3.2 Hybrid and Electric Propulsion

EERE has established a Success Indicator that, "By 2020, vehicles are available that double fuel economy at an incremental cost that is paid back within three years through fuel cost savings." To achieve this success, the cost of hybrid and electric propulsion systems must be significantly reduced. The Hybrid and Electric Propulsion subprogram will reduce the cost of a high power battery subsystem to $20/kW ($500 for a 25 kW subsystem) and a motor-inverter subsystem to less than $12/kW (less than $660 for a 55 kW inverter-motor), providing significant progress toward affordable HEVs. Technology advances in the Automotive Propulsion Materials activity (described in Section 3.4) are applied to the Advanced Power Electronics and Electric Machines (APEEM) activity. Validated technologies from this activity are integrated in Vehicle Systems, as described in Section 3.1 of this plan. The potential location of components within this subprogram in a fuel cell power train is shown in the Figure 3.2-1. As indicated in the figure, most components required for a fuel cell powertrain are being developed through the Hybrid and Electric Propulsion subprogram.

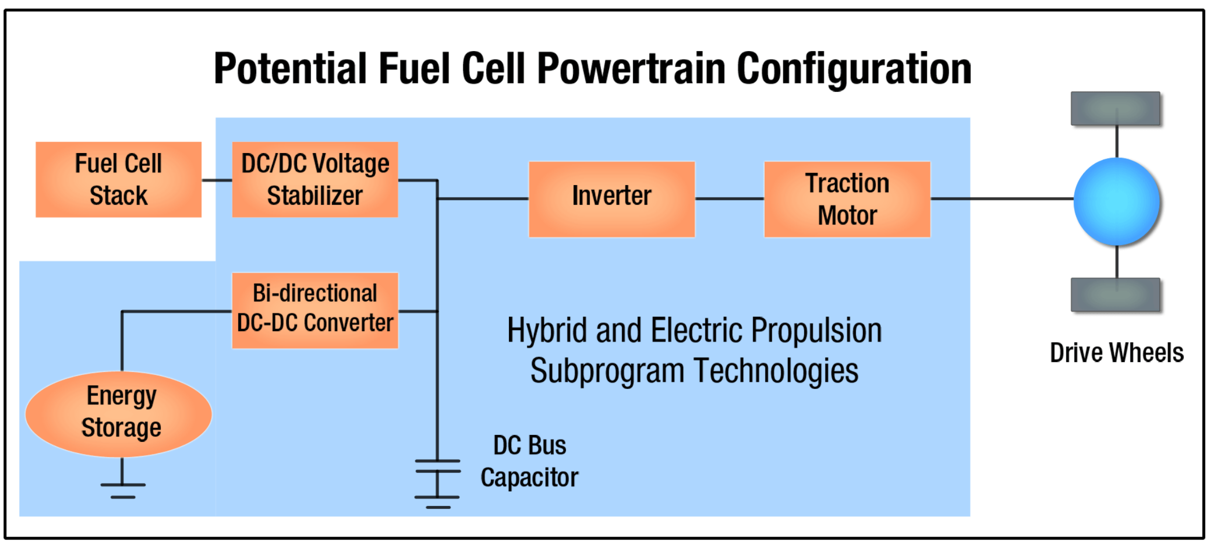


Figure 3.2-1. Components being developed by the Hybrid and Electric Propulsion Subprogram

3.2.1 External Assessment and Market Overview

The Hybrid and Electric Propulsion subprogram includes the Energy Storage and Advanced Power Electronics and Electric Machines R&D efforts. This R&D supports two of the FreedomCAR and Fuel Partnership's goals:

- Develop electric propulsion systems with a 15-year life capable of delivering at least 55 kW for 18 seconds and 30 kW continuous power at a system cost of $12/kW peak; and
- Develop electric drive-train energy storage with a 15-year life at 300 Wh per vehicle with discharge power of 25 kW for 18 seconds at $20/kW.

The subprogram works through the Electrochemical Energy Storage Technical Team and the Electrical and Electronics Technical Team. The technical teams have government and industry participants, an arrangement that seeks consensus on all key goals (such as those above), activities and decisions. Additional goals exist beyond 2010, such as the development of energy storage devices for plug-in hybrids and those for electric vehicles that would have a 300 mile range.

Energy Storage

The primary purpose of developing advanced electrochemical energy storage devices (advanced batteries) is to be able to provide propulsion power and capture regenerative braking energy in vehicles. In general, batteries facilitate the capture and retention of generated energy (regardless of whether it comes from a conventional engine, a fuel cell, or through regenerative braking). Batteries make this energy available for distribution as and when needed by individual components, creating a seamless interface between the power sources. This enables the power generator design to be optimized independent of the power consumption profiles of the components. Energy storage technologies, especially batteries, have been identified as the critical enabling technologies for the successful development of advanced, fuel-efficient, light- and heavy-duty vehicles.

