	2020
Cost, $/kW	<60	<50
Specific power, kW/kg	>1.0	>1.2
Power density, kW/L	>2.0	>3.0
Efficiency @ maximum load	>93%	>94%

4. Requirements

Systems or components that are designed to meet the technical targets also must ensure that they will be useful for HEVs, PHEVs, BEVs, and FCVs. The most important of these requirements include peak power, peak torque, continuous power, and life. For a typical midsize vehicle equipped with a full hybrid system, the electric propulsion system would be expected to meet the requirements listed in Table 5.

Table 5. Requirements for Electric Propulsion Systems for a Typical Hybrid Vehicle

Peak power	55 kW
Peak torque	240 N-m
Continuous power	30 kW
Coolant temperature	105°C for 2015 105° for 2020
Voltage	200-450 V
Motor current	400 Arms maximum
Life	15 years or 150,000 miles

Peak Power

If future vehicles are to have equivalent performance to current vehicles, a rule of thumb for peak power is about 8 kW per 100 kg of vehicle weight. In an ICE hybrid, about half of that power can be expected to come from the engine, but all of it must be supplied by the electric propulsion system in a fuel cell vehicle, dominant electric (30 to 40 mile all-electric range) plug-in hybrid, or electric vehicle. Table 6 illustrates the approximate peak power requirements for various classes of vehicles.

Table 6. Approximate Peak Power Requirements for the Electric Propulsion System in Various Classes of Vehicles

Vehicle Segment	Vehicle Class, kg	Peak Power, kW	
		FCV, EV, or EREV	ICE Hybrid[a]
Compact	1,000	80	42
Mid-size sedan	1,300	104	55
Full-size sedan	1,700	136	72
Light SUV	2,000	160	85
Pick-up truck	2,100	168	89
Full-size SUV	2,300	184	97

a. Includes PHEVs with blended operation.

Based upon Table 6, the requirement of 55 kW peak would be suitable for a mid-size ICE-hybrid sedan but clearly not for larger vehicles.

Peak Torque

A peak torque of about 240 Newton-meters is considered necessary to provide adequate acceleration and hill-climbing capability for a mid-size sedan.

Continuous Power

The requirement of 30 kW for continuous power is based upon a rule of thumb for a mid-size sedan maintaining 55 mph on a 6% grade.

Life

A lifetime for the system of 15 years or 150,000 miles will be required because it is considered part of the vehicle emission system, which is mandated by federal law and to meet the warranty expectations of the customer base.

5. Guidelines

The next few sections will discuss some of the harsh realities of the automotive environment and present some guidelines. If the proposed solution does not meet voltage, current, and temperature guidelines, a viable alternative must be presented.

Coolant Temperature

Adequate heat dissipation is critical to the performance, life, and reliability of power electronics and electric machines. Heat dissipation requirements are defined by the amount of heat generated (power level and efficiency), the package thermal resistance, the heat transfer mechanism (heat transfer coefficient), and the temperature difference between the coolant and the device. A typical automotive power electronics cooling system includes a liquid coolant, solid-to-liquid heat exchanger, pump, coolant lines, fittings, coolant overflow reservoir, and a liquid-to-air heat exchanger (radiator).

Under the PNGV and the first few years of FreedomCAR, requirements were based upon a liquid coolant (water plus ethylene glycol [WEG]) at a maximum temperature of 70°C. Current hybrid vehicles require a separate dedicated cooling system to maintain a maximum junction operating temperature for the switches in the power module. It would be desirable to reduce system complexity and cost by eliminating the extra cooling system and using the existing 105°C engine coolant system to cool the electronics. An acceptable alternative approach would be to continue to use a second, low-temperature coolant system, but the additional weight, volume, and cost would have to be included in the electric propulsion system weight, volume, and cost when comparing to the targets.

Additionally, the ripple-current capability of the capacitors and the life of the electronics decrease rapidly as the operating temperature increases; the ability to remove heat decreases as the temperature difference between the coolant and the electronic components decreases. In spite of those challenges, a coolant temperature requirement of 105°C has been established for 2015 with an intermediate step of 90°C for 2010. Developing technologies that can operate under a range of coolant temperatures will help to mitigate uncertainty in the ultimate vehicle design, including the possibility of integrating electronics cooling with an engine or high-temperature fuel cell stack cooling system.

Ambient Conditions

Ambient conditions in the engine compartment where power electronics and electric machines are expected to be located are harsh. These adverse conditions include temperature extremes, rapid temperature changes, high humidity, exposure to salt and chemicals, and the combined effects of high temperature, shock, and vibrations. These conditions, along with heat generated from powering devices in the inverter, may cause component-level thermal stresses, lower efficiencies, and de-rated performance.

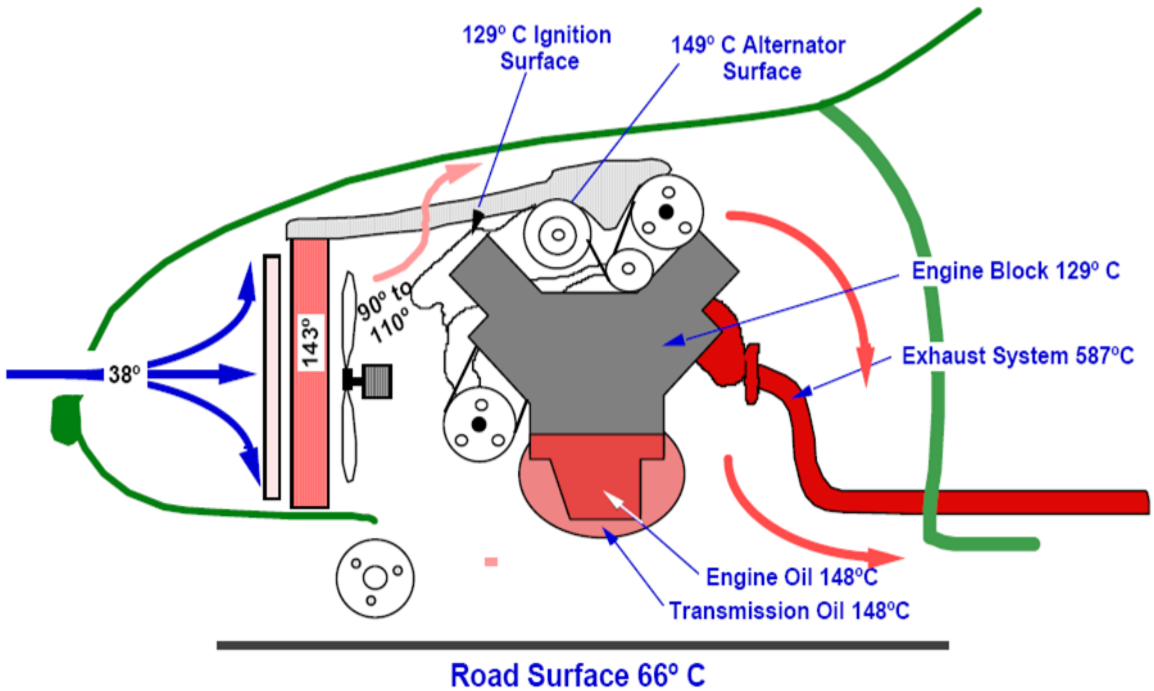

Figure 4. Typical Engine Compartment Thermal Profile

The under-hood ambient air temperature can be a significant factor affecting the performance and life of components beyond the temperature of the liquid coolant. Figure 4 and Table 7 show the thermal profile[11] and ambient conditions[12] within the engine compartment. Maximum sustained temperatures at the power electronics base-plate can range from 125°C in the engine compartment to 140°C when mounted on the engine or transmission. Power-device temperatures can be 25°C higher than base-plate temperatures, depending on the package thermal resistance and the coolant temperature.

[11] M.R. Fairchild, R.B. Snyder, C.W. Berlin, D.H.R. Sarma, "Emerging substrate technologies for harsh-environment automotive electronics applications", SAE Technical Paper Series 2002-01-1052.

[12] R. Wayne Johnson, et. al., "The Changing Automotive Environment: High Temperature Electronics", IEEE Transactions on Electronics Packaging Manufacturing, July 2004.

Table 7. Ambient Conditions within the Engine Compartment

Location	Typical Continuous Maximum Temperature, ^{0}C	Vibration Level, G_{rms}	Fluid Exposure
On Engine On Transmission	140	Up to 10	Harsh
At the Engine (Intake Manifold)	125	Up to 10	Harsh
Underhood Near Engine	120	3 – 5	Harsh
Underhood Remote Location	105	3 – 5	Harsh
Exterior	70	3 – 5	Harsh
Passenger Compartment	70 - 80	3 - 5	Benign

Increasing component temperature is driven by the coolant temperature, the overall package thermal resistance, and ambient air conditions. Most electronic board components are rated for a maximum of 125°C, and commercially available film capacitors for 105°C. Higher-temperature components offer greater flexibility in locating the inverter under hood. In addition, de-rating of the components would not be as severe (or there would be no de-rating), leading to smaller, lighter components and modules.

Voltage

A typical electric propulsion system may be able to operate on input voltages from the fuel cell stack or batteries that range from 200 V to 450 V. If the vehicle design requires higher voltage—which some current motor designs do to achieve a larger constant power-speed ratio (CPSR) or to reduce the current requirements—the cost, weight, and volume of a boost DC/DC converter must be considered in the electric propulsion system.

Current

The maximum input current to the electric propulsion system will be set at 400 amps DC to limit the sizes of the semiconductors and the wiring.

6. Status

The status is a measure of the achievements by R&D efforts conducted within the DOE Program and where those efforts might lead vis-à-vis the targets.

As previously stated, system solutions may employ a variety of cooling schemes. This results in potential system operation in a low-temperature (65ºC coolant) or a high-temperature (105ºC WEG or ambient air coolant) mode. Thus, the status will be reported within this operating temperature range.

Commercial Technology

Production hybrid technology will be used to represent the status of on-the-road technology. Current production hybrid system architectures include a separate cooling system to provide 65ºC coolant to the PEEM system. Thus, the values for specific power, power density, and efficiency obtained in the benchmarking effort were used directly for the low-temperature mode (the weight, volume, and cost of the cooling system are included). The cost estimates were derived from technology assessments performed for the program and from dealer cost information. The benchmarking results indicated that, at the high-temperature end of the spectrum, the Toyota systems power values would be de-rated by about 50%. This de-rating value was used in estimating the status of production hybrid systems to meeting our targets.

Table 8. Status of On-the-Road Technology for Electric Traction Systems

	Low-Temperature Traction Drive System				High-Temperature Traction Drive System			
	($/kW)	(kW/kg)	(kW/L)	Eff.[a] (%)	($/kW)	(kW/kg)	(kW/L)	Eff.[a] (%)
Prius	38.7	0.8	1.6	85	70.5	0.4	0.8	85
Camry	36.4	1.2	3.0	87	68	0.6	1.7	87
Lexus	55.5	1.8	3.8	86	108	0.9	2.0	86
2015 Target	12	1.2	3.5	93	12	1.2	3.5	93
2020 Target	8	1.4	4.0	94	8	1.4	4.0	94

a. Efficiency is specified at the maximum load.

The status of on-the-road technology for both the high- and low-temperature modes is shown in Table 8. The status cost figures refer to just the incremental cost of production, which is not economically sustainable. The targets refer to the total cost to the consumer and include items such as overheads, profit, and amortization of facilities.

As indicated, significant gains have been made in volume and weight as the technology has advanced. However, these gains have been at the expense of cost and efficiency. It should be noted that the Lexus system is a high-power traction drive system on a vehicle that is performance oriented rather than fuel-economy oriented. Given the base cost of the Lexus, the price premium associated with the hybrid drive system was most likely not a primary consideration in the design space. The data also indicate that the high-temperature operation is very far from the targets; this is to be expected since the Toyota system is designed for low-temperature operation. A system designed for high-temperature operation would likely have performance factors somewhere between the high-and low-temperature values indicated above.

R&D Status

The R&D portfolio has focused on technology development rather than system development. Thus, complete traction-drive systems for a specific application have not been produced by the program. System attributes, however, can be estimated by conceptually "building" electric traction drive systems using the technology advances from the R&D effort. Figure 5 plots the cost (in $/kW) against the power density (kW/L) for a variety of systems. The Prius and Camry attributes from Table 8 are presented as a baseline. The area in the lower right indicates the space that meets the targets for the program. The AC Induction point represents the drive technology from the early GM electric car.

