DRAFT
EE TECH TEAM ROADMAP
April 14, 2004

ADVANCED POWER ELECTRONICS AND ELECTRIC MACHINES

1. Mission/Objectives

A. MISSION

Achieving the FreedomCar goals will require the development of new technologies for power electronics and electric machinery. The new technologies must be compatible with high-volume manufacturing; must ensure high reliability, efficiency, and ruggedness; and simultaneously reduce cost, weight, and volume. Key components for fuel cell and hybrid-electric vehicles[1] include motors, inverters/converters, sensors, control systems, and other interface electronics.

B. OBJECTIVES

- Power Electronics – To develop automotive integrated modular power modules for power conversion and control. Building blocks to be developed include power switch stages optimized to run newly developed motors, drives, DC/DC converters, advanced controllers and sensors.
- Electric Motor Drives – To develop advanced motor technologies utilizing high-performance, low-cost materials and incorporating advanced thermal-management technologies that will yield high power density and cost-effective motors for high-production-volume series and parallel hybrid propulsion systems.
- Advanced Integrated Systems – To integrate motor and power-control technologies, focusing on cost and weight reduction and performance enhancement. Develop advanced integrated thermal-management systems, state-of-the-art models, and new techniques for high-volume manufacturing.

2. Technical Targets

A. TARGETS

The FreedomCAR goals and technical targets for 2010 for the electric-propulsion system, as given in Table 1, include the motor, inverter, gearbox, and controller.

Table 1. Goals for Electric Propulsion System for 2010

FreedomCAR Goals[2]	
Peak power	55 kW for 18 seconds
Continuous power	30 kW
Lifetime	>15 years (150,000 miles)
Cost	<$12/peak [<$660][a]
Technical Targetss[3]	
Specific power at peak load	>1.2 kW/kg [<46 kg][a]
Volumetric power density	>3.5 kW/l [<16 l][a]
Efficiency (10 to 100% speed, 20% rated torque)	90%

a) Numbers in square brackets are equivalents for a 55 kW peak-power system.

B. STATUS

It is not currently possible to quantify the characteristics of an integrated system versus the requirements in Table 1 because no suitable integrated system is available for analysis. However, the principal components of a propulsion system—the inverter and the motor—have been under development in the former PNGV program, so their characteristics can be used as a measure of what currently would be possible from an integrated system if potential synergistic benefits of integrated packaging are neglected. It also is necessary to apportion the weight, volume, cost, and efficiency requirements between the two components. This has been done in Table 2, with the recognition that tradeoffs between the components to meet the system requirements may be desirable, depending upon the final design.

Table 2. Approximate Technical Targets for Major Components of a Series Electric Propulsion System[a]

Power Electronics (inverter/controller)	
Specific power at peak load	>12 kW/kg
Volumetric power density	>12 kW/l
Cost	<$5/kW peak
Efficiency (10-100% speed and 20% torque of the drive)	>97%
Traction Motor	
Specific power at peak load	>1.3 kW/kg
Volumetric power density	>5 kW/l
Cost	<$7/kW peak
Efficiency (10-100% speed at 20% rated torque)	>93%

a) These targets are consistent with the system goals in Table 1. Tradeoffs between the components are acceptable so long as the system goals are met.

The performance characteristics of an inverter that was developed under the Automotive Integrated Power Module (AIPM) program and a motor that was developed under the Automotive Electric Motor Drive (AEMD) program are compared with the FreedomCAR requirements in Table 3. Prior development work on an inverter was based upon the assumption of a 70ºC coolant temperature. The numbers in Table 3 are estimated values for a coolant temperature of 105ºC. The lifetime of a system utilizing a coolant temperature of 70ºC would exceed the 15-year target. The voltage and current limits for the traction motor are based upon constraints imposed by the wiring harness, power electronics, torque, and battery.

Gaps between the current characteristics and the desired properties are represented by the spider charts in Figures 1, 2, and 3, where the shaded areas represent the percentage achievement of each of the targets. The cost targets in the spider charts are the inverse of the numbers in Table 3 in order to have a metric for which bigger is better.

Table 3. Gaps for Power Electronics and Electric Machines[4]

Power Electronics (inverter/controller)[a]			
	2010 Target	**2003 Status**	**Gap**
Specific power at peak load (kW/kg)	>12	11	1
Volumetric power density (kW/l)	>12	11.5	0.5
Cost /kW peak	<$5	$6	$1
Efficiency, %	97	97	0
Coolant inlet temperature, °C	105	70	35
Lifetime, years	15	15	0
Traction Motor[b]			
	2010 Target	**2003 Status**	**Gap**
Specific power at peak load (kW/kg)	>1.3	1.0	0.3
Volumetric power density (kW/l)	>5	3.5	1.5
Cost/kW peak	<$7	$15	$8
Efficiency, %	>93 at 10% to 100% max. speed	>90 at 35% to 100% max. speed	10-34% max. speed
Voltage, V	325	325	0
Maximum current, A rms	400	415	15
Peak power for 18 seconds, kW	55	55	0
Continuous power, 8.5-85 mph	30 kW	30 kW, 8.5-77 mph	77-85 mph
Propulsion System (Inverter & Motor)[c]			
	2010 Target	**2003 Status**	**Gap**
Specific power at peak load (kW/kg)	>1.2	0.95	0.25
Volumetric power density (kW/l)	>3.5	2.5	0.9
Cost /kW peak	<$12	$21	$9
Efficiency, %	>90% at 10% to 100% max. speed	90 at 35% to 100% max. speed	10-34% max. speed
Lifetime, years	15	15	0

a) 2003 status based upon recent progress report from Semikron.
b) 2003 status based upon progress review by Delphi on June 13, 2003.
c) Approximated by adding inverter plus motor.