Large and advanced batteries represented a $2.9 billion U.S. market in 2003. Growing at an average annual rate (AAR) of 9.1 percent, this market is expected to reach $4.5 billion in 2008, making it one of the largest and fastest growing technology-driven electrical/electronic sectors. The hybrid electric vehicles/electric vehicles battery market is expected to grow at an AAR of over 50 percent over the next five years to reach nearly $250 million in 2008. The battery technology dominating this market is currently nickel metal hydride (NiMH). The next generation of batteries is expected to use lithium-ion (Li-ion) and lithium polymer chemistries. These offer greater energy and power densities than NiMH and are therefore expected to play an increasing role in this market by 2008, provided the cost (which is the main market barrier) can be reduced through volume production. (*Source: EV world web site.*)

There are currently no major U.S. manufacturers of advanced automotive batteries. The lead-acid battery has historically been the conventional automotive battery technology for starting, lighting, and maintaining ignition. More recently, however, the NiMH battery has entered the automotive field as the power assist battery used in hybrid-electric vehicles from Ford, Toyota and Honda. Major U.S. lead-acid manufacturers include Johnson Controls, Exide Technologies, Delphi Corporation, and East Penn Manufacturing Company. Johnson Controls manufactures and sells an estimated $1.8 billion worth of batteries for more than 35 million vehicles annually. In 2003, Johnson Controls acquired an 80 percent majority ownership in Varta, a major European automotive battery manufacturer headquartered in Germany, which specializes in advanced battery chemistries like NiMH and Li-ion in addition to lead-acid.

Hybrid vehicle growth has driven the demand for NiMH batteries and has spurred development of advanced lithium batteries (more than 120,000 hybrid passenger cars were sold worldwide through 2003) and it is expected to lead to a large demand for Li-ion batteries. In addition, technology spin-offs from this activity will most likely reduce the cost of batteries for other consumer applications.

Advanced Power Electronics and Electric Machines

The APEEM effort is developing components and subsystems required for the production of safe, reliable, and affordable advanced hybrid vehicles with improved fuel efficiency. The ultimate, long-term goal is to develop APEEM technologies for fuel cell vehicles that provide improved efficiency, reliability, and durability, while simultaneously reducing cost, weight, and volume. In the near and mid terms, R&D is focusing on combustion-engine hybrid electric vehicles. Such vehicles will provide an opportunity to introduce and validate relevant technologies for the longer-term fuel cell vehicles.

APEEM technologies condition, control, and transfer electrical power and energy from the fuel cell or from the energy storage subsystem of a combustion engine or fuel cell hybrid electric vehicle to the wheels. Current power electronic and traction motor technologies for advanced hybrid vehicles are not mature. While technologies exist to meet the functional requirements of current hybrid vehicles, future cost-competitive hybrid vehicles will require APEEM technologies at higher efficiency and greatly reduced cost. In addition, the technologies must simultaneously have lower weight and volume.

Motors for industrial applications represent a mature technology; however, for advanced hybrid vehicles no motor technology currently meets the FreedomCAR and Fuel Partnership vehicle requirements for volume, weight, cost and efficiency. Permanent magnet motors appear to be a potential technology for meeting such requirements. Significant work is required to reduce the volume of the motor. As the technology evolves and the allowable motor volume allocation becomes smaller, ever increasing speeds are required, presenting mechanical and electrical challenges that must be addressed by R&D.

The main APEEM components of the drive train in an advanced hybrid vehicle, such as a fuel cell vehicle, include the following:

- An electric traction motor with enough power and torque to accelerate the vehicle from a standing start and propel it to highway speeds.

- A generator to maintain the state of charge in the battery. In some vehicle architectures, the motor can also function as the generator.
- An inverter to convert the DC power from the fuel cell and energy storage subsystem to AC power for the traction motor.
- A DC/DC converter to boost and stabilize the voltage from the fuel cell may be required as fuel cell voltage decreases with increasing current demand.
- A DC/DC buck converter to decrease the operating bus voltage to 14V (and sometimes 42V) for the electrical accessories.

Figure 3.2-1 depicts the Hybrid and Electric Propulsion subprogram components in a potential fuel cell vehicle drivetrain configuration. These components are required for advanced hybrid vehicles; however, they are not currently mass produced.

The APEEM technologies are grouped into four principal categories for R&D: power electronics, electrical machines, thermal control, and integrated systems.

3.2.2 Internal Assessment and Subprogram History

As stated earlier, the Hybrid and Electric Propulsion subprogram includes the energy storage effort and the APEEM efforts, both of which are described below.

Energy Storage

The energy storage effort has supported battery research for automotive applications for more than 25 years. For most of the early years, this work was primarily focused on validation tasks and on exploratory research, examining and evaluating a wide spectrum of electrochemical couples that showed promise for electric vehicles. Upon the formation of the U.S. Advanced Battery Consortium[a] (USABC) in 1991, followed by the establishment of the Partnership for a New Generation of Vehicles (PNGV) in 1993, efforts began to focus on the most promising technologies for hybrid electric vehicle applications, with a much heavier emphasis on development.