The R&D systems plotted in Figure 5 represent a variety of technologies that were developed. They include:

- UQM and Semikron: Uses the high-temperature IPM motor design developed by UQM in 2005 and the Semikron inverter developed in 2003. The performance characteristics of the Semikron inverter were adjusted for high-temperature operation.
- Rockwell and Delphi: A low-temperature system that uses the motor designed and built by Delphi and the inverter designed and built by Rockwell.
- GM: An ongoing project to develop a high-temperature traction-drive system. The performance characteristics shown are the project goals called for in the R&D request for proposals.
- Delphi and GE: Ongoing projects to develop a high-temperature inverter (Delphi) and a high-temperature motor (GE). The performance characteristics of the system represent the project goals. The actual performance of the system has not yet been demonstrated.
- Current Source Inverter, Motor, and Thermal Management: A representative system that combines R&D from a number of ongoing projects to develop high-temperature modules and technologies at ORNL and NREL. Technologies from

PE topology, PE packaging, motor, and thermal management projects were conceptually combined into a system. The Current Source Inverter is an advanced topology that incorporates a boost function in the inverter and minimizes capacitance requirements. An advanced power module packaging concept using the direct cooled substrate concept is included. The motor component is an advanced non-permanent magnet motor design. Thermal management techniques to increase the effective heat transfer have also been incorporated into the conceptual design.

It is highly probable that the 2010 targets will be met by technology resulting from current R&D projects.

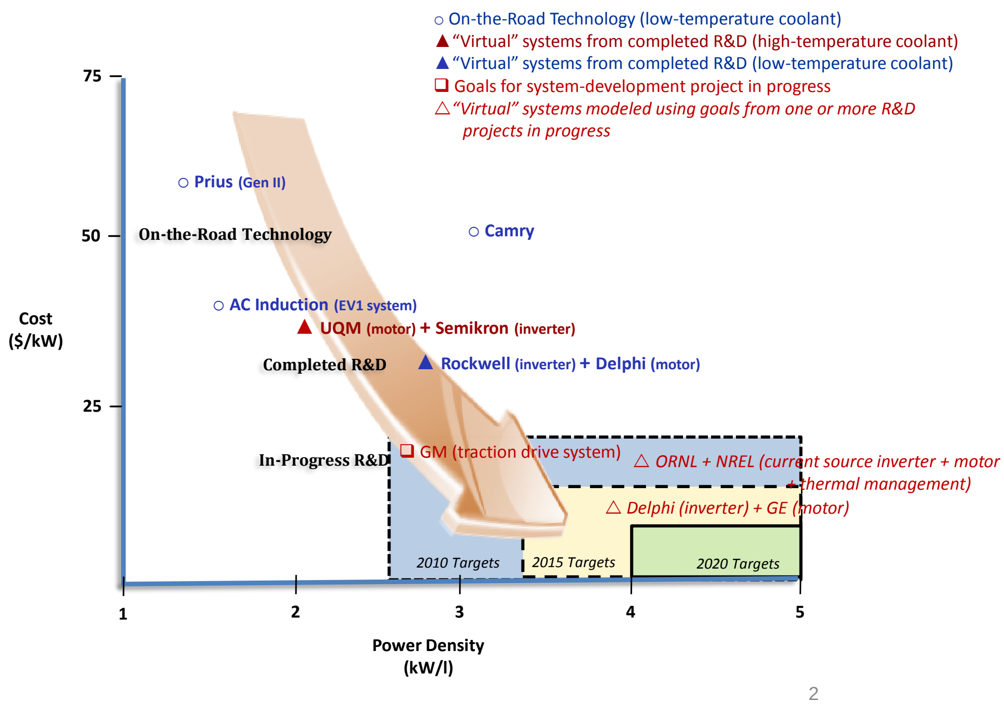

Figure 5. R&D Progress Versus Targets

The plot indicates that high-temperature systems at present suffer cost and power-density penalties compared to low-temperature R&D systems. The cost and weight savings from eliminating the separate cooling system are exceeded by things such as a larger heat exchanger, expensive currently available high-temperature materials, and more capacitors to compensate for the loss in capacitance at higher temperatures. Also, the high-temperature R&D was begun only within the last several years. However, as the plot also shows, *if* the current portfolio of projects is *completely successful*, systems with the current portfolio of projects can potentially meet 2015 targets. However, future plans must include the possibility that those projects may not be completely successful and that more work will be needed.

Meeting the systems targets will require successful R&D in a number of areas. While the current portfolio of projects is promising, it is unlikely that all projects will be completely successful, and new areas of inquiry will be needed to continue the progress in meeting the 2020 targets. In the interim, low-temperature systems will similarly need further R&D. The separate cooling system alone consumes $3.18 of the $8/kW target, leaving less than $5/kW for the traction-drive hardware. To eliminate the separate cooling system, further advances in packaging and thermal management will be required. Thus, an aggressive R&D portfolio is needed to achieve the cost target.

7. Gaps

The on-the-road technology status presented in Table 8 was used to identify the gaps that must be bridged to meet the program targets. Figures 6 and 7 illustrate the gaps between the on-the-road technologies, not adjusted for a 105°C coolant, and the 2015 and 2020 targets. Figures 8 and 9 illustrate the gaps between the on-the-road technologies, adjusted for a 105°C coolant, and the 2015 and 2020 targets. The spider charts in those figures show the ratio of the status to the target. For example, for a property that exactly meets the target, the value on the spider chart would be plotted at 1.0; a property that is 60 % of the target would be plotted at 0.6. The specific-power ratio is plotted on the right horizontal axis, which is labeled kW/kg. The power-density ratio is plotted on the lower vertical axis, labeled kW/L. The upper vertical axis represents the cost in terms of kW/$. It was necessary to use the reciprocal of the cost numbers in Table 8 so that falling short of the target would result in a fraction less than 1. The efficiency is plotted on the left horizontal axis. A value of 75% (rather than zero) was used as the baseline for efficiency to make the charts more readable. Numbers on the efficiency axis represent the difference between the actual value and 75%. This approach was chosen to more effectively illustrate the magnitude of improvement accomplished or needed.

The parallel strategy of developing both low-temperature systems and high-temperature systems (please refer to the Technical Targets section) and assessment of both options is described in the following paragraphs.

Low-Temperature Systems

Through the benchmarking activities, three systems are compared against the technical targets for 2015 in Figure 6. The spider chart shows that the Lexus system exceeds the specific power target and is close to achieving the power density target; however, it falls short of the efficiency target and is far short of the cost target. This is not unexpected as this particular system is designed with an emphasis on performance (high power) and is done for a luxury brand vehicle that is not as cost sensitive as mainstream vehicles. The Camry system is the next closest system to achieving the specific power and power density targets. This also is in line with expectations as this system is targeted to provide a balance of V6 like performance, and thus more power, with a good balance of fuel economy for improved efficiency. However, it too is far from achieving the cost target. Finally, the last system represented is the Prius system which is more focused on efficiency than power and comes closer to the efficiency target but moves farther from the specific power and power density targets. This system is also the most package constrained as it is a smaller vehicle. Even this system is far from achieving the cost target.

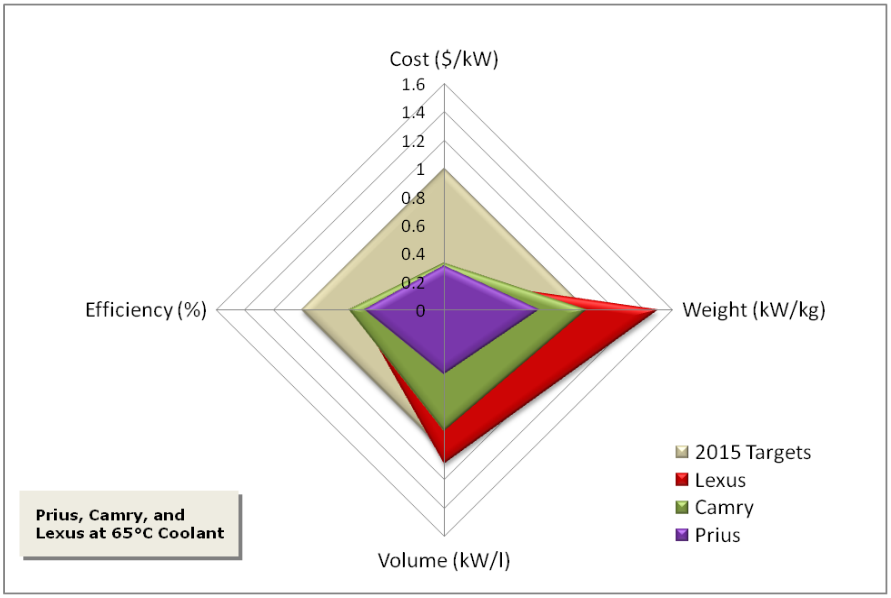

Figure 6. Gaps Between On-the-Road Technology (Not adjusted for 105°C coolant) and 2015 Targets Expressed as Ratios of Actual Values to Target Values

If we compare the status of the same systems to the 2020 targets, then we can see that the systems are even farther away from achieving the targets, with only the Lexus system achieving the specific-power target.

Figure 7. Gaps Between On-the-Road Technology (Not adjusted for 105°C coolant) and 2020 Targets Expressed as Ratios of Actual Values to Target Values

The cost target will be very difficult to achieve with a dedicated coolant system as the dedicated system represents a significant percentage of the overall system cost. Because of this difficulty, the parallel path of investigating breakthrough technologies that will enable the elimination of a dedicated cooling system has the greater long-term possibility of improving on the cost target.

High-Temperature Systems

To understand how these technologies without a dedicated cooling loop would measure against the targets, the three benchmarked systems were de-rated to the capability possible if the coolant temperature for the system was allowed to be 105°C. As shown in Figure 8, all three systems degrade in power output and efficiency, and thus the systems are farther away from meeting the specific power, power density, and efficiency targets. Also, even though the absolute cost improved, the power at the higher temperature decreased further, and thus the overall cost per kW decreased compared to the low temperature systems. With some research breakthroughs in high temperature materials and systems, this will enable higher power and higher efficiency systems. This is expected to turn around to the point where the high-temperature system will greatly exceed the potential of the low-temperature system.

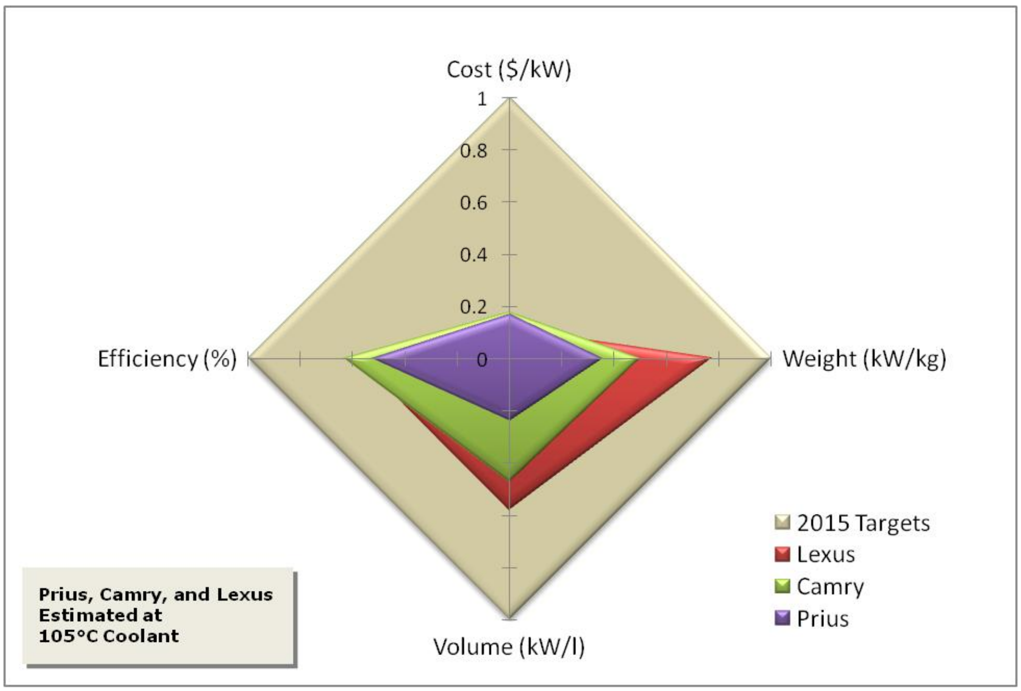

Figure 8. Gaps Between On-the-Road Technology (Adjusted for 105°C coolant) and 2015 Targets Expressed as Ratios of Actual Values to Target Values

Finally, the status of the three systems is shown against the 2020 target in Figure 9. This plot reinforces the magnitude of the difficulty in being able to achieve the targets and the need for increased research and development of the entire system down to component levels.