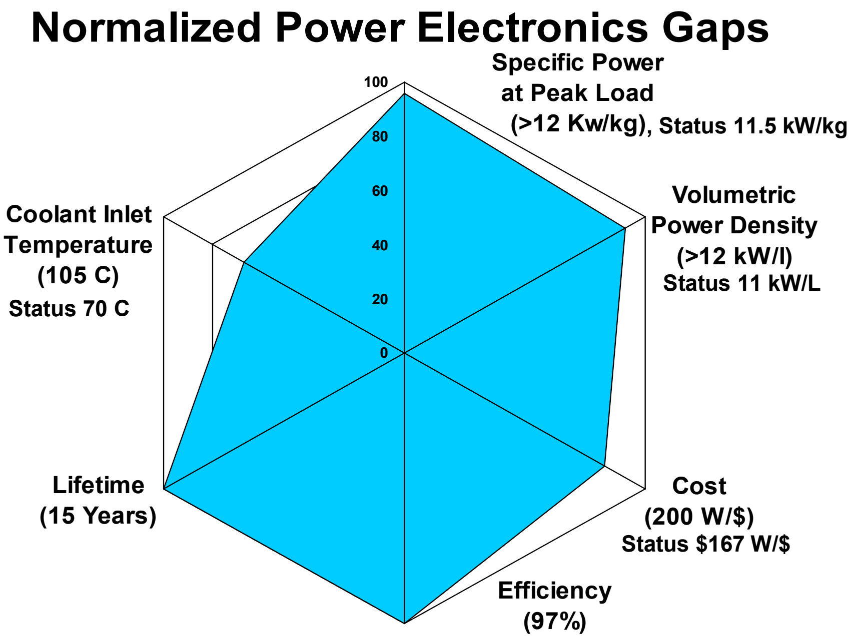

Figure 1. Spider Chart Showing Gaps Related to Inverters

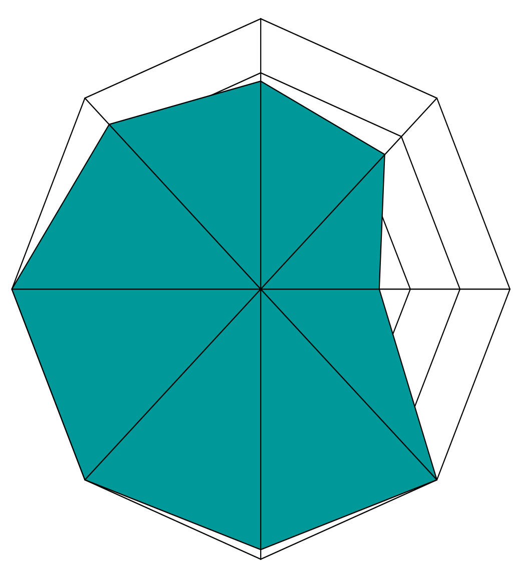

Figure 2. Spider Chart Showing Gaps Related to Electric Motor Drives

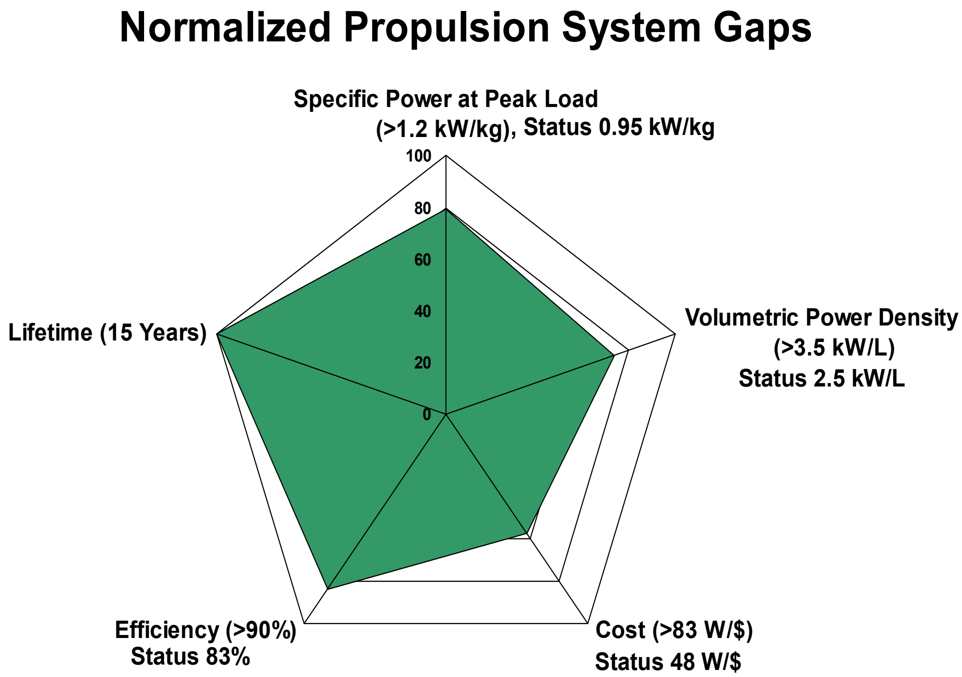

Figure 3. Spider Chart Showing Gaps Related to Advanced Integrated Systems

3. Gap Analysis

It is apparent from Table 3 and the spider charts in Figures 1, 2, and 3 that significant challenges remain in terms of cost, weight, and volume—especially with respect to the motor. The lifetime for the inverter with a coolant temperature of 105ºC is the most significant challenge for that component. Numerical values of the gaps are summarized in Table 4, and the relative magnitudes of the technical challenges are indicated qualitatively, where red indicates a severe challenge, green represents a reasonable level of confidence that the target can be met, and yellow indicates an intermediate level of difficulty.

Table 4. Gap Analysis for Power Electronics and Electric Machines

Requirement	Inverter	Motor	Integrated System
Specific power @ peak load (kW/kg)	1	0.3	0.25
Volumetric power density (kW/l)	0.5	1.5	0.9
Cost per kW	$1	$8	$9
Efficiency, 10-100% speed, 20% rated torque (%)	0	10-34% max. speed	10-34% max. speed
Peak power (kW)	0	0	0
Continuous power (kW)	0	0	0
Battery operating voltage (Vdc)	0	0	0
Maximum current, rms (A)	0	15	15
Torque ripple (%)	NA	0	0
Coolant inlet temperature	35	35	35

4. Technical Strategy to Address Target Gaps

A. POWER ELECTRONICS

1. INVERTER

Semiconductor Switches

Currently, 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. Recent developments in high-power device technology have made possible high-voltage MOSFETs with significantly reduced on-resistance and high-speed IGBTs that can switch at frequencies of up to 300 kHz. These latest power devices should be investigated both analytically and experimentally to evaluate the benefits that these improvements might bring to inverters and DC/DC converters.