Based on the above, battery modules (including LiAl/FeS_2, NiMH, Li-ion, and Li/polymer) were built and tested against electric vehicle (EV) and hybrid electric vehicle (HEV) targets (developed by the PNGV and USABC). Even after significant development, not one of these systems was able to simultaneously meet the requirements, especially the cost limit (although modules designed for higher-power applications [HEV applications] came closer to meeting or exceeding their performance targets than systems built for higher-energy applications [EV applications]). The current cost of the advanced batteries exceeds targets by a factor of almost four for EV batteries and a factor of two for HEV batteries. The main cost

[a] The U.S. Advanced Battery Consortium was formed as a partnership between major automotive manufacturers in January 1991 to develop advanced batteries for rapid commercialization of EVs (as per the original scope of work) and expanded in subsequent scopes of work to include those for other applications including HEVs, 42V systems, and FCVs.

drivers included the costs for raw material, material processing, and cell and module packaging.

In 1997, developers faced a set of closely related challenges in developing Li-ion batteries – primarily in areas of calendar life, abuse tolerance, and cost. To address these, DOE initiated an applied battery research activity, also called Advanced Technology Development (ATD). It consists of five national laboratories working together with flexibility to quickly change focus as current obstacles are overcome and new challenges are identified. In 2000, a long-term exploratory research activity was organized around specific baseline systems. Teams of scientists were organized to address six research areas (cell development, anodes, cathodes, electrolytes, diagnostics, and modeling) with resources focused on identifying, understanding, and addressing long-term technical barriers. This activity is called the Batteries for Advanced Transportation Technologies (BATT) activity.

Projects in both the applied and exploratory research activities are peer reviewed and assessed periodically, and new developments in the field are monitored to identify new research areas. Several projects have been initiated and discontinued, including a new project in the applied research activity to investigate low temperature performance of Li-ion batteries, and another in the exploratory area to investigate ionic liquids, and a now-discontinued project (due to insufficient progress) focused on the Li-sulfur battery technology and another on solid polymer electrolytes. In the applied research activity an investigation into cycle life of high power batteries was redirected when the calendar life was identified as more critical.

Advanced Power Electronics and Electric Machines

The APEEM effort was initiated in 1993 as a cooperative effort with the Department of Defense (Navy) to develop multi-kilowatt power electronics building blocks. Following the formation of PNGV, the Electrical/Electronics Technical Team was formed in 1996 to assist PNGV and DOE in establishing the requirements for the development of an automotive electric motor drive (AEMD) and an automotive integrated power module (AIPM).

The AEMD effort resulted in a radial-gap, surface permanent magnet (PM) motor that fell considerably short of PNGV goals, especially with respect to cost, weight, and volume. The AIPM procurement resulted in an inverter which came close to meeting the original PNGV targets, which included a 70°C inlet cooling temperature thermal control system. The principal components of a propulsion system—the inverter and the motor—had been under development for three years in the former PNGV when in 2002, DOE announced the FreedomCAR Partnership with a focus on hybrid electric and fuel cell vehicle technologies.

3.2.3 Federal Role

The hybrid and electric propulsion R&D focuses on high-risk, high-payback, longer-term technologies utilizing the unique expertise and capabilities of industry and the national laboratories. National laboratories provide independent research, testing and evaluation, and serve as independent experts for critical assessment of R&D progress in the commercial sector. The R&D focuses on breakthroughs in critical enabling technologies for hybrid, fuel cell, and electric vehicles. It effectively leverages the best government and industry expertise to jointly conduct pre-competitive, high cost R&D, providing a model for teamwork and cooperation.

It is impractical and infeasible for industry to conduct such research on energy storage and advanced power electronics technologies on its own. The R&D is longer-term, the risks are high, and with significant technical and cost barriers the outcomes are highly uncertain. The automotive industry and its supporting supplier base are focused on nearer-term technologies. The Partnership sponsored R&D is directed toward technology development and validation by 2010 and later and, accordingly, these technologies may not appear in production vehicles until well past 2010. This activity is ideally suited for Federal R&D.

3.2.4 Approach

Achievement of the Hybrid and Electric Propulsion subprogram goal requires addressing the principal market barrier of cost. There are also certain technical barriers. For Energy Storage, technical barriers include improving life and incorporating an ability to withstand certain abuse conditions. Within the APEEM activity there are barriers of weight, volume and temperature control. These technical barriers must be addressed, and many could now be met on an individual basis if cost was not an issue.