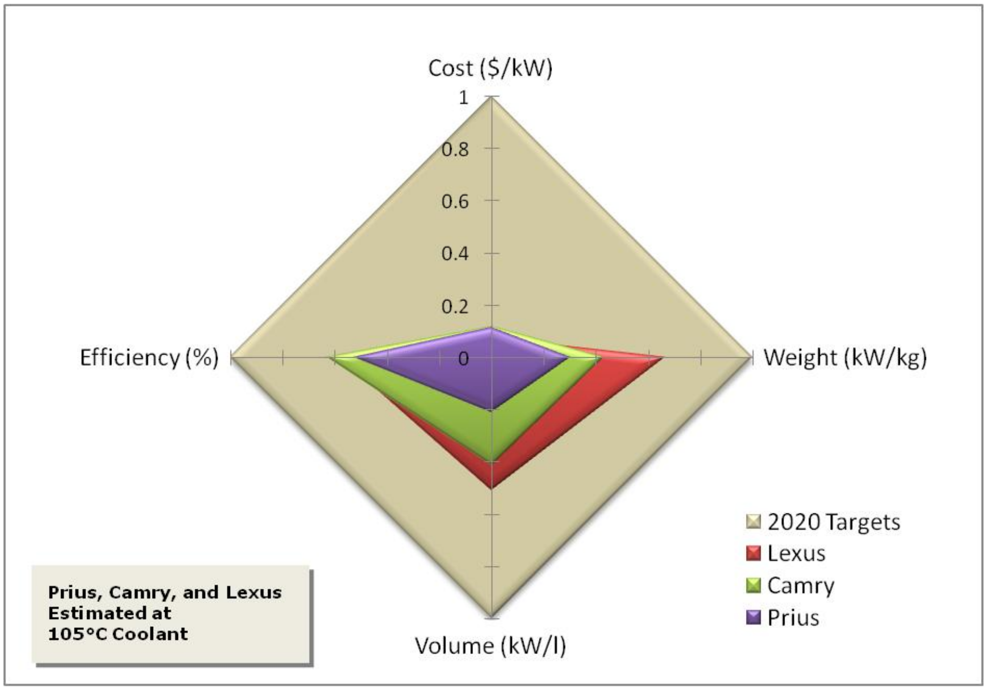

Figure 9. Gaps Between On-the-Road Technology (Adjusted for 105ºC coolant) and 2020 Targets Expressed as Ratios of Actual Values to Target Values

Only with the concerted effort in all areas of the electric drive system will it be possible to overcome the cost, power, and efficiency hurdles that will then allow the widespread adoption of these systems in vehicles.

8. Technical Barriers

The major technical barriers to closing the gaps between the current status and the targets are the high cost of the materials and components, the weight and volume of the components, and the ability of the materials and components to withstand the temperatures that they will encounter.

Cost of Materials and Components

To reduce the cost of the electric propulsion system, the initial focus obviously should be on the most costly components.

The relative contributions to the cost of a permanent magnet (PM) motor have changed significantly within the past few years. A few years ago, the prices of sintered rare-earth magnets were decreasing. More recently, the prices have risen significantly. For example, see Figure 10[13]. Furthermore, it is not clear whether the worldwide supply will be sufficient to meet the demand. Therefore, motor concepts that require less rare-earth magnet material or that are feasible with non-rare-earth magnets or no magnets need to be reconsidered. Although the exact costs would depend upon the specific design, an example of approximate cost contributions for a typical IPM motor is shown in Table 9.

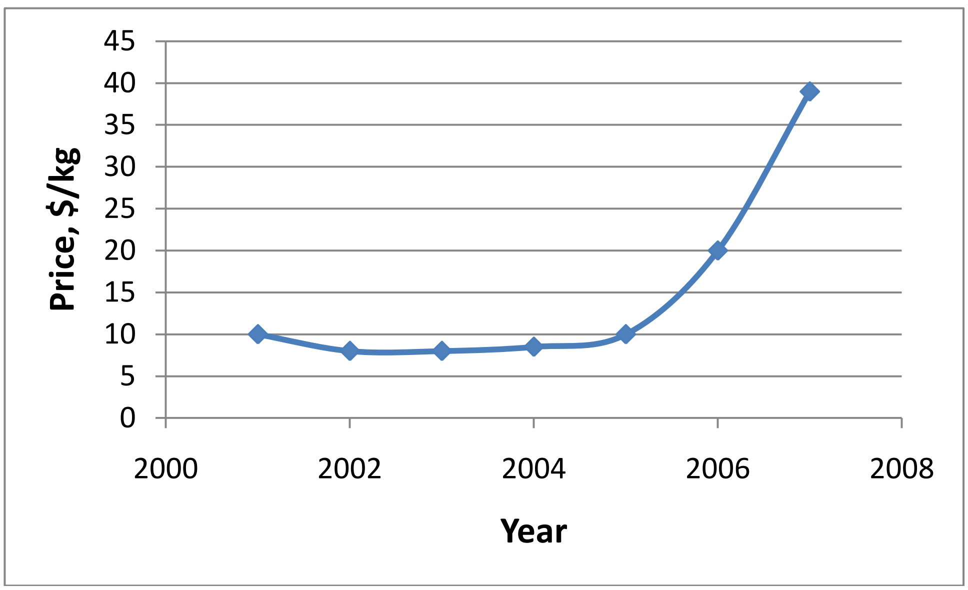

Figure 10. Annual Price Trend for Neodymium Metal

[13] . Metal Pages Ltd.: www.metal-pages.com

Table 9. Approximate Contributions to Cost of Motor (Typical Interior Permanent Magnet[14])

Laminations	30%
Copper	10%
Sintered magnets	30%
Housing	20%
Miscellaneous	10%

Cost elements for an inverter vary widely depending upon the specific topology. The most important cost elements for a typical voltage-source inverter (VSI) used in today's HEVs are listed in Table 10.

Table 10. Major Cost Elements of a Typical VSI

Power switches/switch frame	Up to 33%
Capacitors	Up to 23%
Sensors	3 to about 13%
Bus bars/connectors	10 to 15%
Miscellaneous	About 30%

Component Weight and Volume

Weight reductions are essential because fuel efficiency is inversely proportional to weight. As Table 11 shows, the heaviest parts of a PM motor are the stator core, the rotor core, and the copper windings.

Table 11. Approximate Contributions to Motor Weight (Interior Permanent Magnet)

Stator core	**42%**
Copper windings	15%
Rotor core	20%
Magnets	3%
Housing & cover	20%

PM motors have high specific power relative to other motor designs, and one of the most promising ways to reduce the weight would be to use a higher-speed motor. Since power of a motor is directly proportional to the speed, increasing the speed, in principle, is an obvious way to increase power density. This approach, in fact, has been used in recent commercial motors for HEVs. Currently, maximum speeds are in the range of 16,000 to 20,000 rpm; still higher speeds may be impractical for a number of reasons:

[14] Current industry experience.

- Resulting high centrifugal forces will make it difficult to retain the magnets in IPM designs
- Increased core losses at high speed will reduce efficiency
- Traditional gears and bearings may not be able to tolerate the higher speeds
- Additional requirements on the mechanical components to enable high speed operation of the gear box may offset the motor savings

As for the inverter, Table 12 shows that almost 70% of the weight of an inverter consists of the heat sink, the capacitors, and the bus bars.

Table 12. Approximate Contributions to Inverter Weight

Heat sink	**32%**
Capacitors	23%
Bus bars	14%
Housing	10%
Other	21%

With ICE hybrids and fuel cell powered vehicles, all existing engine-driven loads, including the air-conditioning compressor, must be driven by electric motors. This will require an auxiliary inverter for the compressor drive. It should be possible to substantially reduce component count, size, and cost by integrating the auxiliary inverter with the main traction-drive inverter. Possible topologies for different auxiliary motor types will be investigated.

Temperature Limits of Components

To achieve the strategic vision of having the electric traction system cooling function integrated with an existing onboard cooling system, the operating temperature of the components will increase. Increasing the temperature of the coolant will create many challenges for the electric propulsion system. For example, as the operating temperature of a motor approaches the Curie temperature of the magnets, the intensity of the magnetic field decreases rapidly toward zero. It may be necessary to develop special magnet materials with higher-temperature capabilities.

The performance and lifetime of many power electronics components also degrade rapidly with increasing temperature.

- **Switches and diodes:** Silicon power devices typically can be operated at continuous junction temperatures up to 150°C. With a coolant at 105°C instead of 70°C, the temperature difference between the device and the coolant would be cut approximately in half, which would reduce the rate of heat extraction by a factor of two, with all other things remaining the same. Therefore, it may be necessary to operate the inverter or converter at reduced power or to use more silicon devices. Alternatively, wide-band-gap semiconductors, such as SiC or GaN (gallium nitride), could be used at those higher temperatures, but they currently are much more expensive than silicon.

- **Packaging:** The properties and performance of packaging materials such as solders, gels, and plastics for the housing are strongly affected by temperature.
- **Capacitors:** Polymer-film capacitors typically are used in inverters for electric traction systems. For systems with a 70^{o}C coolant, they have good to excellent performance and a reasonable cost. However, they occupy up to 40% of the volume, which is incompatible with the volume target, and the performance degrades rapidly with increasing temperature. Commercially available polymer-film capacitors that can tolerate higher temperatures require materials that are too expensive. Ceramic capacitors have excellent performance characteristics, but cost may be prohibitive. Previous concerns about the failure mode have been addressed in recent research.

The efficiency of the inverter is largely dependent on the power components comprising the inverter. These include the semiconductor switches and diodes. The losses within the switches are comprised of both switching and conduction losses. These are frequency and temperature dependent as well as being a function of the optimum operational point for the device. The diode voltage drop is also one of the prominent factors affecting the inverter efficiency. Semiconductor manufacturers are constantly striving to develop improved devices in an effort to lower these losses. Secondary barriers to increasing the inverter efficiency include the bus capacitor's equivalent series resistance (ESR), the resistance in the module's bus bar structure, as well as all the cabling present in and external to the inverter.

Thermal Management of Power Electronics

The overall technical challenge for thermal management of automotive PEEM systems is to develop an efficient and reliable method for removing several kilowatts of heat in a confined space under harsh ambient conditions without adding to the overall system cost, complexity, or parasitic-power requirements. The thermal management system is a critical enabling technology for increased power density, but it has been historically treated as an "add-on" to the electronics system after other components and packaging are designed. The technical challenges associated with thermal management of power electronics include heat generation due to component inefficiencies, steady-state and transient heat dissipation, device-temperature limitations, temperature-dependant efficiency, high heat flux, low thermal resistance, balanced thermal expansion, and reduced overall system complexity and parasitic-power concerns.

Thermal Driving Potential—Higher Temperature Operation or Lower Coolant Temperatures

The force that drives heat to flow through a resistive thermal network is the temperature difference between the hot and cold side—usually referred to as delta-T (or ΔT). From a heat-transfer standpoint, it is desirable to maintain as high ΔT as possible. In an electronics package, the ΔT is equal to the maximum junction temperature (T_{jmax}) minus the coolant temperature (T_c). A lower thermal driving potential (i.e. smaller ΔT) requires more aggressive heat-transfer mechanisms to dissipate the same amount of heat. The ΔT can be increased either by increasing the maximum allowable device operating temperature or by reducing the coolant temperature. A reduced coolant temperature typically requires a separate coolant system, which adds to the overall system cost, volume, weight, and complexity. High-temperature operation not only requires high-temperature-tolerant switches and diodes, but also high-temperature wire bonds, interfacial bonds, connectors, and bus bars, as well as high-temperature components such as the gate-driver boards and capacitors. The focus for achieving the targets is to remove the separate cooling system and target higher-temperature operation.

Electronics Package Thermal Resistance

An additional technical challenge for efficient heat removal is to minimize package thermal resistance while maintaining overall functionality and reliability of the devices and components. Critical and sometimes conflicting tradeoffs exist between achieving low thermal resistance while maintaining system functionality, buffering transient thermal loads, balancing thermal-expansion coefficients, and minimizing the induced thermal stresses.

Another aspect of thermal resistance is encountered in transferring heat from the solid wall of a heated surface to the cooling fluid. This resistance is typically expressed as a combination of the surface area available for heat transfer and the wall heat transfer coefficient. The technical challenge is to find compact and effective ways to increase the available surface area and the heat-transfer coefficient.