Semiconductor switches have a large impact on the cost of the inverter, typically accounting for about ¼ 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 temperature below 125°C for IGBTs and 150°C for MOSFETs.

Silicon carbide is an attractive alternative to silicon because SiC devices can operate at temperatures up to 350°C, 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 Si, production quantities are low, and scrap rates are high because manufacturing processes are not mature.

A considerable amount of research into SiC 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 will be to monitor the research being conducted by other organizations and test devices for automotive applications as they become available.

Capacitors

Capacitors represent the second largest input to the cost of an inverter, and they also account for a major fraction of the volume and weight. For voltage levels below 450 V, motor inverters have predominately used aluminum electrolytic capacitors. Besides occupying about 60% of the volume of the inverter and a similar proportion of the weight, aluminum electrolytic capacitors cannot tolerate high temperatures, they tolerate very little ripple current, they suffer from short lifetimes due to drying of the electrolyte, and, when they fail, they sometimes do so catastrophically.

Polymer-film capacitors are used for voltages above 450 V. They have soft-breakdown (benign-failure) characteristics, and it appears that an affordable polymer-film capacitor can be manufactured with a volume about 40% of that of an equivalent aluminum electrolyte capacitor. However, polymer-film capacitors are more expensive than aluminum electrolytic capacitors for lower voltages, such as those in the anticipated drive system, and they currently cannot tolerate sufficiently high temperatures for future applications.

Theoretically, ceramic capacitors have the greatest potential for volume reduction; they could be as small as 20 percent 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. There is a concern about the possibility of catastrophic electrical discharge and mechanical failure of ceramic capacitors. 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.

Until now, the EE Tech Team has treated the capacitor as an individual component. No one capacitor has been able to meet all the requirements of an automotive traction system. The solution for a traction application may come from using a combination of the capacitor types. A hybrid capacitor bank may be a solution that should be investigated. Treating the capacitor bank as a subsystem may yield the performance needed to make electric traction systems viable.

Anticipated requirements for a dc bus capacitor bank in 2010 are listed in Table 5. The main technical targets for 2010 would be to reduce the weight, volume, and cost per micro Farad by a factor of 2.

Table 5. Desired DC Bus Capacitor Bank for Inverters

	2010 Typical Capacitor Bank Requirements
Capacitance, µF	2000+/- 10%
Voltage rating, VDC	600
Peak transient voltage for 50 ms	700
Leakage current at rated voltage, ma	1
Dissipation factor, %	<1
ESR, mohm	<3
ESL, nH	<20
Ripple current, amp rms	250
Temperature range of ambient air, ºC	-40 to +140
Weight requirement, kg	10.8
Volume requirement, l	0.4
Cost	$30
Failure mode	Benign
Life @80% rated voltage	>10,000 hr, 20 amps rms, +85ºC

A qualitative summary of the advantages and disadvantages of the three types of capacitors is given in Table 6.

Table 6. 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	To be demonstrated
Cost	Excellent	Good	Poor

Because polymer-film capacitors and ceramic capacitors both have potential for large benefits but also face significant technical challenges, both technologies will be pursued. 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.

Heat Exchanger

Another major contributor to the weight and volume of an inverter is the heat exchanger. This subject is treated later in the section on integrated systems.

Topology

With 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.

New topologies need to be investigated that can improve system performance. Higher system voltages can improve efficiency and cost of the power inverter but may drive up system cost and reduce efficiency. One new topology combines the DC/DC converter with the DC/AC inverter into a single-stage power-conversion circuit has recently been suggested. It is called the Z-source converter. With it, significant reductions in cost, size, and weight could be possible. It also can produce a wider constant power speed ratio (CPSR). Research into this concept will be initiated in FY 2004.

Future inverter designs also should strive for greater flexibility such that they can accommodate various power levels without requiring a completely new design.

2. <u>CONTROLLER</u>

Today's motor controller technology revolves around commercially available digital signal processors (DSPs). These chips are able to perform the complicated high-speed mathematical functions necessary for motor control. In some cases, DSP manufacturers have included additional circuitry within the chip, specifically for use in control applications. However, external circuitry is still required to accomplish all the functions necessary for efficient motor control. Current controller hardware typically consists of up to 500 parts. The ability to fabricate a controller on a chip would therefore provide an opportunity for considerable cost reductions and reliability improvements, but the temperature capacity of the chip will be important.

Research will start in FY 2004 on an architecture that is intended to achieve cost reduction through the integration of functions and inclusion of necessary external circuitry within a single semiconductor device. Additionally, cost reduction will be realized by the development of a flexible modular control system suitable for use with drive systems of varying power levels. Through the reduction in parts count and manufacturing efforts, it is hoped a cost reduction of 30% can be realized in high-volume production. Initial production volume levels for these controller chips are estimated to be 100,000 per year. Cost analysis will consider annual production volumes of 100,000, 500,000 and 1,000,000. It is anticipated that this project will be separated into two phases. Phase I will involve a detailed cost study and analysis of potential processes and packaging methods that will meet the requirements detailed in the statement of work. Technological innovations are highly encouraged. Phase II will culminate in the delivery of a functioning packaged controller chip. It is estimated that this project will take two years.

Control algorithms are considered proprietary to the individual auto makers. The controller determines the "feel" of the car and therefore is a competitive issue.

3. DC/DC CONVERTER

HEVs and fuel cell powered vehicles will have multiple voltage systems: 14 V, 42 V, and high-voltage (200-500 V) buses.

The 14-V electrical system in present automobiles has reached its limits of capability and cannot meet the demands of future electrical loads and the increasing desire for replacing more engine-driven mechanical and hydraulic systems with electrical systems to increase efficiency. 42-V systems have been proposed to cope with the increasing electrical loads. During the transition to a 42-V system, most automobiles are expected to employ a 14/42-V dual voltage system, in which a bi-directional DC/DC converter is required to connect the two voltage networks.