In order to address the challenges of both market and technical barriers, the Energy Storage activity has established a dual research pathway which needs to be followed; one that can distinguish between near-term and long-term barriers, employing different approaches for each. This dual pathway is created by separating the work on current (state-of-the-art) technologies (which are usually proprietary in nature and may target niche markets) from work which has intermediate and longer-term applicability to a greater range of technologies. Those technologies are not proprietary and would capture a larger segment of the market, perhaps even 100 percent in the long term, if radically different so as to make changes which would fundamentally affect the market. The former work, done by private developers, is channeled through the USABC, and is funded in partnership with FreedomCAR partners, while the latter work is conducted by the national laboratories and subcontractors, as shown in Figure 3.2-2. Although the bulk of funding for hybrid and electric propulsion research occurs as shown in the figure, occasionally universities and developers too, like the national laboratories, can receive some funding for research related to newer and fundamentally different technologies.

Before entering into an agreement to develop a full system (which can span several years and entail a significant cost), technology assessments are often conducted. These limited 12-month tasks assess a developer's current capabilities and validate technical claims by independent testing. The purpose is to assess the developer's current technology status as well as the developer's ability to develop and deliver a full-scale, fully packaged battery. Current energy storage assessment tasks include cells based on Li-ion gel technology, a Li-ion battery enclosed in soft packaging, and a new $LiFePO_4$ cathode active material. The power electronics and electric machine activity is performing assessments on thermal control techniques to maximize component cooling while minimizing system cost.

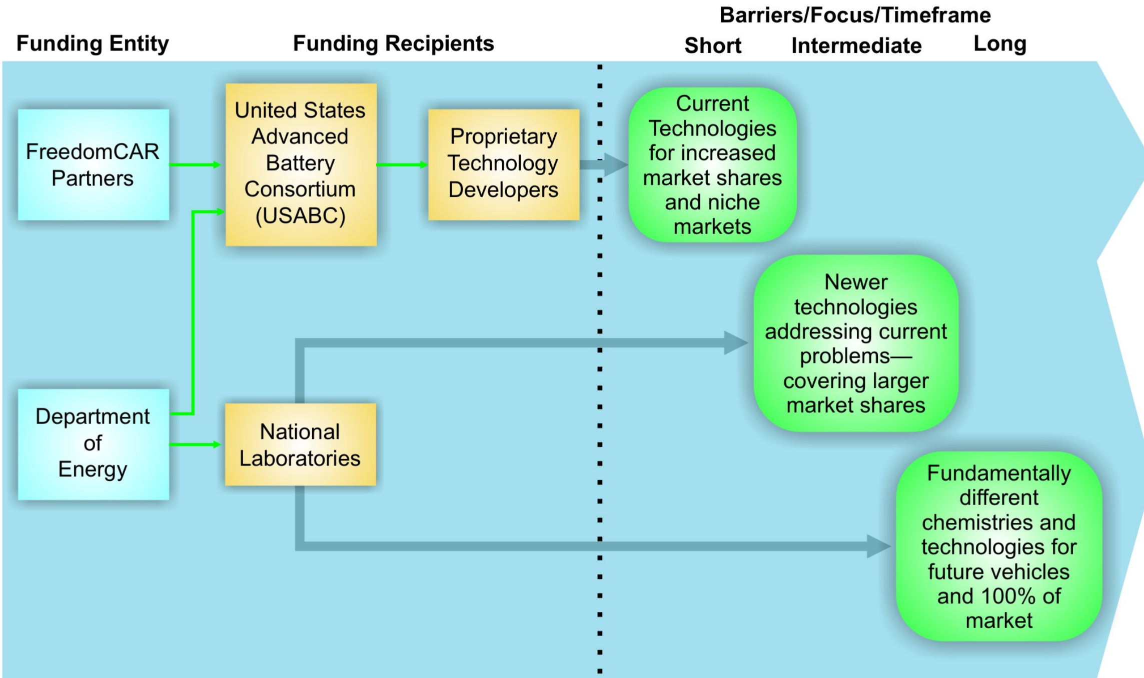


Figure 3.2-2. USABC Energy Storage Targets for 42-V Systems: M-HEV (Mild Hybrid Electric Vehicle) and P-HEV (Power Assist Hybrid Electric Vehicle)

Benchmark testing of emerging technologies is important to remaining abreast of the latest industry developments. FCVT works with the national laboratories to purchase and independently test hardware versus manufacturer specifications and technical targets. Recently completed benchmark testing included that of a production HEV drive system, energy storage full modules with Li-ion cells in soft packaging, a 42V battery system, and several ultra-capacitors, against the appropriate HEV and EV targets.

For the APEEM technologies, FCVT partners with industry and the national laboratories. Such cooperation ensures that the technical attributes, large-scale manufacturing, and cost sensitivities be addressed in a timely manner and the resulting technologies remain with companies willing and able to supply derived products to the automobile companies. National laboratories, universities, and small businesses focus high-risk enabling technology R&D on overcoming the critical technology barriers. This research is coordinated with the FreedomCAR Electrical and Electronics Technical Team.