Heat Flux

A key APEEM technical target is the reduction in overall system volume. As the overall size of the power electronics package is decreased, the heat generated is concentrated into smaller areas. Heat flux is defined as the amount of heat to be dissipated divided by the area over which it is spread. The technical challenge is to develop thermal management technologies that meet the heat flux requirements without increasing overall system cost, volume, or complexity. Heat transfer coefficients are limited by the heat transfer mechanism (such as channel flow, jet impingement, evaporative cooling), physical properties of the coolant (such as the fluid density and heat capacity), and the coolant flow rate. Overall heat dissipation is increased with increasing coolant flow rates, but at a cost of increased pressure drop or pumping power. The power required to run a coolant pump is considered a parasitic power because it does not contribute to the overall operation of the vehicle.

Thermal Stresses and Reliability

Thermally induced stress is a major issue related to power electronics reliability, which is directly linked to heat dissipation and the electronics package configuration. Thermally induced stresses in the bonded interfaces and wire bonds from thermal cycling are the leading cause of failures in power modules for advanced vehicles.[15] APEEM technical targets include the requirement for a 15-year lifetime. Currently, APEEM does not have validated modeling processes or testing resources to conduct a rigorous assessment of the relative impact on reliability and lifetime of innovative new power electronics and motor designs. Vehicle manufacturers and component suppliers must run extensive life and reliability testing on all new technologies and designs to understand the response to thermal cycling, shock, vibration, and other environmental conditions. The industry reliability verification process is costly and time consuming and often occurs late in the technology-development cycle. The need to verify the robustness of a given technology for an application can often result in a technology not being brought forward to market in a timely manner, if at all.

The technical challenge is to develop and validate advanced predictive modeling processes using techniques such as "physics of failure" to evaluate the impacts of new technologies on thermal stresses, life, and reliability early in the technology-development process. The ultimate goal is to reduce the amount of testing and the cost and time to market for new technologies. Predictive modeling tools, applied early in the development process, can help guide research decisions, streamline development time, and identify potential barriers to meeting life and reliability goals. Physical modeling techniques will be used in conjunction with accelerated life testing to identify failure modes and relative impacts on reliability beyond what is currently available.

Thermal Management of Electric Machines

Thermal constraints are a primary limitation on the performance of electric machines (EMs).[16] The thermal management of EMs limits the peak and continuous power of the machine. Over-sizing the EM is one solution to improve performance of EMs within the

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[15] Bailey, C.; Tilford, T., and Lu. H (2007). "Reliability Analysis for Power Electronics Modules". 30th *IEEE International Spring Seminar on Electronics Technology*.
[16] E. Jih, K. Chen, and T. Abraham, "Thermal Management for the HEV Liquid-Cooled Electric Machine," SAE 2001-01-1713, May, 2001.

thermal constraints[17], but it is not practical in cost-, weight-, and volume-sensitive applications. For this reason, effective thermal management is needed to reduce size and improve electric machine performance. The technical challenges related to thermal management of EMs include system integration, temperature effects, continuous-power limitations, high-speed operation, and high-temperature coolants.

The temperature rise from heat losses is a primary limit in the rating of EMs[18]; the operating temperature of EMs is directly tied to operating life. Heating in induction machines can reduce the capability of rotor conductors to resist bending forces causing deformation or even melting. Permanent magnet (PM) machines suffer from degraded performance as the magnet material temperature increases. The barriers and difficulties in reducing or maintaining acceptable EM temperatures are magnified by trends to increase continuous power, increase rotor speeds, and use higher-temperature coolants. The continuous power of an electric machine is thermally limited, and improving the continuous power requires increasing the motor size or improving the thermal management. The transition to PHEVs from current commercial HEVs leads to increased continuous-power demands approaching all-electric drive applications such as fuel cells or electric vehicles.

Charging for PHEVs

The successful implementation of PHEVs and the degree to which these vehicles gain market acceptance will be intricately tied to the PHEV charging system. Gains in fuel economy, reductions in emissions, reliability, and the convenience of fewer refueling stops are all key factors in establishing the benefits of PHEVs.

Developing charger designs with high efficiency will be particularly critical since losses during power conversion are wasted as heat. Highly efficient chargers using less input power will ensure that more charging power is delivered to the battery pack in less time. Low-power chargers around 1.5kW or less are probably suitable for passive air cooling; however, the vehicle design must have the air or conductive surfaces to handle the heat load. Higher-power chargers may require liquid cooling with the added parasitic power drains from pumps. Battery cooling during charging is also a system-design consideration.

System designs must also consider nuisance tripping. Ground fault circuit-interrupter outlets and breakers can be sensitive to high-frequency power supplies, which will be

[17] C. Liao, C. Chen, and T. Katcher, "Thermal Analysis for Design of High Performance Motors," ITHERM, May, 1998.
[18] A. Fitzgerald, C. Kingsley, and S. Umans, “Electric Machinery,” 6th Edition, McGraw Hill, New York, 2003.

required to meet size and weight targets, particularly for on-board chargers. Power factor Correction is also a design concern to maximize charge power and minimize charge time, cost, and nuisance tripping of branch circuit breakers.

9. Programmatic Strategy

Achieving long-term future oil savings in highway vehicles is directly tied to successful market penetration of advanced electric vehicles. Successful market penetration requires consumer acceptance of advanced electric vehicles in terms of the following attributes[19]:

- Vehicle price
- Fuel economy
- Range
- Maintenance cost
- Acceleration
- Top speed
- Passenger and luggage space

Of these, vehicle price and fuel economy are the most important. The cost goal in particular is important since the addition of power electronics, traction motor(s) and controls to the gasoline or fuel cell power plant adds several thousand dollars to the cost. As a result of these additional components, electric vehicle cost (and price) will continue to exceed that of conventional vehicles. A principal objective of the R&D is to reduce component and subsystem cost, so that the additional vehicle cost is recoverable in three years through fuel savings.

Important elements of the strategy:

- **Develop technologies, not vehicles:** The intent of the program, in support of the FreedomCAR Partnership, is not to design or build a vehicle but rather to develop a set of technologies that can be adopted (and modified, if necessary) by the OEMs and their suppliers to enable them to manufacture a PEEM system that meets the program goals.
- **Explore multiple technologies.** Since different manufacturers will have different requirements and design strategies, and no single new technology will enable achievement of all of the targets, the APEEM program must deal with a wide variety of technologies. Clearly, improvements must be made to both the motor and the power electronics. For the motor, it is necessary to consider issues such as new designs, magnet materials, and manufacturing methods. For the power electronics, it is necessary to consider semiconductor switches, capacitors, magnetics, packaging, and new topologies. Added to all of those issues is the challenge of controlling the temperature of the modules.

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[19] Norland, D.; Jenkin, T. *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs, Appendix J – GPRA06 Vehicle Technologies Program.* NREL/TP-620-37931. Golden, CO; National Renewable Energy Laboratory, May 2005.

- **Pursue parallel paths:** In order to meet the very challenging technical targets, it is necessary to pursue high-risk concepts. To reduce the overall risk of technical failure, it therefore is necessary to pursue more than one path toward each objective. Multiple parallel paths also are more likely to produce technologies that meet the needs of more than one manufacturer.
- **Ensure technology transfer:** New technologies will not have an effect on fuel consumption until they are incorporated into commercial vehicles. Although the basic mission of DOE is long-term, high-risk R&D, the program needs to contain some short-term R&D to carry the technologies to the point where industry can adopt them. In many cases, this shorter-term R&D will be conducted in partnership with industry or by industry alone.

10. Program Structure

The basis for the programmatic structure is illustrated in Figure 11. The program starts with the DOE mission to reduce oil consumption and accomplishes that DOE objective via electrification of automotive drives in an effort to displace or eliminate oil use in the transportation sector. Minimum requirements are defined in order to be responsive to a range of vehicles. In addition, targets are defined at the systems level and then disaggregated to power electronics and electric motors. It is important that the system level targets be met. However, the targets established at the PE and EM level are guides and can be traded against each other.

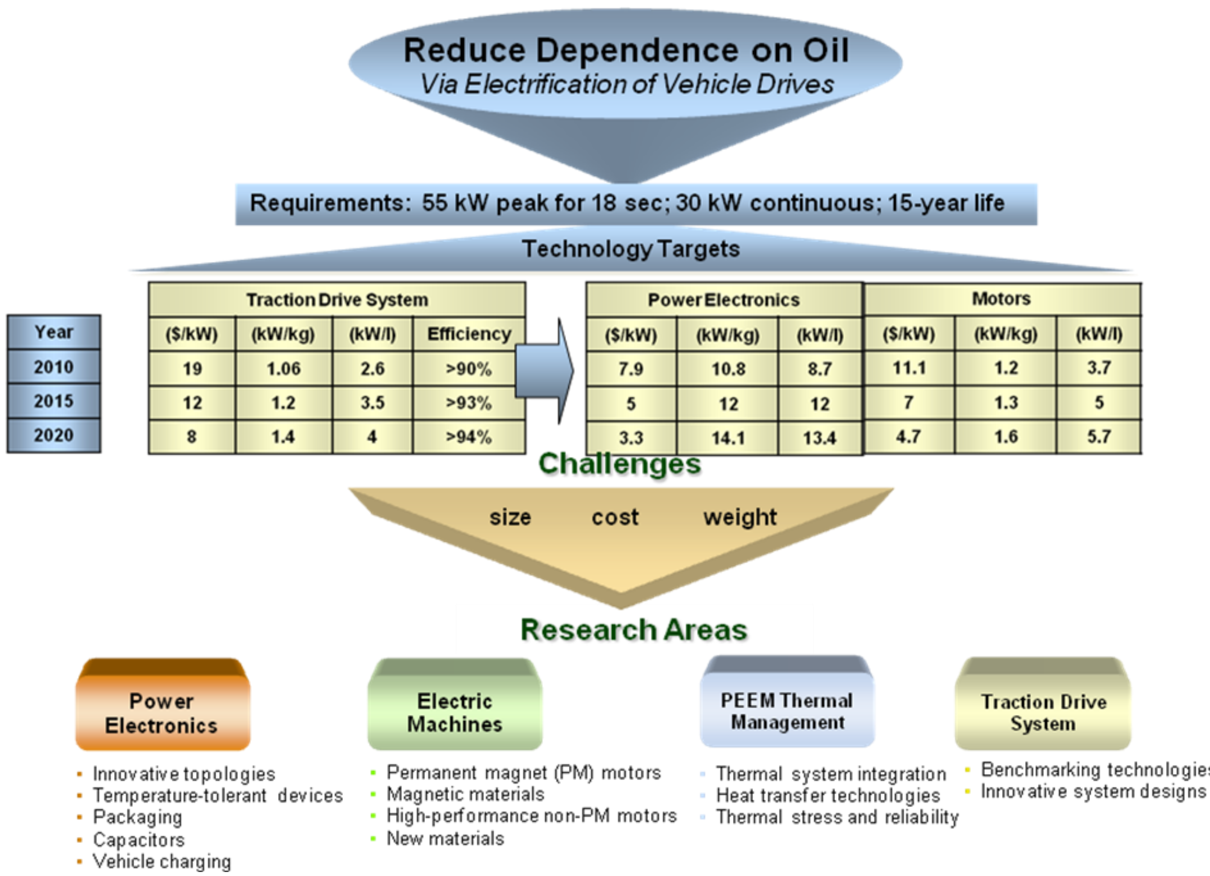

Figure 11. APEEM Program Overview

In response to the development challenges faced with meeting the targets, four research areas have been established: Power Electronics, Motors, Thermal Management, and Traction Drive Systems. For each research area in the program, a number of focus areas have been identified. These areas have been developed using Value Engineering principles and were defined in a Functional Analysis Systems Technique (FAST) study. The focus areas listed under each research area in Figure 11 are described in subsequent sections of this document. In order to achieve the targets, contributions will be needed from most, if not all, of the focus areas and the parallel paths that are embedded in them. All focus areas need to be pursued simultaneously.

Flow of R&D Activities

As shown in Figure 12, the program consists of three developmental levels: core research, application of core technology into power electronics and electrical machines (PEEM) modules, and development of vehicle-ready PEEM solutions. This structure flows from a basic technology concept (e.g., a new magnet material, a new inverter topology) all the way through to the development of a motor, inverter, or traction drive system that can be used on a vehicle. In the early stages of development, the work usually is conducted at research organizations such as national laboratories, small businesses, and universities.