Fuel cell powered vehicles will require a DC/DC converter to interconnect the fuel cell power high-voltage bus and the low-voltage bus for vehicle auxiliary loads. An energy-storage device also is required for fuel cell start-up and for storing the energy captured by regenerative braking in electric vehicle applications. One way to accomplish this is to utilize the vehicle's 14-V battery with a bi-directional DC/DC converter to maintain compatibility with the majority of today's automobile loads. During vehicle starting, the high-voltage bus could be boosted up to around 300 V by the DC/DC converter drawing power from the 14-V battery. This high-voltage bus then supplies power for the fuel cell compressor motor and brings up the fuel cell voltage, which in turn feeds back to the high-voltage bus to reduce the loading from the battery.

The fuel cell application requires a DC/DC converter with a relatively high power rating of 3 kW continuous, aside from bi-directional power control capability. 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 electromagnetic interference (EMI) and switching losses. Other expected requirements for this converter are outlined as follows:

- The terminal voltage of the battery can swing from 8 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 to 450 V.
- A maximum battery charging power of 3.5 kW is required for a maximum duration of 20 seconds during regeneration. Each such charging event is at least 1 minute apart.
- The high-voltage bus capacitance must be less than 2000 μF.
- Start-up time is less than 200 ms with load engaged when the voltage of the high-voltage bus is higher than 200 V.

An RFP was issued in 2003 to solicit innovative designs while also demonstrating commercial viability in high-volume production. Technical issues to be addressed include choice of topology, filtering requirements, switches, switching frequency, RFI considerations, thermal management, and selection and type of magnetic components. Cost, reliability, weight, and volume are critical factors.

B. ELECTRIC DRIVE MOTORS

1. TECHNOLOGY OPTIONS

Motor/generator candidates for the electric propulsion system include induction, permanent magnet (PM), and switched reluctance (SR) machines.

During the drive cycle, automobiles typically operate at a fraction of rated speed and power. True energy savings in the motor and drive system come from higher efficiencies at low-speed and low-power operation.

Induction motors have the advantage of being the most reliable and widely manufactured and utilized motors in industry today. Unfortunately, they cannot meet the FreedomCAR requirements. They have low specific torque and require multi-stage gear reducers that add weight and reduce system efficiency by 2 to 4%. Because of the mature nature of this technology, the likelihood of achieving the required additional improvements in cost, weight, volume, and efficiency is low.

A *permanent magnet motor* has the highest power density while maintaining high efficiency over the entire drive cycle. A major challenge is to increase the constant power speed range. One approach is field weakening, but there is a concern about the associated losses in efficiency. Another major issue is high cost, due to both the high costs of magnets and rotor fabrication. Other challenges include thermal management and the temperature rating of the electrical insulation and magnet materials.

Switched reluctance motors potentially are the lowest-cost candidate, but they have serious problems in terms of high torque ripple, high noise, and low power factor. They also require expensive sensors and inverter technology, which make the system cost comparable to others.

2. MOTOR DESIGN

The AEMD program resulted in a radial-gap, surface PM motor that fell considerably short of FreedomCAR goals, especially with respect to cost, weight, and volume. The next approach will be to consider interior PM motors that are expected to have attributes much closer to the FreedomCAR goals.

3. MAGNETS

To meet the cost and performance objectives of PM motors for automotive applications, it is essential to improve the alloy design and processing of PM powders. There are two primary objectives for PM materials in order to enable the widespread introduction of electric drive automobiles: (1) to increase the useful operating temperature for magnets to 200°C and (2) to reduce the active magnet material cost to about 25% of its current level. Currently, bonded magnet material can operate at temperatures from 120 to 150°C. On the other hand, sintered magnets are available today that can operate at temperatures as high as 180°C to 200°C. The finished cost of sintered magnet material is approximately $90/kg. In the technical community, some believe that polymer-bonded particulate magnets offer the benefit of greatly simplified manufacturing, but at a more moderate level of stored magnetic energy that is still compatible with innovative PM motor designs; and, to exploit the potential of bonded PM materials for such motors, it is necessary to develop a particulate magnet material with high-temperature properties that can be loaded to a high-volume fraction in an advanced polymer binder. However, others believe that the energy product of bonded magnets is too low to be used for the motors in the FreedomCAR and electric-vehicle applications, even if the operating temperature of bonded magnets can be raised to 200°C, and, as such, the low-cost benefit of the bonded magnet cannot be realized for these motor applications due to its low magnet property. Regardless, the goal will be to identify the best PM material for high-volume, low-cost production of advanced electric drive motors while meeting the system performance targets.

C. ADVANCED INTEGRATED SYSTEMS

1. INTEGRATION OF MOTOR, INVERTER, AND CONTROLLER

Ultimately, an integrated 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 that an advanced integrated system be developed that is manufactureable and compatible with automotive high-volume production. It also is critical that a vehicle-level electrical and electronic infrastructure be developed to accommodate the motor and its electronics to ensure system reliability and safety. The development of this infrastructure must not be overlooked.

While it would be desirable to start working on an integrated system as soon as possible, it is felt that improvement in the performance and cost of motors, power electronics, and thermal management technologies are necessary before work on an integrated system would be meaningful. The situations with respect to motors and power electronics are covered in their respective sections of the roadmap. A discussion of thermal management technologies and the vehicle electric/electronic infrastructure follows.

2. THERMAL MANAGEMENT

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. This thermal problem could be solved from three separate, but very much related, approaches:

- The operating efficiencies of motors and their associated power electronics must be maximized. Increasing efficiencies over a wide range of operating conditions will reduce the amount of losses and waste heat.

- The tolerance of components to heat must be increased. Most of today's automotive electronics are rated at 85ºC, and their lifetime will diminish if exposed to higher temperatures. New technologies such as SiC devices are designed to operate at temperatures as high as several hundred degrees C. This will allow a higher-temperature operation and reduce the amount of waste heat that must be removed.