A phased R&D strategy for addressing the barriers is shown in Figure 3 of Section 2. The following phases are encountered in addressing the subprogram barriers:

- ***Requirements Definition.*** The performance requirements are continuously reaffirmed for batteries and APEEM. Systems analyses are performed to assure that propulsion system requirements are compatible with fuel cell hybrid vehicles. High-energy batteries are considered to reach the end of life when they suffer a 20 percent loss in capacity or power. High-power batteries are considered to reach the end of life when they are no longer able to deliver 25kW in a 10-s discharge period or their net available energy is less than 300Wh. The established cycle-life and calendar-life test procedures (published by the USABC) are used to verify that the requirements are met. The Energy Storage and APEEM activity goals were developed by the Electrochemical Energy Storage (EES) Technical Team and the Electrical and Electronics Technical Team respectively, through consensus of the government and industry participants. Goals for the Plug-in Hybrid Electric Vehicle (PHEV) subsystems will be developed in the same manner.
- ***Exploratory Research.*** Long-term research activities address fundamental problems impeding the development of high-temperature electronics and advanced batteries, developing and evaluating novel battery materials, and broadening advanced diagnostic and modeling capabilities. For example, a specific task includes research into cathode materials such as low cost, stable, and abuse resistant $LiFePO_4$ and high voltage, high capacity $LiNi_xM_yMn_{1-x-y}O_2$.
- ***Applied Research.*** The applied research phase is focused on immediate technical barriers that inhibit the attainment of established performance and cost targets. As an example, the Energy Storage activity includes the development of an accelerated life test to help manufacturers validate the life of their technologies. For APEEM, these efforts include integrated inverters; wide band-gap materials, such as SiC for higher temperature power electronic components capability; capacitors using a polymer-film dielectric as well as those using high-dielectric-constant and a thin-film; and fundamental R&D activity to support long-term (post 2010) requirements. In most cases, the benefits would be reduced cost, volume, and weight, but there could be additional benefits as well, such as increased specific power and efficiency, reliability and robustness.
- ***Technology Development.*** This includes projects with suppliers to develop hardware for validation testing against technical targets. Examples of such projects include 42V and 40kW lithium-ion systems and lithium-sulfur technologies. Electric motor development activities are focused on advanced interior permanent magnet traction motors and generators for both combustion engine and fuel cell hybrid vehicles, as well as R&D on bonded magnetic materials to reduce motor manufacturing cost. Thermal system activities target improvement in the thermal characteristics of power electronics and motors with combinations of high-temperature materials and advanced cooling strategies.

- ***Technology Validation.*** Independent validation testing is performed on promising battery and APEEM technologies. Examples include benchmarking lithium-ion/manganese spinel chemistries against HEV and EV energy storage targets and validating performance of power electronic devices and electrical machines.

Also, as part of management activities, merit reviews before an independent panel of technology experts are held to assess the quality and relevance of the work.

3.2.5 Performance Goals

The Hybrid and Electric Propulsion subprogram performance goals are as follows:

- By 2010, develop electric drive train energy storage with a 15-year life at 30 Wh and a discharge power of 25 kW for 18 seconds and $20/kW cost.
- By 2015, develop an integrated inverter/motor subsystem that costs no more than $12/kW peak and can deliver at least 55 kW of power for 18 seconds and 30 kW of continuous power with an operational lifetime of 15 years. The goal is based on an inlet coolant temperature of 105ºC (FreedomCAR and Fuel Partnership goal).
- By 2020, develop an integrated inverter/motor subsystem that costs no more than $8/kW and can deliver 55 kW peak and 30 kW continuous while meeting component targets for a hybrid and fuel cell vehicle.

A set of performance targets have been set in order to reach the above goals for hybrid electric vehicle battery systems, 42-V systems, and electric vehicle battery systems. These targets, along with the current status are shown in Table 3.2-1 through 3.2-3. The targets for ultra-capacitors are shown in Table 3.2-4. As indicated earlier for goals, the energy storage targets have been developed through a consensus of the EES Technical Team government and industry participants. The color scheme for current status of performance parameters denotes how close they are to the targets – green indicates that the targets is already met or close to being met, red indicates a wide gap between the current status and the target, and yellow indicates a status in-between. It should be noted that no current status is provided for start-stop hybrid electric vehicle batteries, ultra-capacitors, and fuel cell vehicle batteries, since the work in these areas has started only recently.