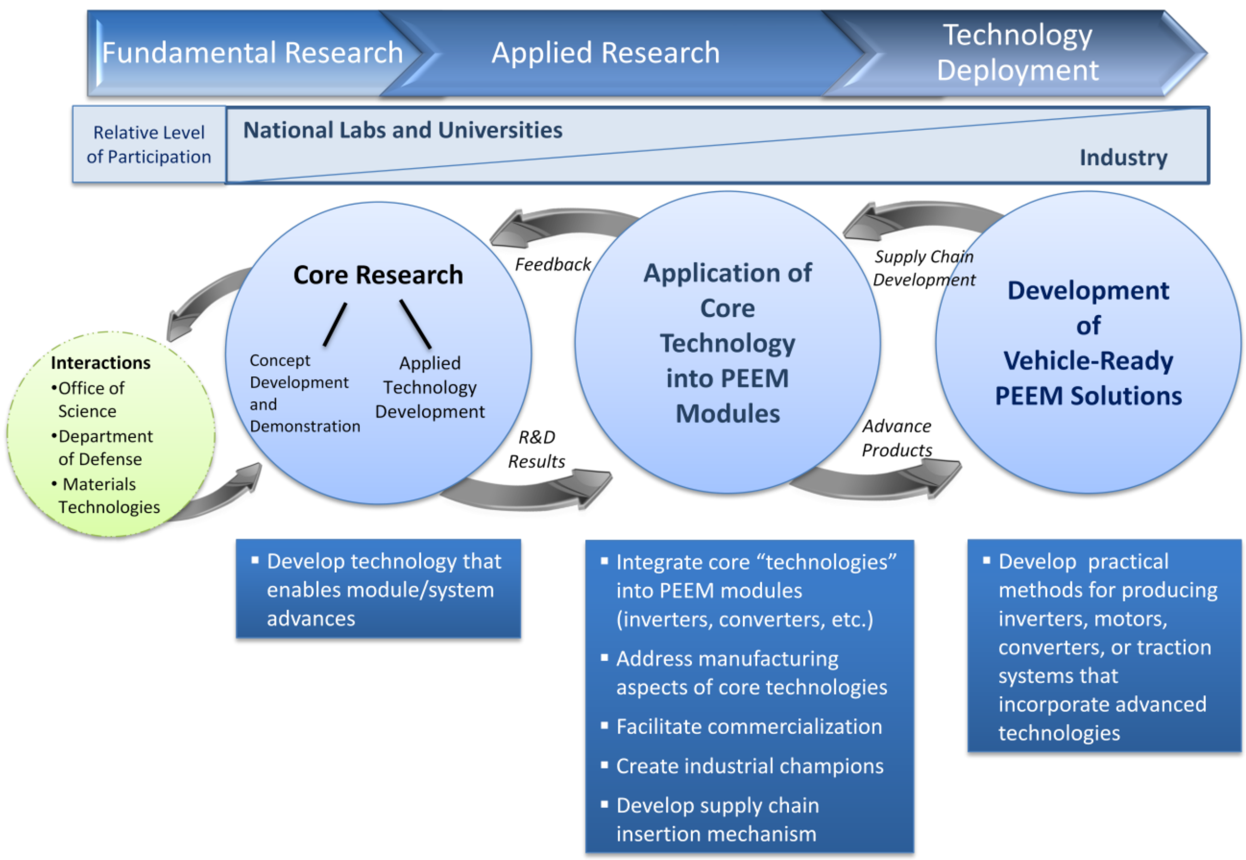

Figure 12. APEEM Program Structure

As the technologies mature and are integrated to form modules (e.g., an inverter package and topology are combined with an advanced thermal management technology into an inverter), the work is performed through collaboration between the national labs and industry (primarily the supplier base). At the end of the development cycle, industrial teams (OEMs and suppliers) produce vehicle-ready PEEM solutions. A more detailed discussion for each development level is presented below.

Core Research

The core research is guided by the program focus areas and includes both concept development/demonstration and applied technology-development activities. The defining line between the two is somewhat fuzzy but, in general, the concept-development work has a stronger basic science component than does the applied technology development work. For example, developing a new magnet material would be concept development whereas developing a motor design to use the new magnets would be in the applied area. The scope of activity in this stage is defined by the focus areas for the program as described below.

Core research is performed largely by the national labs, universities, and other research organizations. It is focused on demonstrating the feasibility of new technology (e.g., new inverter topology or packaging, new motor concepts, thermal management methods, capacitor and magnets) that enables PE and EM modules and traction drive systems to move closer to the weight, volume, cost, and efficiency targets. This effort interacts with efforts from other organizations such as the DOE Office of Science program, DoD, and the DOE Vehicle Technology Program's lightweight materials programs to learn from and coordinate with their developments and provide vehicle-application-specific input to their R&D activities. Core research results are used in the next stage of development to produce advanced modules. In addition, feedback from the application effort is used to focus the core research activities into high-payoff areas.

Application of Core Technology into PEEM Modules

Technologies successfully demonstrated in core research are integrated into prototype advanced PEEM modules (inverters, motors, and converters). This activity is carried out via collaborative efforts involving national labs and industry. For example, an inverter supplier may be contracted to work with the power electronics lead national laboratory in the development of a current-source inverter using wide band-gap materials, direct-cooled substrate packaging, and advanced heat-transfer technology. This increases the chances for commercialization by bringing a manufacturing element to the work, creates industrial champions for successful technologies, and develops a mechanism for inserting these technology advances into the supply chain. Interaction between national labs and industry is critical to the success of these efforts, typically carried out via subcontracts from the national labs to industry to ensure that the necessary interaction occurs.

The prototypes produced by these efforts provide a valuable portfolio of options for the next stage of development within the program. In addition, the feedback provided by the PEEM vehicle solutions effort is used to refine the prototype efforts.

PEEM Vehicle Solutions

This is the final stage in the R&D development chain and is directed at producing vehicle-ready PEEM inverters, motors, converters, and traction-drive systems. Because this effort is so closely aligned to industry application, it is conducted via cost-shared contracts with industrial teams consisting of OEMs and suppliers. The lessons learned in these efforts supply feedback to the module development efforts conducted by suppliers working with the national laboratories. This assists in developing a supply chain that is responsive to auto manufacturer needs.

Roles

The APEEM program involves a number of different types of organizations to develop new technologies, convert those technologies into commercial products, and incorporate those products into automobiles.

DOE

DOE funds the R&D, which includes activities at the national laboratories, automotive suppliers, universities, small businesses, and other research institutions. Direct funding from DOE to partner companies or consortia is limited. In general, DOE competitively selects cost-shared R&D projects with industry, and DOE R&D funding decisions are made independently.

The APEEM team also coordinates with other DOE programs doing relevant work in related areas to maximize the return on DOE's technology investments in this area. Close cooperation with the Office of Science, the Office of Electricity, and the solar and wind programs provides valuable technical and programmatic support. The team also coordinates with The Hydrogen, Fuel Cells & Infrastructure Technologies Program within the Office of Energy Efficiency and Renewable Energy on the development of components that can be used in FCVs as well as hybrids.

National Laboratories and Universities

Several national laboratories and universities are involved in early-stage research to develop new concepts or new materials. Projects are selected based upon the perceived potential for meeting key R&D goals. Cost is considered in a qualitative sense, but accurate cost analyses depend on the details of the manufacturing process and therefore are left to the OEMs or their suppliers. The labs also provide a window to relevant research at universities and other government laboratories, assist DOE in establishing program targets and R&D priorities, provide evaluation and benchmarking of competitive and alternative technologies to assess R&D status and to help identify future R&D needs, and do confirmatory testing of prototypes that are developed in DOE-supported industry-led projects to see if the prototypes meet specifications.

Original Equipment Manufacturers and Suppliers

Ultimately, OEMs are responsible for incorporating new technologies into their vehicle designs. To make sure that new concepts will be compatible with their needs, OEMs provide insight and guidance regarding technologies and projects to address critical issues. One forum for these interactions has been established through the EETT. Input also is welcomed from the Vehicle Systems Tech Team, the Energy Storage Tech Team, the Grid Interaction Tech Team, and the Fuel Cell Tech Team.

The auto manufacturing partners and suppliers independently undertake their own research activities relevant to their business plans. The OEMs can participate jointly on collaborative, pre-competitive R&D of technologies such as SiC devices and ceramic capacitors. These cost-shared projects are conducted to demonstrate and validate new technologies and develop a meaningful cost analysis. Some prototype components may be sent to national labs for evaluation. However, the auto manufacturing partners make independent decisions on commercialization based on their business cases.

Small Businesses

Small businesses are encouraged to develop innovative solutions through the SBIR Program. Each year, several subtopics are released for proposals, and awards are made to small businesses to meet research needs of the APEEM program.

Intergovernmental

Interagency coordination on APEEM development is conducted through the government-sponsored Interagency Advanced Power Group (IAPG) that brings together representatives from the Department of Energy, NASA, NIST, the Army, the Navy, and the Air Force. In particular, this coordination has been helpful with meeting the challenges associated with high-temperature operation.

11. R&D for Motors

Allocation of Targets

Although the technical targets have been established at the system level, an approximate allocation of the targets between the motor and the power electronics is useful as guidance for projects that address one or the other. The values in Table 13 estimate how much can be achieved with improvements to the motor and, along with comparable numbers for the power electronics to be presented later in this document, are consistent with the system-level targets.

Table 13. Approximate Technical Targets for Motors

	2015[a]	2020[a]
Cost, $/kW	<7	<4.7
Cost, kW/$	>0.143	>0.213
Specific power, kW/kg	>1.3	>1.6
Power Density, kW/L	>5.0	>5.7

a. Based on a maximum coolant temperature of 105°C

It is important to note that certain motor designs may have an impact on the weight, volume, and cost of other parts of the vehicle. For example, a design that minimizes the back EMF might eliminate the need for a boost converter, while a design that involves higher speeds might require the addition of a gear box. Whenever a new concept is compared to the targets, it will be essential to clearly state and consider those effects.

Although many vehicle architectures require two electrical machines, one as a motor and another as a generator, some architectures make use of a single machine for both purposes. The targets in Table 13 refer to one machine.

Design Considerations for Motors

A number of design considerations for motors are summarized in Table 14.

Table 14. Design Considerations for Motors

Parameter	Limited by	Enhanced by
Flux density	Magnetic saturation, air gap size, adjustability, PM strength	Improved soft magnetic materials, stronger PM, external field injection
Current density	Winding temperature	Improved cooling, higher insulation temperature, higher slot-fill factors
Torque	Flux density, current, loading, volume	Additional reluctance torque, stronger magnets, higher active current.
Speed	Bearings, material strength, back EMF, voltage	High-strength steel, external field injection, boost converter
Power	All of the above	All of the above
Motor mass	Speed, housing, stator, rotor, windings, bearings, magnets, cooling	Improved specific power, lightweight materials for the housing
Motor size	Speed, housing, stator, rotor, windings, bearings, magnets, cooling	Improved power density
CPSR	Back EMF, voltage, inductance	Boost converter, flux control
Temperature	Losses, PM and wire temperature ratings, cooling	Improved efficiency and thermal management
Cost	Materials, manufacturing, maintenance, reliability	Production process, volume, and innovation
Efficiency	Core loss, copper loss, stray losses	Improved materials, better cooling
Reliability	Bearing, magnets, and winding failures	Improved cooling, Higher-coercivity magnets, higher insulation temperature

Major Types of Motors

Typically, during 75% of the drive time, automobiles operate around 50% of maximum speed and at a fraction of maximum torque/power. True energy savings in the drive system will come from higher efficiencies at these speeds and torque/power operation. Motor/generator candidates for the electric propulsion system include interior permanent magnet (IPM), surface mount permanent magnet (SPM), induction, and switched reluctance (SR) machines.

IPM machines have high power density and maintain high efficiency over the entire drive cycle except in the field-weakening speed range, where there are losses in motor efficiency. This presents a challenge to increase the constant power range without loss of efficiency. Other major issues are failure modes and the high cost of the motor. These machines are relatively expensive due to the cost of the magnets and rotor fabrication. Major challenges are to develop bonded magnets with high energy density capable of operating above 200^{o}C and motor designs with high reluctance torque. This may result in reducing the magnet cost. Other challenges include thermal management and the temperature rating of the electrical insulation.