- The cooling system technology must be improved. More capable cooling technologies must be developed which would allow the efficient removal of waste heat.

Currently, the motor and inverter in a hybrid vehicle are cooled by a single-phase fluid – air, water, or oil. Much more efficient cooling would be possible using two-phase cooling, in which a liquid coolant is allowed to evaporate, thus taking advantage of the latent heat associated with the phase change. This would permit a significantly more efficient heat exchanging process and reduce the total energy required for cooling.

The primary emphasis of the thermal management research in the near term will be on two-phase cooling. Various approaches will be examined on the device level and from a system's perspective. One of the options to be considered is expanding the air conditioning system to provide cooling for the motor and inverter.

The two primary cooling methods being considered are non-pressurized spray and pressurized immersion/jet spray. Each of these methods has its pros and cons. All of them need to overcome obstacles and concerns such as sealing, cooling fluids' compatibility with various materials, durability, and serviceability, etc. These technologies must all be developed and proven for the automotive mass production environment.

3. VEHICLE ELECTRICAL AND ELECTRONIC INFRASTRUCTURE

The vehicle electrical and electronic (E/E) infrastructure is a mandatory subject of development, and it is too often overlooked. Regardless of which motor technology and its supporting electronics and cooling system are selected, the installation into an actual vehicle will involve a major overhaul of the existing vehicle electrical system.

The developed electrical system will operate at a much higher voltage than the current 12-V system, and it will be delivering power in the tens of kilowatts versus today's 2-3 kilowatts. Along with this high voltage and high power operation comes the obligation to ensure system reliability and safety. This would mean the development of an electrical power distribution system with fail-safe designs and many protection features which are not required at 12 V. The E/E infrastructure must be designed to alleviate or at least minimize any unintentional electrical faults that could result in major vehicle damage or personal injuries.

For example, a chaffed high-power wire would short to the closest ground, and it would start and sustain arcing and cause major vehicle damage if undetected. Another example is that of a high-voltage connector being unplugged by a customer without disabling power; this could also cause arcing and possibly injury to the customer.

There are many scenarios one needs to consider, and there is much development required in the E/E infrastructure area to create the economies of scale for safety components such as wiring connection systems, safety shutdown switches, and other circuit protection devices.

D. LEVELS OF EFFORT

DOE funding for FY 2004 is expected to be $13.52 million, which will be divided among the three thrust areas as shown in Figure 4. Further breakdowns for the Power Electronics funding and the Electric Machines funding are shown in Figure 5 and 6 respectively. All of the funding on Integrated Systems will be devoted to thermal management in FY 2004.

The proportions of funding for Electric Machines and Integrated Systems are expected to increase over the next few years, and ultimately the funding for integrated systems will dominate.

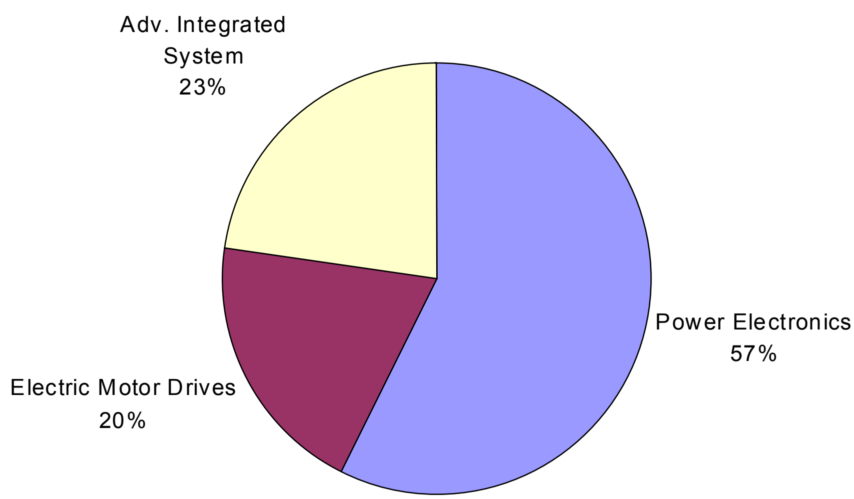

Figure 4. Anticipated Funding in FY 2004 for Power Electronics and Electric Machines

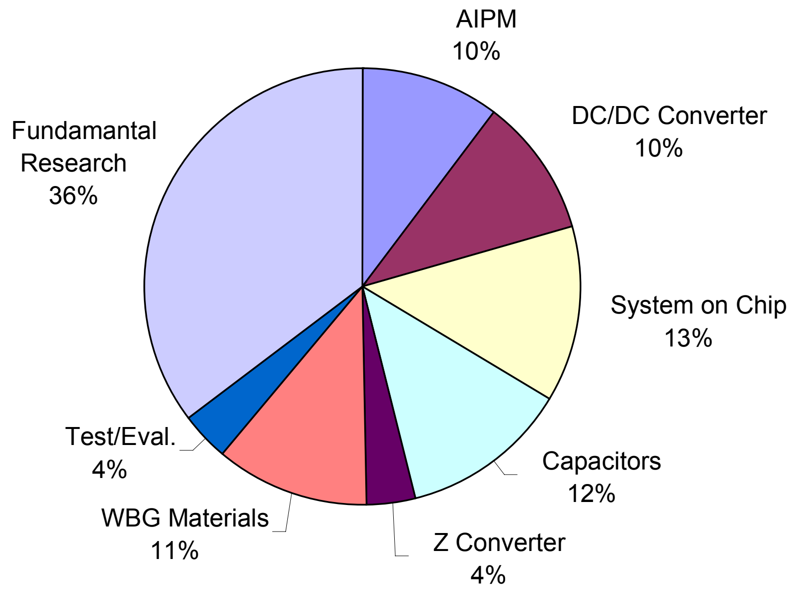

Figure 5. Distribution of Anticipated Funding for Research on Power Electronics in FY 2004