Table 3.2-1. *Energy Storage Targets for Hybrid Electric Vehicle (2010)*

FreedomCAR HEV goals Characteristics	Power-assist Current Status	Power-assist Target	
		Minimum	Maximum
Pulse discharge power (kW)	29.5 (for 18 seconds)	25 (for 10 seconds)	40 (for 10 seconds)
Maximum regenerating pulse (10 s; kW)	35.3 (2 seconds)	20 (50 Wh pulse)	35 (97 Wh pulse)
Total available energy (kWh)	0.78 (includes beginning of life margin)	0.3	0.5
Round trip efficiency (%)	>90–25 Wh cycle	>90–25 Wh cycle	>90–50 Wh cycle
Cycle life for specified SOC increments (cycles)	200-k 25-Wh cycle (4.75 MWh)	300-k 25-Wh cycle (7.5 MWh)	300-k 50-Wh cycle (15 MWh)
Cold-cranking power at -30ºC (three 2-sec pulses, 10-s rests between; kW)	6	5	7
Calendar life (years)	15	15	15
Maximum weight (kg)	36.5	40	60
Maximum volume (liters)	35	32	45
Production price @ 100k units/year ($)	1,035 (Selling Price)	500	800
Maximum operating voltage (Vdc)	140	<400 maximum	<400 maximum
Minimum operating voltage (Vdc)	105	$>0.55 \times V_{max}$	$>0.55 \times V_{max}$
Maximum self-discharge (Wh/d)	<50	50	50
Operating temperature (ºC)	+10 to +35	-30 to +52	-30 to +52
Survival temperature (ºC)	-46 to +66	-46 to +66	-46 to +66

Table 3.2-2. *USABC Energy Storage Targets for 42-V systems: M-HEV and P-HEV*					
Characteristics	**Current Status**		**Commercialization Goals**		
	M-HEV	**P-HEV**	**Start-Stop**	**M-HEV**	**P-HEV**
Discharge pulse power (kW)	13 (for 2 seconds)	18 (for 10 seconds)	6 (for 2 seconds)	13 (for 2 seconds)	18 (for 10 seconds)
Regenerative pulse power (kW)	8 (for 2 seconds)	18 (for 2 seconds)	N/A	8 (for 2 seconds)	18 (for 2 seconds)
Engine-off accessory load (kW)	OK	OK	3 (for 5 minutes)	3 (for 5 minutes)	3 for 5 minutes
Available energy (Wh @ 3 kW)	425	550	250	300	700
Recharge rate (kW)	2.6 kW	4.5 kW	2.4 kW	2.6 kW	4.5 kW
Energy efficiency on load profile (%)	OK	OK	90	90	90
Cycle life, profiles (engine starts)	OK	OK	150 k (450 k)	150 k (450 k)	150 k (450 k)
Cycle life and efficiency load profile	Partial power assist (PPA)	Full power assist (FPA)	N/A	Partial power assist (PPA)	Full power assist (FPA)
Cold cranking power @ -30°C (kW)	3.3	6.5	8 (21 V minimum)	8 (21 V minimum)	8 (21 V minimum)
Calendar life (years)	OK	OK	15	15	15
Maximum system weight (kg)	16.7	19	10	25	35
Maximum system volume (liters)	26	13	9	20	28
Self discharge (Wh/day)	OK	OK	N/A	< 20	< 20
Maximum operating voltage (Vdc)	27	27	48	48	48
Maximum open circuit voltage (Vdc)	48	48	N/A	48 (after 1 second)	48 (after 1 second)
Minimum operating voltage (Vdc)	27	27	27	27	27
Operating temperature range (ºC)	20 to 52	20 to 52	-30 to 52	-30 to 52	-30 to 52
Selling price ($/system @ 100k units)	554	864	150	260	360

Table 3.2-3. *Energy Storage Targets for Electric Vehicles: 40 kWh*

Characteristics	Current Status	Minimum Goals for Long-term Commercialization	Long-term Goals (2020)
Power density (W/L)	430[a]	460	600
Specific power - discharge, 80 % DOD/10 sec (W/kg)	350[b]	300	400
Specific power - regeneration, 20 % DOD/10 s (W/kg)	N/A	150	200
Energy density - C/3 discharge rate (Wh/L)	145	230	300
Specific energy - C/3 discharge rate (Wh/kg)	120[a]	150	200
Power : energy ratio	N/A	2 : 1	2 : 1
Total energy (kWh)	N/A	40	40
Life (years)	N/A	10	10
Cycle life - 80 % DOD (cycles)	N/A	1000 to 80 % DOD, 1600 to 50 % DOD, 2670 to 30 % DOD	1000
Power and capacity degradation (% of rated spec.)	N/A	20	20
Ultimate price - 10,000 units @ 40 kWh ($/kWh)	N/A	< 150 ($75/kWh desired)	100
Operating environment (ºC)	N/A	-40 to 50 20 % performance loss (10% desired)	-40 to 85
Normal recharge time (hours)	N/A	6 (4 Desired)	3 to 6
High rate charge	N/A	20–70 % SOC in <30 minutes @ 150 W/kg (< 20 min.@ 270 W/kg desired)	40–80 % SOC in 15 minutes
Continuous discharge in 1 hour - no failure (% of rated energy capacity)	N/A	75	75

[a] *Battery performance calculated from cell performance by applying a burden factor based on design.*
[b] *Specific power at 80% DOD/30 second.*