SPM machines (among other types of machines) are candidates for integrated starter alternator applications. The SPM machines have magnet blocks glued on the surface of the rotor and wrapped over with a fiber sheet. SPM machines have high power density due to low reactance and a radial magnetic field. These machines produce high starting torque and offer high design flexibility due to a low sensitivity to air-gap variation. The major drawback of SPM machines is the difficulty in achieving constant power over a wide speed range because of the constant magnet flux, which causes the back EMF to increase linearly with speed. In addition, SPM machines suffer from thermal management issues due to the presence of relatively high magnets losses.

Induction motors are the most reliable; they have high starting torque and are widely manufactured and utilized in the industry today. Unfortunately, they cannot meet the cost, power-density, and efficiency targets. Because of the mature nature of this technology, the likelihood of achieving the required additional improvements in efficiency, cost, weight, and volume is low.

SR motors potentially are the lowest-cost, high-efficiency machines, and they have a rugged structure for use at high temperatures and speeds. These machines have serious problems in terms of high torque ripple leading to high noise levels, and they have a low power factor. They also require expensive sensors and inverter technology, which make the system cost comparable to others.

Approach for Motors

Though initial assessments indicated that traditional induction motors might be an acceptable option, after several years it was determined that the specific power and power density of these machines would not meet the targets. IPM machines became the motor of interest because it appeared that they could meet these targets and the cost of permanent magnets (a major cost item of these motors) was falling. The promise of smaller, lighter motors has been largely achieved by IPMs by increasing the maximum speed of the machine to values above 15,000 rpm and using the reluctance torque component to augment the permanent magnet (PM) torque. However, the potential to meet the cost target has been diminishing because of the increasing cost of the permanent magnets and the need for a boost converter in the power electronics to overcome the back EMF generated by the motor. As shown in Table 15, R&D for motors includes four focus areas:

- PM Motors
- Magnetic Materials
- Non-PM Motors
- New Materials

Table 15. APEEM Focus Areas for Motors

Focus Area	Impact
PM Motors *Reduce cost & maintain performance*	Cost is major concern for IPM (cost reductions of 75% are required to meet 2020 target). Work on all aspects of motor design may reduce cost by 25% to 40%.
Magnetic Materials *Reduce cost & increase temp.*	Magnetic materials cost 50% to 75% of the motor targets for 2015 and 2020, respectively. Work should focus on reducing cost and increasing temperature capability could reduce motor cost by 5% to 15%.
Non-PM Motors *Greatly reduce motor and PE cost*	Non-PM machine technology matching the performance of IPM machines yields the greatest opportunity for motor and system cost reduction • PM cost of $200 is about 75% of the 2020 motor cost target; eliminating PMs reduces motor cost by 30% • Back EMF of IPM requires boost converter which adds cost component to PE greater than 2015 or 2020 cost target; eliminating boost saves 20% in PE cost • Poor power factor of IPM causes larger currents, increasing size and cost of PE; save 15% PE cost • Increase CPSR to 8:1 (current systems are 4:1) to effect savings in transmission
New Materials *Reduce motor cost*	Other materials in motor must be addressed because PMs are about 30% of current IPM cost. New materials for laminations, cores, etc. could save 20% of motor cost.

PM Motors

Because of their superior power density and specific power, IPM motors have become the industry workhorse in HEV applications, and this is anticipated to hold true for the next decade. The 2015 and 2020 cost targets for the traction motor are $385 and $260, respectively; to achieve the 2015 and 2020 cost targets, the motor cost must be reduced by as much as 65-68%. This requires reductions in all cost elements in the motor and application of advanced materials, designs, and manufacturing processes. Investigation of motor designs that use less-costly (but lower-performing) PMs is also needed.

Magnetic Materials

Current IPM motors use neodymium iron boron PMs because of their superior magnetic properties. However, these magnets are expensive; in a typical 55 kW IPM, the magnets cost in the range of $100 to $200 (this is about 50% of the 2015 motor cost target and 60% of the 2020 motor cost target). In addition, their Curie temperature places thermal limits on the motor that require either limiting the duty of the motor or investing in thermal management systems to transport heat from the motor. Magnetic materials that possess magnetic properties similar to neodymium iron boron magnets but cost less and have higher temperature limits are needed if the IPM has a reasonable chance of meeting the cost targets.

Non-PM Motors

Because of the disadvantages of IPM motors noted above, the development of motors that do not use permanent magnets but yield IPM-like performance is being pursued. This program includes R&D to solve issues with existing motor designs that will allow their use in advanced vehicle applications, such as switched reluctance motors, as well as novel designs, such as the U-machine that was made possible by the novel flux-coupling method developed by the APEEM effort. The objective of these development efforts is to overcome the PM motor deficiencies noted above but yield characteristics (power density and specific power) similar to PM technology.

New Materials

Achieving cost targets will require improvement in all design elements of the motor. Because of their prominence in the motor cost, permanent magnets have been given much attention. However, they represent only about 30% of the motor cost for existing IPM designs. Attaining the levels of cost reduction required to meet 2015 and 2020 motor cost targets (50% to 75%) requires expanding the effort to all materials in the motor. New lamination materials, soft magnetic core materials, and a number of other alternatives should be examined, since they may enable new design freedoms that can reduce the gaps in reaching the targets.

12. R&D for Power Electronics

Allocation of Targets

Although the technical targets have been established at the system level, an approximate allocation of the targets between the motor and the power electronics is useful as guidance for projects that address one or the other. The values in Table 16 estimate how much can be achieved with improvements to the power electronics and are consistent with the system-level targets.

Table 16. Approximate Technical Targets for Power Electronics

	2015[a]	2020[a]
Cost, $/kW	<5.0	<3.3
Cost, kW/$	>0.200	>0.303
Specific power, kW/kg	>12.0	>14.1
Power density, kW/L	>12.0	>13.4

a. Based on a maximum coolant temperature of 105°C

Major Power Electronics Modules

The major power electronic modules are inverters, boost DC/DC converters, power-conditioning DC/DC converters, and, for PHEVs, chargers.

Inverters

A major focus of the PE work is on inverters, which are required to drive all of the electric motors as part of the traction drive system in HEVs, PHEVs, and BEV/FCVs. The specific design may vary, as will the power rating, number of phases, topology, and module packaging method. The decision on the inverter design is intimately tied to the type of motor that the inverter must drive; the inverter and motor must operate as a system efficiently and seamlessly.

Boost DC/DC Converters

Boost DC/DC converters are used in some traction drive architectures. The choice to use a DC/DC boost converter depends on system considerations, including the motor design, the battery technology and cost, or the integration level of the power electronics with the battery and the motor.

There are presently no Vehicle Technology Program targets for a separate boost DC/DC converter; the volume, weight, and costs must be absorbed within the PE targets. Major cost elements for a DC/DC converter include the switches and the magnetic components.

The current approach within the program is to work towards PE topologies that have the ability to incorporate the boosting function within a single PE module that contains both the boost and the inverter functions and is able to operate with high-temperature coolants. Through the integration of functions, the part count is reduced, resulting in a more reliable, lower-cost system.

Technologies developed for the inverter are expected to be applicable to the DC/DC converter as well. However, a buck DC/DC converter also contains a transformer, which represents a major fraction of the weight.

Power-Conditioning DC/DC Converters

HEVs, PHEVs, BEVs, and FCVs will require lower-voltage buses for traditional vehicle loads and, therefore, require a step-down DC/DC converter from the high-voltage buses. Most applications will require a power-conditioning DC/DC converter with a relatively high power rating of 3 to 5 kW continuous for auxiliary loads. The converter also needs to provide galvanic isolation between the low- and high-voltage buses. Furthermore, soft switching is preferred over hard switching because of the reduced level of EMI and switching losses. Other expected requirements for this converter are

- The terminal voltage of the battery can swing from 8 V to 16 V during either direction of power flow.
- The nominal voltage of the high-voltage bus is 325 V, with an operating range of from 200 V to 400 V.

As the power-management system is not a part of the traction drive system, research in this area has not been given a high priority. When resources have allowed, projects have been developed around these auxiliary converters as they are considered to be vehicular power electronics. However, since they are not in the traction drive line, their cost, weight, and volume are not budgeted for within the PE technical targets.

Chargers

The PHEV charger design involves not only understanding the vehicle environment and its electronic circuitry but also the AC supply infrastructure. In designing PHEV chargers that interface with the utility grid system, design considerations must be given to the impacts on the electrical grid, residential EMI emissions and susceptibility, UL standards, and owner safety.

Battery chargers for PHEVs can be based upon proven, traditional, high-frequency charger circuits and can be located either on or off board the vehicle. Additionally, on-board concepts that integrate the charging function into the existing power electronics and utilize the inductance of the motor can be developed. Conductive and inductive charging designs each have benefits. In all cases, designs must be realized with a small footprint, be light weight, and have low cost, high efficiency, and high reliability.

The Society of Automotive Engineers (SAE) has developed standards to establish criteria for conductive charging (e.g., SAE Standard J1772). Table 17 details charge levels, nominal supply voltages, and maximum current values for three proposed charging scenarios.

Table 17. Charge Method Electrical Ratings (North America)

Charge Method	Nominal Supply Voltage	Maximum Current	Branch Circuit Breaker Rating
AC Level 1	120 V AC, 1-phase	12 A	15 A minimum
AC Level 2	208 to 240 V AC, 1-phase	32 A	40 A
DC Charging	600 V DC maximum	400 A maximum	As required

These charging levels will define the PHEV battery recharge time. As bigger battery packs are utilized in PHEVs with larger all-electric ranges, higher power and shorter recharge times will become important.

Major Components of Inverters and Converters

The major components of inverters and converters that need to be addressed include

- **Semiconductor Switches:** Current state-of-the-art inverters use insulated gate bipolar transistors (IGBTs) for high-power and high-voltage applications, such as automotive traction drives and metal oxide semiconductor field effect transistors (MOSFETs) for low-voltage, low-power applications. Standard IGBTs are only capable of switching up to 20 kHz compared to several hundred kilohertz for MOSFETs. The high on-resistance of standard MOSFETs prevents their application at 600 V and above for high-power conversion. High switching frequency is desirable to reduce the size of capacitors and magnetic components in DC/DC converters.

  Semiconductor switches have a large impact on the cost of the inverter, typically accounting for about 33% of the total cost. They also have an indirect effect on size and weight of the system because of the cooling requirement to keep the junction temperature of the device below 125ºC for IGBTs and 150ºC for MOSFETs.

New IGBTs based on trench technology show significant improvements over the non-punch-through (NPT) IGBT. Both the saturation voltage and the switching losses are reduced by about 20% along with an increase in the allowable junction temperature to 150°C. To take advantage of this higher temperature rating, new packaging technologies must be explored. Silicon carbide is a long-term attractive alternative to silicon because SiC devices can operate at temperatures up to 350ºC, and they have high thermal conductivity, higher breakdown voltages, low switching losses, and the capability to operate at high switching frequencies. The main problem is cost; SiC is more expensive than silicon, production quantities are low, and scrap rates are high because of immature manufacturing processes.

A considerable amount of research into wide band gap (WBG) devices is being conducted by the military and the electronics industry. In view of the comparatively small effort that could be funded by the automotive industry and the very small market share represented by the automotive industry, the strategy with respect to semiconductor switches consists of monitoring the research conducted by other organizations and testing devices for automotive applications as they become available. Recently, though, the potential of SiC in some automotive applications may dictate the specific development by the industry of devices, such as SiC diodes, to increase inverter efficiency.

- **Capacitors:** Capacitors typically represent the second largest cost component of an inverter, and they also account for a major portion of the volume and weight. Polymer-film capacitors are used in most HEVs today, but they currently cannot tolerate sufficiently high temperatures for future applications that will require 150°C. Many current polymer-film capacitors typically are rated at 85°C, but more-expensive ones are available that can operate up to 105°C.

  Theoretically, **ceramic capacitors** have the greatest potential for volume reduction; they could be as small as 20% of the volume of an aluminum electrolytic capacitor. Ceramics offer high dielectric constants and breakdown fields and, therefore, high energy densities. They also can tolerate high temperatures with a low equivalent series resistance (ESR), enabling them to carry high ripple currents even at elevated temperatures, although the capacitance may vary strongly with temperature. In addition to cost, the possibility of catastrophic electrical discharge and mechanical failure of ceramic capacitors is a concern. However, a technique similar to that used in polymer-film capacitors for ensuring benign failure has been developed, and at least two manufacturers have demonstrated graceful-failure ceramic capacitors, although they have not yet been implemented into a product because there is no strong customer demand.