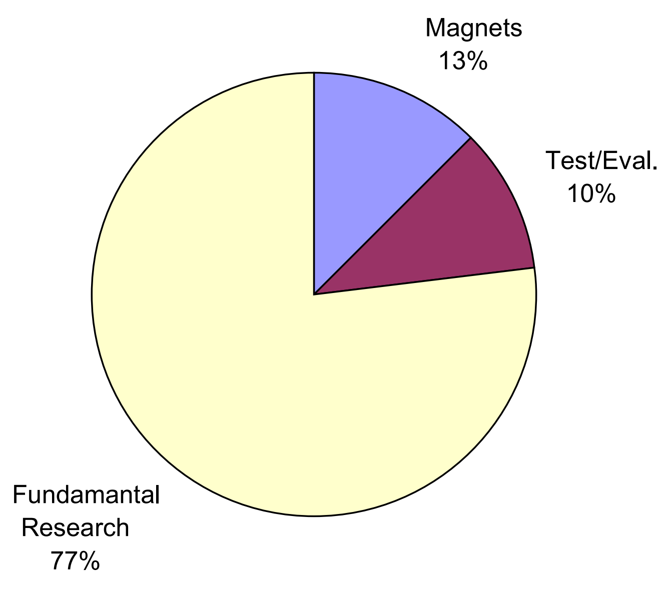

Figure 6. Distribution of Anticipated Funding for Electric Machines in FY 2004

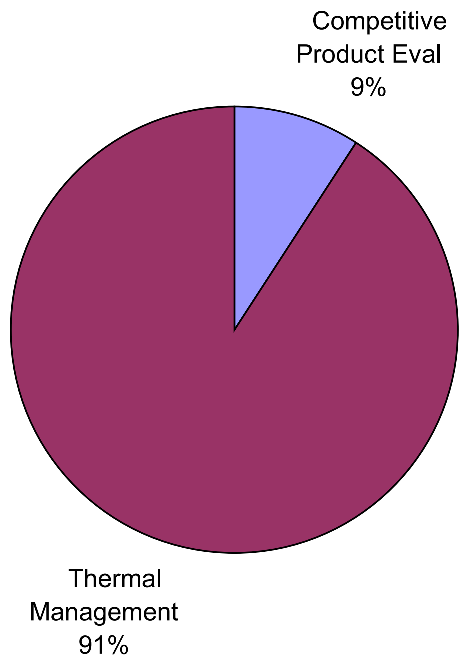

Figure 7. Distribution of Anticipated Funding for Advanced Integrated Systems in FY 2004

5. Programmatic Strategy

A. SPLIT BETWEEN NATIONAL LABS AND CONTRACTORS

In general most of the basic scientific studies are conducted at the National Labs or at universities and the development work is done by contractors. Applied research may be done at either type of organization. The anticipated split between national labs and contractors for FY 2004 is shown in Figure 8.

B. MILESTONES

Table 7. Milestones for Power Electronics and Electric Machines

Milestone	Description	Estimated Date (CY) Q = Quarter
	Power Electronics	
1.	Deliver prototype AIPM	1 Q 2004
2.	Deliver controller on chip for evaluation	1 Q 2005
3.	Build inverter utilizing SiC components and evaluate thermal and performance improvements	2 Q 2005
4.	Deliver DC/DC converter for evaluation	3 Q 2005
5.	Receive improved capacitor for test and evaluation	2 Q 2008
6.	Evaluate sensorless technology in an automotive application	1 Q 2009
	Electric Motor Drives	
7.	Deliver prototype internal PM motor for evaluation	2Q 2007
8.	Validate contribution of development in magnet materials to technical targets for motors	3 Q 2007
	Advanced Integrated System	
9.	Trade-off study for various approaches to two-phase cooling	4 Q 2004
10.	Complete a common motor/inverter thermal management system	2 Q 2009
11.	Complete integrated motor/inverter system	4Q 2010

C. CURRENT PROJECTS

A brief description of the projects to be funded in FY 2004 is given in the Appendix.

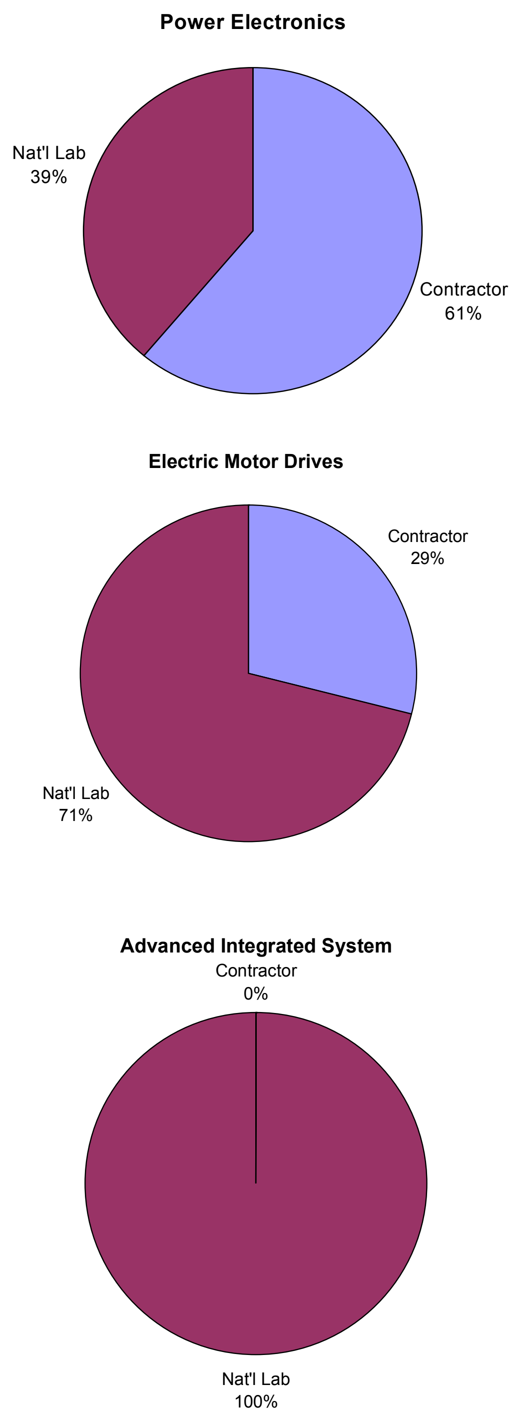

Figure 8. Distribution of FY 04 Funding Between Contractors and National Labs

APPENDIX

CURRENT PROJECTS ON POWER ELECTRONICS AND ELECTRIC MACHINES

1. POWER ELECTRONICS

1.1. Automotive Integrated Power Module (AIPM)

Contractor: Semikron
To be Completed by March 2004
Purpose: To develop an inverter for a system that is capable of 55 kW peak power, 30 kW continuous power, and a 15-year (150,000 mile) lifetime. Weight, volume, and cost targets are 5 kW/kg, 12 kW/l, and $7/kW respectively.
Status: Preliminary indications are that all 2004 targets will be met or nearly so, but future needs, such as the ability to operate at higher temperature, will not be completely satisfied.