Table 3.2-4. *Energy Storage Targets for Ultra-capacitors*						
System Attributes	**12V Start-Stop (TSS)**		**42V Start-Stop (FSS)**		**42V Transient Power Assist (TPA)**	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s
Regenerative Pulse	N/A		N/A		8 kW	2s
Cold Cranking Pulse @ -30°C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.
Available Energy (CP @1kW)	15 Wh		30 Wh		60 Wh	
Recharge Rate (kW)	0.4 kW		2.4 kW		2.6 kW	
Cycle Life / Equiv. Road Miles	750k / 150,000 miles		750k / 150,000 miles		750k / 150,000 miles	
Cycle Life and Efficiency Load Profile	UC10		UC10		UC10	
Calendar Life (Yrs)	15		15		15	
Energy Efficiency on Load Profile (%)	90		90		90	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%	
Maximum Operating Voltage (Vdc)	17		48		48	
Minimum Operating Voltage (Vdc)	9		27		27	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	
Maximum System Weight (kg)	5		10		20	
Maximum System Volume (Liters)	4		8		16	
Selling Price ($/system @ 100k/yr)	40		80		130	

Table 3.2-5 identifies the 2005 status and 2010 technical targets for APEEM. Status is based on APEEM technologies in commercially available 2005 hybrid vehicles. The 2010 APEEM targets are based on the FreedomCAR and Fuel Partnership goal of 55 kW peak and 30 kW continuous with coolant temperature of 90°C. Table 3.2-7 identifies APEEM targets for 2015 and 2020. System requirements for these vehicles are not known at this time, but may justify lower cooling temperatures and may require higher power electric machines. Since it is easier to scale an electric machine up and still meet cost, specific power, and volume power requirements, the power ratings of 55 kW and 30 kW have been retained.

In addition to the inverter – motor subsystem, R&D is also underway on DC/DC converters and component technologies such as DC bus capacitors, magnetic materials for permanent magnet motors, high-temperature semiconductor materials/devices, and thermal control systems for cooling the power electronics and motors. The R&D objective is to reduce technology gaps: weight, volume, and cost and improve component/system durability. It also is an implicit objective to develop the technologies which have promise of being successfully introduced into the marketplace in support of improved fuel efficiency.

Table 3.2-5. *Technical Status and Targets for APEEM*

Parameter	2005 Status	2010 Target
Integrated Electric Propulsion System (Traction Motor and Power Electronics Inverter/Controller)		
Peak Power, kW	50	55
Continuous Power, kW	21	30
Specific Power at Peak Load, kW/kg	0.86	>1.06
Volume Power Density, kW/L	1.82	>2.60
Cost, $/kW	33.25	<19.00
Efficiency 10% to 100% speed, 20% rated torque	>82	>90
Coolant Temperature, ºC	70	90

It also should be noted that the targets in Table 3.2-5 for power electronics are limited to the inverter/controller. This reflects an earlier emphasis on ICE hybrids, which were the focus of the PNGV program. As mentioned previously, fuel cell vehicles will require at least two DC/DC converters in addition to the power electronics modules that are used in an ICE hybrid.

The proposed targets for fuel cell vehicle battery systems are shown in Table 3.2-6.

Table 3.2-6. *Proposed Energy Storage Targets for Fuel Cell Vehicles*

Characteristics	Target
Pulse Discharge Power (kW)	25 for 18 sec
Maximum Regenerative Pulse (kW)	20 for 5 sec
Total Available Energy (Wh)	250
Round Trip Efficiency (%)	>90
Cycle Life (cycles)	TBD (15 year calendar life equivalent)
Calendar Life (years)	15
Cold start at -30°C (kW)	5 for TBD min
Maximum Weight (kg)	40
Maximum Volume (liter)	32
Production Price at 100,000 units/year ($)	500
Maximum Operating Voltage (Vdc)	<=440
Minimum Operating Voltage (Vdc)	>=0.5Vmax
Maximum Self-discharge (Wh/d)	50
Operating Temperature (°C)	-30 to +52
Survival Temperature (°C)	-46 to +66

Table 3.2-7. *Proposed APEEM Targets for Advanced Hybrid and Fuel Cell Vehicles*

Parameter	2010 Target	2015 Target	2020 Target
Integrated Electric Propulsion System (Traction Motor and Power Electronics Inverter/Controller)			
Power Level, peak/continuous, kW	55/30	55/30[a]	55/30[a]
Specific Power at Peak Load, kW/kg	>1.06	>1.2	>1.4
Volume Power Density, kW/L	>2.60	>3.5	>4.0
Cost, $/kW	<19	<12	<8
Efficiency 10% to 100% speed, 20% rated torque	>90	>93	>94
Coolant Temperature, °C	90	105	105
DC/DC Converter (approx 5 kW) and Transmission			
Specific Power at Peak Load, kW/kg	0.8	>1.0	>1.2
Volume Power Density, kW/l	1.0	>2.0	>3.0
Cost, $/kW	75	<50	<25
Efficiency 10% to 100% speed, FTP drive cycle	93	95	96
Coolant Temperature, °C	90	105	105

[a]Fuel cell vehicle power requirements may be higher than 55/30 kW; however, it is deemed easier to scale up to specific vehicle requirements and still meet cost and performance targets.