Glass capacitors operate at high temperature and are constructed from low-cost materials. The use of glass capacitors has generally been restricted to low volume military markets; however, this technology is very promising for large-scale DC capacitors.

Until now, the EETT has treated the capacitor as an individual component. No single capacitor has been able to meet all the requirements of an automotive traction system. The solution for a traction application may come by minimizing the capacitance needed through the overall system design.

The anticipated requirements for a DC bus capacitor bank in 2015 are listed in Appendix B. The main technical targets would be to reduce the weight, volume, and cost per micro Farad by a factor of two. Table 18 gives a qualitative summary of the advantages and disadvantages of the three types of capacitors.

Table 18. Qualitative Comparison of Candidate Technologies for Bus Capacitors

	Electrolytic	Polymer Film	Ceramic
Size, weight	Poor	Good	Excellent
ESR	Marginal	Excellent	Excellent
Temp. stability	Marginal	Good	Excellent
Reliability	Marginal	Excellent	Excellent
Ripple current	Marginal	Good	Excellent
Failure mode	Poor	Excellent	Acceptable failure modes have been demonstrated
Cost	Excellent	Good	To be determined

- **Heat Exchanger:** Another major contributor to the weight and volume of an inverter is the heat exchanger; discussed further in the section on thermal management.

- **Controller:** Market developments in microprocessors are increasing the potential to reduce cost, complexity, and size of control boards. Through the reduction in parts count and manufacturing efforts, it is hoped that a cost reduction of 30% can be realized in high-volume production.

- **Gate Drives:** The drivers for IGBTs are frequently located on the control board. Further integration is being investigated to reduce weight, volume, and cost.

Opportunities for weight reduction with the power electronics include reducing the number and/or size of the capacitors; reducing the size of the heat sink; eliminating the dedicated cooling system; and eliminating magnetic components in the converter.

Approach for Power Electronics

The power electronics area has undergone several changes in focus. With the use of high-temperature coolants, innovative heat-transfer and packaging concepts are necessary. The emerging requirement for a boost converter made achieving the targets even more difficult, and emphasis on integrating boost functionality within the inverter was initiated. As shown in Table 19, the R&D for power electronics includes five focus areas:

- New Topologies
- WBG Semiconductors
- Packaging
- Capacitors
- Vehicle Charging

New Topologies

The topology work focuses on minimizing the need for bus capacitance and integrating functionality. Topologies are being explored to reduce the required bus capacitance need by 50% or more, thereby helping to attain the volume targets. By integrating multiple functionalities into the inverter (such as integrating the boost converter and the inverter or integrating inverter function for the traction drive system and accessory loads), reduced part counts are possible, thus saving cost, volume, and weight and increasing reliability.

WBG Semiconductors

WBG semiconductors using SiC or GaN offer higher temperature capability and would be very useful in applications where the inverter is subjected to high ambient temperatures (such as under hood or on the transmission) or where higher temperature coolants are employed. In addition, they offer the potential for increased inverter efficiency such that, if they were available at no or small cost premium (when compared to Si switches), they would be the favored technology.

Table 19. APEEM Focus Areas for Power Electronics

Focus Area	Impact
New Topologies *Decrease size and cost, and improve reliability*	Avenue to achieve significant reductions in PE weight, volume, and cost and improve performance • Reduce capacitance need by 50% to 90%, yielding inverter volume reduction of 20% to 35% and cost reduction • Reduce part count by integrating functionality thus reducing inverter size and cost and increasing reliability • Reduce inductance, minimize EMI and ripple, reduce current through switches all result in reducing cost
WBG Semiconductors *Enable high-temp*	Produces higher reliability, higher efficiency, and enables high-temperature operation
Packaging *Greatly reduce PE size, cost, and weight with higher reliability*	Provides opportunity for greatly decreased size and cost • Module packaging can reduce inverter size by 50% or more, cost by 40%, and enable Si devices to be used with high-temp coolant for cost savings of 25%, • Device packaging to reduce stray inductance, improve reliability, and enable module packaging options When coupled with heat transfer improvements, gains are enhanced
Capacitors *Reduce inverter volume*	Improved performance can reduce capacitor size by 25%, reducing inverter size by 10%, and increase temperature limit
Vehicle Charging *Provide function at minimum cost*	Provide the vehicle charging function in a policy-neutral manner at virtually no additional cost with bi-directional capability

Packaging

Attaining the size, weight, and cost reductions and reliability requirement needed to meet the 2015 and 2020 targets will require innovative module and device packaging. At the module level, the elements associated with removing heat (the spreader, TIM, and cold plate) occupy a substantial volume. Industry trends associated with cost reduction paths are likely to result in these elements getting larger. The desire to reduce cost by using less silicon will increase the heat flux that must be accommodated, which will increase the size of these heat rejection components. Integrating the power electronics cooling system with an existing cooling system (as a means of reducing cost) is likely to result in higher-temperature coolants that will further exacerbate the situation. If packaging advances are not made, the volume implications of these trends are that the volume of the heat transfer components themselves could equal or exceed the inverter volume targets for 2015 and 2020. Innovative module packaging can mitigate these size increases by eliminating existing interface layers and providing cooling at or very near the heat sources. This could also enable high-temperature coolants to be used with existing silicon devices, resulting in further potential cost savings.

Packaging could also result in reliability and performance improvements through improved bus structures, die-attach methods, materials that provide thermal-expansion matching, as well as techniques that enable double-sided cooling. Advanced device packaging could also result in packing techniques (such as three-dimensional formations) that would contribute greatly to achieving volume targets.

Power electronics packaging improvements go beyond just looking at semiconductor-device-level innovations. There are opportunities to reduce size, weight, and costs of the power electronics through improvements in gate-drive packaging, current sensors, and capacitors and magnetics that will provide better performance and more reliable and higher temperature operation.

Capacitors

Current power electronics solutions employ a voltage source inverter (VSI), which uses a bus capacitor to protect the battery from ripple currents generated in the inverter. In a typical inverter, the bus capacitor occupies about 35% of the inverter. This volume nearly equals the 2015 volume target for the complete inverter and exceeds the 2020 inverter volume target. The situation may be exacerbated by recent trends that result in inverter temperature increases because the ability of capacitors to accommodate ripple currents is severely impacted by elevated temperatures. For example, increasing the capacitor operating temperature from 85°C to 105°C decreases the ability of current commercial polymer-film capacitors to handle ripple currents by 80%. This results in the capacitor size growing by fivefold to accomplish its ripple filtering function. Capacitor performance improvements, particularly at temperatures in the 100°C to 125°C range, can provide the PE development effort with smaller capacitor volumes, which will be important if inverter volume targets are to be achieved.

Polymer-film capacitors and ceramic capacitors will be pursued; both have potential for large benefits but also face significant technical challenges. Recent research has produced polymer films with substantially higher temperature capabilities, but manufacturing problems have prevented the fabrication of large capacitors suitable for an inverter DC bus. The near-term emphasis will be to solve those manufacturing problems, and longer-term efforts will be devoted to reductions in cost and further improvements in performance. The near-term emphasis for ceramic capacitors will be to further demonstrate a design that will prevent catastrophic failures of thin-film capacitors based on ceramic ferroelectric materials, antiferroelectric/ferroelectric phase-switch ceramics, and glass ceramics. After benign failure modes are assured, future efforts will be devoted to material selection and processing methods to improve performance and reduce cost.

Vehicle Charging

Substantial petroleum savings are possible if grid electricity can be used to replace petroleum fuels in a vehicle. The PHEV concept seeks to capture this benefit and deliver petroleum savings. This is achieved by having a large battery pack on the vehicle and fully charging that pack using grid electricity. Several charging systems are being evaluated, ranging from stand-alone chargers to charging systems that utilize a modified inverter system as the charging circuitry. The later offers many benefits (such as V2B and V2G capability) not currently available with stand-alone technology. In addition, it provides the vehicle charging capability for essentially no additional cost.

13. R&D for Thermal Management

Background

Since neither the motor nor the power electronics operates at 100% efficiency, the losses associated with these components have to be dissipated in the form of heat. For high-power operations, a large amount of heat must be removed from the system.

Figure 13 illustrates a traditional method of die packaging.

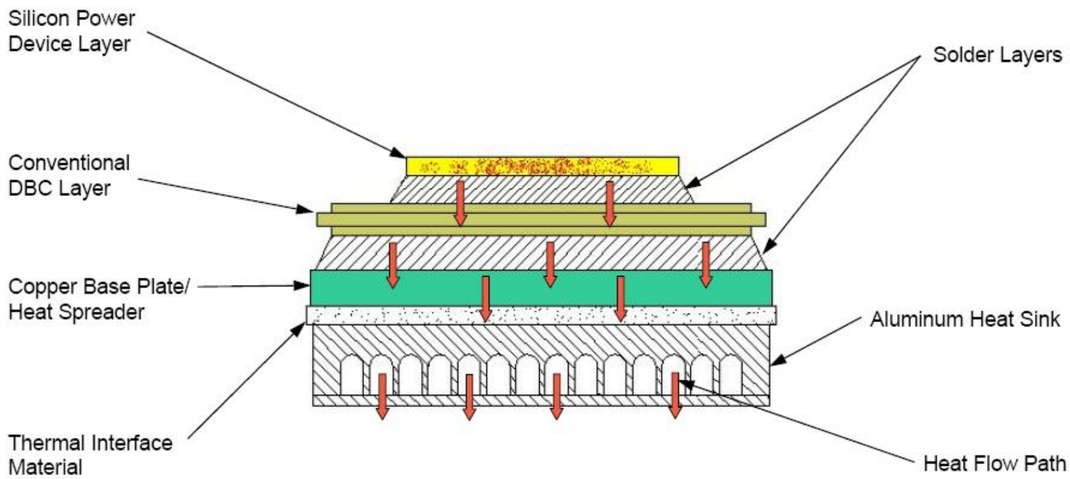

Figure 13. Die Package Stack

The direct bonded copper (DBC) layer is composed of a ceramic substrate sandwiched between braised copper layers. The top layer of copper is etched to form the conductive ‘runs’ for the circuit path and the connections between the top of the semiconductor die and the runs are made with wirebonds. The bottom copper layer is soldered to the base-plate/heat spreader, which functions to spread the heat generated and also as a structural support for rigidity. Thermal interface material is typically silk screened onto the heat sink, and then the base plate is bolted onto the heat sink. The thermal interface material functions to fill voids due to irregularities in the heat sink so that a good thermal interface is achieved.

Thermal Management of Power Electronics

The thermal performance of a power module is measured by the maximum temperature rise in the die at a given power dissipation level with a fixed heat sink temperature. Excessive heat can degrade the performance, life, and reliability of power electronic components. Conventional silicon devices must be maintained at temperatures below

125°C, and even lower die temperatures would improve electric performance and reliability. In current commercial inverters, the temperature is maintained by flowing a 70°C liquid coolant through a heat exchanger under the inverter. In order to meet the technical target for volume, the available area for heat transfer needs to be reduced significantly, which will impose serious challenges for the thermal management system.

The problem will be exacerbated by the use of a 105°C coolant. Therefore, optimization of existing thermal technologies and the development of new pioneering cooling methods are needed to enable higher power densities and lower system cost while maintaining the reliability of the drive system components. The development of advanced thermal management technologies is critical to nearly all viable technology pathways.

Thermal Management of Electrical Machines

Past thermal management efforts focused on power electronics used within electric drive applications. However, as the trend to electrify vehicle propulsion systems increases, the impact of thermal management on the electric machine will increase.

Current commercially available HEVs use PM electric machines for their traction drives because of their efficiency and performance to size benefits. The thermal management of the machines relies heavily on their thermal mass, to enable high-power transient operation. However, the machines are actively cooled using transmission oil within the transaxle or transmission case, and the oil also provides cooling and lubrication to gears and bearings. The gasoline engine drives the oil pump and gears (dependent on vehicle speed), splashing or dripping oil onto the stator end windings. An oil-to-coolant heat exchanger extracts heat from the oil using the water/glycol coolant system that is shared with the power electronics module. A separate air-to-coolant radiator at the front of the vehicle rejects the heat from the power electronics, electric machines, and transmission.

Thermal management of electric machines is critical because of the impact of temperature on machine operation. The performance, efficiency, and reliability of the machine are all reduced with increasing temperature. For example, the performance of the PM material degrades with increasing temperature, and, at certain temperatures, this degradation is permanent. This degradation affects the performance of the machine and vehicle. The increase in temperature also reduces machine efficiency because of increased I^2R losses in the motor windings for an electric machine. The increased winding losses result in even higher winding temperatures, compromising winding insulation durability. If the machine thermal management is insufficient, the machine controller or vehicle controller is forced to de-rate the machine operation to protect itself.