1.2. Controller on a Chip

Contractor: TBD
RFP issued; contract to be let early 2004
Purpose: To develop a System on a Chip motor controller for use in a broad range of applications such as hybrid and fuel cell based vehicles. The architecture is intended to achieve a cost reduction of 30% through reduction in parts count and manufacturing effort resulting from the integration of functions and inclusion of necessary circuitry within a single semiconductor device.
Status: The project will be conducted in two phases. Phase I will involve a detailed cost study and analysis of potential processes and packaging methods that will meet the requirements. Phase II will culminate in the delivery of a functioning controller chip.

1.3. DC/DC Converter

Contractor: TBD
RFP issued; contract to be let early 2004
Purpose: To design and fabricate an isolated DC-to-DC converter for use in a broad range of hybrid and fuel cell based vehicles. Volume and weight are not to exceed 5 liters and 6 kg respectively. Cost is a key concern, and a cost study shall be completed.

1.4. Evaluation of Prototypes for Contract Support

Contractor: ORNL
Ongoing
Purpose: To provide an independent evaluation of deliverables (such as an AIPM, a controller on a chip, and a DC/DC converter) from commercial contractors.

1.5. Power Electronics Fundamental R&D

Contractor: ORNL
Ongoing

Task 1.5.1. Wide Band-Gap Materials

Purpose: To develop simulation tools for wide bandgap (WBG) semiconductor-based power devices with a focus on silicon carbide (SiC) in relevant transportation applications. Once developed, these tools can be used to assess the impact of expected performance gains with SiC devices and determine areas of greatest impact. Project objectives include updating state-of-the-art in WBG semiconductor devices, especially SiC diodes, junction field-effect transistors (JFET), and metal oxide semiconductor field-effect transistors (MOSFET); revising the system models; simulating performance of an HEV traction drive and DC/DC converter using these device models; and performing parametric analyses to determine device parameters that need to be modified to improve the system performance. The objectives also include building a scaled-down prototype all-SiC inverter unit to validate the system models and demonstrate the system-level benefits.

Task 1.5.2. Integrated DC/DC Converter for Multi-Voltage Bus System

Purpose: To demonstrate low-cost, integrated DC/DC converters for 14V/42V/high-voltage (200~500V) bus systems for HEVs and fuel cell vehicles, and to analytically and experimentally investigate the latest, commercially available power devices to explore their benefits due to improved performance in terms of reduced size and improved efficiency of DC/DC converters. Project objectives are to produce hardware that will provide quantitative evaluation of the DC/DC converters' cost and performance, and provide an analytical model that will enable optimized selection of the latest power devices to minimize the size and maximize the efficiency of the DC/DC converters. This project also will investigate alternative power circuit assembly techniques. Presently, discrete MOSFETs are screwed and soldered on copper buses, which are then laid on a heat sink with thermally conductive and electrically insulating material. This assembly technique is not suitable for an automated assembly line.

Task 1.5.3. Integrated Inverter for HEVs and Fuel Cell Powered Vehicles

Purpose: Possible inverter topologies suitable for different auxiliary motor types will be investigated by simulation studies to aid in the selection of the best topology. A prototype based on the selected topology will be designed, fabricated, and tested. Based on the testing data and analysis, a quantitative evaluation will be conducted of the integrated inverter drive system's ability to reduce the cost and volume of the power electronics system. The goal is to develop an integrated inverter topology for multiple motor drives in order to reduce the size and cost of power electronics systems for HEV traction drive and auxiliary motor drives.

Task 1.5.4. Dual Mode Inverter Control (DMIC) Cost Study

Purpose: To determine if there is a cost benefit if a PM motor is driven by DMIC rather than by phase advance alone. The objective is to answer the question, "Is the cost of adding two antiparallel thyristors in each of the three phases of a brushless dc machine (BDCM) offset by the size reduction cost of the motor and inverter and by the cost of safety devices that would otherwise be required?" Starting with a design for a commercial PM motor, a smaller low-inductance PM motor will be designed with the same performance characteristics with lower voltage and current specifications permitted by the DMIC. Likewise, an inverter will be sized to drive the smaller motor. Component lists of each will be used to tally the costs. The safety systems required to protect the drive from loss of the voltage source, bypass of the voltage source, and loss of the gate signal will be identified along with their costs. Costs of the six thyristors will be determined for limited production and for large quantities.

1.6. Z-Source Converter

Contractor: Michigan State University
To be started in FY 2004
Purpose: To design and build a Z-source converter, which combines a DC/DC converter with a DC/AC inverter into a single-stage power-conversion circuit. The magnitude of potential reduction in cost, size, and volume will be determined, as well as the ability of the device to produce a wider constant power-speed ratio.

1.7. Higher-Temperature Inverter

Contractor: To be determined
Purpose: To develop methods for increasing the operating temperature of inverters from 70ºC to 105ºC. One of the most important approaches will be to use SiC semiconductor devices rather than Si semiconductor devices.