This in turn reduces machine performance and forces the vehicle to operate at reduced power or reduced efficiency.
A number of challenges associated with increasing the PEEM coolant temperature arise from the following items: 1) continuous power limitations, 2) high-speed operation, and 3) high-temperature coolants. The continuous power of an electric machine is thermally limited, and improving the continuous power for a given speed and torque requires increasing the motor size or improving the thermal management.

Figure 14 illustrates how continuous power demands increase through the transition to PHEVs from current commercial HEVs, approaching all-electric drive applications such as fuel cells or electric vehicles. Machine speed also impacts the thermal stress on the motor. Higher-speed machines enable increased power density, but, as machine speed increases, the core losses within the stator and rotor increase. The increase in rotor losses is a particular concern because of the difficulty in removing heat from the rotor. Finally, a desire to use higher-temperature coolants impacts the ability to draw heat away from the machine, driving up component temperatures.

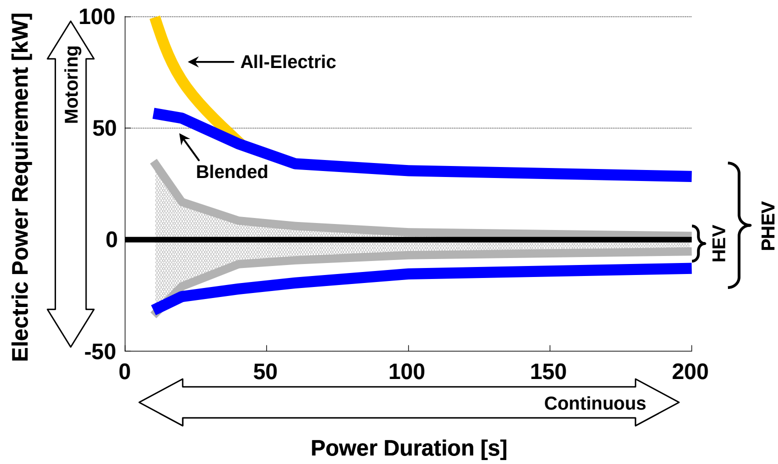

Figure 14. Midsize Parallel Hybrid Electric Power Requirements

Approach for Thermal Management of Power Electronics

The Advanced Thermal Management for Vehicle Power Electronics and Electric Machines research activity is focused on developing thermal management technologies that enable advanced power electronics and electric machine technologies that are efficient, small, light, low cost, and reliable. Specifically, it is concerned with addressing and overcoming any and all thermal barriers to these systems within the systems context of the entire vehicle—ultimately working towards a total vehicle thermal system that is low-cost, small, light, reliable, effective, and efficient.

Close cooperation with industry and research partners is important in developing candidate thermal management technologies to meet the program goals. Additionally, there are close ties to the power electronics packaging focus area. The power electronics package, including the device layout, material selection, and topology, define the package thermal resistance and required heat flux levels and the induced thermal stresses. Conversely, aggressive heat transfer performance may enable higher power densities and novel package designs.

As shown in Table 20, the thermal management research is organized into three distinct focus areas:

- Thermal System Integration
- Heat Transfer Technologies
- Thermal Stress and Reliability

Table 20. APEEM Focus Areas for Thermal Management

Focus Area	Impact
Thermal System Integration *Enable technology integration at lower system cost*	• Guides thermal research objectives • Defines thermal requirements • Facilitates viable thermal solutions • Links thermal technologies to electric traction drive systems
Heat Transfer Technologies *Enable increased power density at lower cost*	• Provides detailed characterization of the thermal performance of candidate heat transfer technologies • Provides experimental data and fundamental thermal models • Develops and demonstrates promising technologies to enable program targets
Thermal Stress and Reliability *Improve reliability of new technologies*	• Develops advanced predictive thermal stress and reliability modeling tools • Will guide research decisions, streamline development time, and identify potential barriers to meeting life and reliability goals

Thermal System Integration

The objective of this focus area is to facilitate the integration of APEEM thermal management technologies into viable advanced electric traction drive systems including hybrid electric, plug-in hybrid electric, electric, and fuel cell vehicles. It is widely recognized that innovative thermal management is needed to protect power-electronics components from excessive heat and is key to enabling program targets of cost, volume, weight, and life. However, there is a wide variety of potential thermal technologies; a given thermal solution can impact the electronics design space including package configuration, architecture, and material selection. Conversely, these parameters, along with the vehicle architecture, define the thermal requirements.

This research area is focused on understanding the tradeoffs and matching the thermal requirements of the electric traction drive with a range of packaging options and heat transfer mechanisms. Rapid parametric models are being developed and applied early in the design process to help select the most appropriate thermal management technology for a given traction drive system. Inputs into the models include fundamental heat transfer performance characteristics, package geometry, various material properties, and a range of system thermal requirements. Outputs include both steady-state and transient thermal loading and device temperatures under various conditions.

Characterization and Development of Heat-Transfer Technologies

This activity seeks to provide an accurate and objective characterization of the thermal performance of heat transfer technologies within the context of automotive requirements, and to further develop and demonstrate the promising technologies that enable reductions in cost, volume, and weight. On the characterization side, this research includes fundamental characterization of heat-transfer mechanisms such as the performance of single-phase and two-phase jets and sprays, air-cooled heat exchangers, pool-boiling techniques, surface-area-enhancement techniques as well as thermal-materials performance. Detailed numerical modeling of the technologies such as computational fluid dynamics and finite-element analysis are used to further understand the heat-transfer mechanisms and the conditions under which these technologies may be suitable for electric traction drive cooling.

Promising technologies from the fundamental investigations may be further refined and optimized to the point of a prototype development in which the heat exchanger is integrated into an actual inverter or other PEEM component. Recent examples include the floating-loop inverter, which used two-phase pool boiling of a refrigerant, a liquid jet-impingement heat exchanger that was integrated into an existing automotive inverter, and an inverter designed around a direct-cooled substrate concept. In each case, the total package with integrated heat exchanger was evaluated for performance and measured against program targets of cost, weight and volume. Performance data from both fundamental characterizations and prototype demonstrations are published and transferred to industry partners.

Thermal Stress and Reliability

This research activity will develop predictive modeling capabilities to assess the impacts of thermal stress on the life of advanced inverter package designs and to demonstrate the modeling approach by evaluating dynamic thermal stresses of advanced PEEM designs. Thermally induced stress is a major issue related to reliability, which is directly linked to heat dissipation and the electronics package configuration. Vehicle manufacturers and component suppliers must run extensive life and reliability testing on all new technologies and designs to understand the response to thermal cycling and environmental conditions.

This effort will closely engage industry to develop and validate advanced predictive modeling processes using techniques such as "physics of failure" to evaluate the impacts of new technologies on thermal stresses, life, and reliability. The ultimate goal is to reduce the amount of testing and the cost and time to market for new technologies. Predictive modeling tools, applied early in the development process can help guide research decisions, streamline development time, and identify potential barriers to meeting life and reliability goals. Physical modeling techniques will be used in conjunction with accelerated life testing to identify failure modes and relative impacts on reliability beyond what is currently available.

Analysis of the thermal requirements of competing electric traction drive system architectures and component topologies along with the thermal performance of candidate heat transfer technologies helps to guide thermal research objectives and increases the likelihood that technology meets program targets and is viable within an automotive system context.

14. R&D for Systems

Background

Ultimately, a traction drive system must be developed that meets the overall vehicle system requirements. The design choice of the motor technology will dictate the type of power electronics and controller necessary to drive the particular electric machine. It is essential to develop an advanced traction drive system that can plausibly be manufactured and is compatible with automotive high-volume production. It also is critical to develop a vehicle-level electrical and electronic infrastructure that accommodates the motor and its electronics for ensuring system reliability and safety. The development of this infrastructure must not be overlooked.

It should be recognized that new technologies may not appear to merit incorporation on a standalone basis, but, when incorporated with other technologies in a system, they may provide significant improvement. Making the significant improvements that are needed in the performance and cost of the traction system will require the integration of motors, power electronics, and thermal management technologies. When combining these technologies, considerations must be made for vehicle applications, flexibility, and overall system benefits.

Approach for Systems

As is shown in Table 21, the R&D for systems includes:

- Traction Drive System Development
- Benchmarking

Table 21. APEEM Focus Areas for Systems

Focus Area	Impact
Traction Drive System *Meet future system targets*	Working on both modular and integrated solutions to meet size, weight, and cost 2015 and 2020 targets for drive system.
Benchmarking *Program planning*	Vital to program planning and project performance activities.

Traction Drive System Development

To significantly reduce system weight, cost, and volume, concepts must be developed that are capable of reliable higher-temperature operation. In order to attain long-term goals, concepts that advance the state of the art in the following areas must be considered:

- Advanced cooling technologies
- Inverter and motor topologies
- Packaging innovations
- Buss structures
- Semiconductor devices
- Capacitors
- Sensors
- Magnetics
- Rotor and stator manufacturing processes

Benchmarking

Benchmark testing of HEV drive trains and power electronics and electric motor components is an integral part of the program and compliments the R&D portfolio. It is performed to fully characterize the performance of the technology across the complete range of electrical and thermal parameters that are applicable for vehicle applications, and it is coordinated with the vehicle-level benchmarking within the DOE Vehicle Technologies Program. In most cases, this is information that is not available from the manufacturer or is information the manufacturer chooses not to make available.

Benchmarking information is used to assist in program planning efforts and developing and executing specific projects. The specific contributions of benchmarking in each area are the following:

- Program Planning
    - Define benchmark performance for motors, inverters, and components to establish baseline performance data when developing performance goals
    - Confirm the realism of performance goals for the technologies and components and identify technology gaps
- Project Performance
    - Benchmarking data are used to validate modeling efforts, thus confirming that the validated modeling methods can be used appropriately to develop new technologies
    - Confirm the realism of performance goals for the technologies and components and identify technology gaps
    - Provide technical insights that can be used to guide research efforts
- EETT
    - Provide the auto company partners with a consistent, open-literature source for complete characterization of technology recently introduced in the marketplace

Appendix A: Status for 2010 and Technical Targets for 2015 and 2020

Table A-1. Status and Technical Targets for Electric Traction System

	R&D Status	Targets	
	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

a. Based on a maximum coolant temperature of 90°C

b. Based on a maximum coolant temperature of 105°C or air

Table A-2. Status and Technical Targets for 3 kW DC/DC Converter

	R&D Status	Targets	
	2010	2015	2020
Cost, $/kW	<75	<60	<50
Specific power, kW/kg	>0.8	>1.0	>1.2
Power density, kW/L	>1.0	>2.0	>3.0
Efficiency @ maximum load	>92%	>93%	>94%

Table A-3. Status and Approximate Technical Targets for Motors

	R&D Status	Targets	
	2010[a]	2015[b]	2020[b]
Cost, $/kW	<11.1	<7	<4.7
Cost, kW/$	>0.090	>0.143	>0.213
Specific power, kW/kg	>1.2	>1.3	>1.6
Power Density, kW/L	>3.7	>5.0	>5.7

a. Based on a maximum coolant temperature of 90°C

b. Based on a maximum coolant temperature of 105°C

Table A-4. Status and Approximate Technical Targets for Power Electronics

	R&D Status	Targets	
	2010[a]	2015[b]	2020[b]
Cost, $/kW	<7.9	<5.0	<3.3
Cost, kW/$	>0.127	>0.200	>0.303
Specific power, kW/kg	>10.8	>12.0	>14.1
Power density, kW/L	>8.7	>12.0	>13.4

a. Based on a maximum coolant temperature of 90°C

b. Based on a maximum coolant temperature of 105°C

Appendix B: Typical Capacitor Bank Requirements

Table B-1. Typical Capacitor Bank Requirements

	Typical Capacitor Bank Requirements
Capacitance, µF	1000 +10%/-0%
Operating voltage, VDC	450
Peak transient voltage for 50 ms, VDC	650
Leakage current at operating voltage, ma	≤1
Dissipation factor at 10 kHz[a], %	<2
Equivalent series inductance, (ESL),nH	≤5
Ripple current, amp rms	90
Temperature range of ambient air, °C	-40 to +140
Volume requirement, L	≤0.6
Cost	≤$30
Failure mode	Benign
Life @operating conditions, hr	>13,000

a. $ESR = DF/2\pi fC$ where DF is dissipation factor, f is frequency in Hz, and C is the capacitance in F.