1.8. Capacitors

Task 1.8.1. DC Bus Capacitors

Contractor: Sandia National Laboratory
Ongoing
Purpose: To develop a capacitor technology that will replace current electrolytic DC bus capacitors in power electronic modules. The need for a replacement capacitor technology is being driven by requirements for higher voltage and higher under-hood operating temperatures plus the desire to reduce the size of the largest component of power electronic systems – the DC bus capacitors. Multilayer capacitor technologies offer a superior alternative to electrolytic capacitors for higher voltage and higher temperature operation. Polymer dielectrics, based on material systems, such as, polyphenylene sulfide (PPS), polypropylene, and SNL hydroxylated polystyrene (PVOH), can be fabricated as multilayer or wound capacitors. The cost associated with these polyfilm capacitors will be lower than for ceramic capacitors, and they offer the benefit of a non-catastrophic electrical breakdown failure. A critical issue will be to improve polymer film dielectric performance at high temperatures (110ºC and above).

Task 1.8.2. High-Dielectric Capacitors

Contractor: Argonne National Laboratory with subcontract to Penn State University
Ongoing
Purpose: To develop new high performance, high volumetric efficiency, economic technologies for power electronic modules. ANL's program is focused on developing high-performance, low-cost capacitors by miniaturization of bulk ceramic capacitors to microelectronic dimensions. The intention is to develop high-performance capacitors scaled from being the size of a coke cans down to the size of a credit card. The approach is to utilize ferroelectric thin films on base-metal foils. Penn State will develop nanocrystalline glass-ceramics for high-energy-density capacitors. These will be produced by the crystallization of nano-scale ceramic particles in a glass matrix. As compared with conventional ceramics, which typically have a low breakdown strength due to flaws and pores in the ceramic, glass-ceramics have no porosity and avoid the flaws associated with ceramic boundaries.

2. ELECTRIC DRIVE MOTORS

2.1. New-Configuration Machine

Contractor: TBD
New RFP to be issued in FY 2004
Purpose: To develop an internal PM motor that will meet the FreedomCAR goals for a series drive system.

2.2. Evaluation of Power Electronics Prototypes for Contracts Support

Contractor: ORNL
Ongoing
Purpose: To provide an independent evaluation of contractor deliverables such as the motors from the AEMD projects.

2.3. Electric Machinery Fundamental R&D

Contractor: ORNL
Ongoing

Task 2.3.1. Radial Gap Permanent Magnet Motors

Purpose: To compare two commercial PM motor s with ORNL's 1999 radial-gap PM motor design and determine whether one of the three motors is a superior choice for an HEV FreedomCAR drive system. Attributes that will be compared include estimated physical deformations and performance as a function of speed, material requirements, material costs, manufacturability, total weight, power density, specific power, reliability, and drive-ability.

Task 2.3.2. HSUB Hybrid Electric Vehicle Traction Drive System

Purpose: To build hardware to demonstrate the new High (Magnetic) Strength Undiffused (flux) Brushless (HSUB) motor's direct field control capability and power factor control as an alternate HEV traction drive system; to design, build, and evaluate a prototype HEV traction drive system; and to quantify cost benefits at the system-level. The objective is to have an alternate robust, manufacturable, easily cooled, brushless HEV traction drive system with a high constant power speed range that can meet FreedomCAR's 2010 electric propulsion system goals. This project will cover a two-year period, at the end of which a final test report and evaluation of the HSUB traction drive's ability to meet the 2010 FreedomCAR goals will be delivered.

2.4. Permanent Magnets

Contractor: Ames Laboratory
Purpose: To increase the useful operating temperature for magnets to 200ºC and to reduce the finished magnet cost to about 25% of its current level by developing a particulate magnet material with high-temperature properties that can be loaded to a high volume fraction in an advanced polymer binder. Innovative PM alloy design and processing technology will be developed for production of improved PM alloy powders with a tolerance for high temperatures based on the $Nd_2Fe_{14}B$, or "2-14-1" phase, for bonded isotropic PM magnets. Melt spinning will be used to select alloy modifications that boost coercivity, remanence, and energy product at elevated temperatures (up to 200ºC) and that improve alloy quenchability for optimum yield from a gas atomization process. The magnetic properties of bonded isotropic power samples will be determined as a function of loading

fraction, powder size, annealing schedule, coating treatment, and temperature, up to a maximum of 200ºC, in collaboration with an industrial partner.

3. ADVANCED INTEGRATED SYSTEMS

3.1. Thermal Management

Contractor: ORNL and NREL
Ongoing
Purpose: To determine the potential of various thermal management systems available with the intention of pushing the technology to meet automotive requirements. Near-term efforts will concentrate on the following areas:

- Simulations of a total thermal management system, design of a prototype, fabrication, and tests
- Modeling, analysis, and optimization of spray cooling and jet-impingement cooling configurations
- Submerged jet impingement cooling for power electronic dies, cascaded die mounting, and coefficient of performance (COP) improvements
- Investigation of required cooling environment for various components, including coolants, effects of coolants, impingement, and pressure
- Hermetic terminal development, terminal arrangements, and seals
- Simulations of motor direct and indirect refrigerant cooling and COP improvement
- Investigations into component sharing in submersed spray cooling
- Verification of models using Semikron inverter.

3.2. Studies of Competitive Products

Contractor: ORNL
Purpose: To understand technical approaches employed by competitors of U.S. automotive manufacturers for electric drive systems.

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END NOTES

1. FreedomCAR Partnership Plan, September 5, 2002, p. 12: "The FreedomCar Partnership will address... Electric propulsion systems applicable to both fuel cell and internal combustion/electric hybrid vehicles (e.g., power electronics, electric motors)."

2. FreedomCAR Partnership Plan, September 5, 2002, p. 13:

3. The technical targets for the system were calculated from the numbers in Table 2. For example, a target of 5 kW/kg for the inverter/controller corresponds to 11 kg total mass for a 55 kW system. Likewise a target of 1.6 kW/kg for the motor corresponds to a mass of 35 kg. The sum of the two masses is 46 kg, which, when divided into 55 kW, results in a target for the system of 1.2 kW/kg. The volumetric power density was calculated in the same way.

4. The 2010 targets were taken from Tables 1 and 2. The 2003 status for power electronics was taken from a recent progress report from Semikron, and the 2003 status for motors was taken from a recent progress report from Delphi.