3.2.6 Strategic Goals

The primary strategic goals of the Hybrid and Electric Propulsion subprogram are:

- Accelerate the adoption of advanced battery technologies and APEEM technologies into U.S. automobiles;
- Encourage the development of U.S. manufacturing capability for these technologies; and
- Reduce the incremental cost of hybrid vehicles such that consumers can recover that cost through fuel savings in three years.

3.2.7 Market Challenges and Barriers

A. ***Cost.*** High cost is the primary market barrier to the technologies being developed by the Hybrid and Electric Propulsion subprogram. This applies to advanced battery and APEEM technologies, for both of which cost is the overriding factor. All other factors must always be pursued with a continual consideration of impact on the cost.

As an example, state-of-the-art batteries meeting some or most of the FreedomCAR and Fuel Partnership performance targets generally fall short of the cost goals. Batteries are typically designed for either high-power or high-energy applications. In the former case, the electrodes are constructed with very high surface area, resulting in a very high ratio of inactive materials (such as separator and current collectors) to active materials. For higher-energy systems, the reverse is true; electrodes are made as dense and thick as possible to maximize the energy density. Therefore, based on the type of the technology, relative component costs can vary widely. The major contributors to battery cost are its components associated with the separator, the cathode, and the processing of highly reactive components into a functioning battery.

In addition, materials, processing, and fabrication technologies for APEEM are currently considered too costly for automotive applications. Addressing the cost barrier requires identifying the key cost issues; developing and evaluating lower-cost components, packaging alternatives, and processing methods; and working with potential U.S. suppliers to implement these low cost solutions.

3.2.8 Technical (Non-Market) Challenges/Barriers

B. ***Performance.*** Hybrid and electric propulsion systems for different applications may need to meet different performance targets. For example, batteries can be designed to achieve either a high power-to-energy ratio, as in HEV, or a moderate power-to-energy ratio, as in an EV. Today, batteries designed for high power-to-energy ratios can deliver 300,000 shallow discharge cycles in a lifetime, and they meet or exceed many of the performance targets. However, larger, energy-dense systems have difficulty meeting the requirement of 1,000 deep discharge cycles over the life of the battery.

Several general barriers limit the adoption of batteries and capacitors including, for batteries, low-temperature performance, high-energy system performance and, for ultra-capacitors, the low energy density. The issue of the low-temperature performance of advanced batteries is being addressed at a fundamental level in both the applied battery and long-term research activities.

In PNGV the targets were based on 70°C cooling and were revised upward to 105°C for the FreedomCAR and Fuel Partnership. The 105°C cooling target is associated with the 2015 and 2020 targets, while an intermediate cooling target of 90°C is associated with the 2010 targets. The basis for the higher temperature is to permit the use of engine coolant, thus potentially avoiding a separate (hence added cost) cooling loop to cool the power electronics/motor. The higher temperature, however introduces technical and cost issues. The insulated gate bipolar transistors (IGBT's), which are the principal silicon-based semiconductor transistor components in the power electronics, need to operate at temperatures not in excess of 125°C. At this temperature conventional cooling techniques, such as forced convection, are incapable of removing high heat fluxes in the range of 250 W/cm^2 at a temperature difference of only 20°C.

C. ***Life.*** Hybrid systems with conventional engines have a life target of 15 years. EVs are expected to achieve a life target of 10 years. Three technical barriers must be overcome to achieve these life goals.

These include addressing the facts that accurate life predictions are presently not available, that a correlation of life to micro changes is lacking, and that the continual introduction into the market of new low cost battery materials requires a rapid method of screening to identify those that can meet the life requirements. The calendar life requirement of 15 years is challenging, more so with new low cost materials and fabrication technology. In addition, mechanisms that lead to a poor calendar life become more dominant as the temperature of the system increases. This requires additional effort in thermal management and the development of more robust chemistries. Addressing these requires identifying the life-limiting mechanisms, investigating and developing materials for advanced cell components to extend cell life, and developing and validating accelerated life test methods.

D. ***Abuse tolerance, reliability and ruggedness.*** It is critical that any new technology introduced in a vehicle be safe under both routine and extreme operating conditions. The barriers include abuse tolerance during a high-temperature exposure, under conditions of overcharge, and under crush impact situations. Abuse tolerance studies for advanced batteries focus on investigating failure modes through comprehensive cell testing and diagnostic activities, screening new abuse tolerant materials and additives, investigating separators that shut down at elevated temperatures (to inhibit thermal runaway by resisting current flow), assessing the behavior of vehicle-size modules under abusive conditions, and developing and evaluating technologies to mitigate abusive conditions (such as overcharge and overheating).

Currently, APEEM components that meet the requirements for size, weight, and volume are not sufficiently rugged or reliable to operate in harsh automotive environments for the desired 150,000 miles or 15 years.

E. ***Weight, volume and thermal control***. APEEM components are bulky and difficult to package for automotive applications. Current thermal control technologies are inadequate to dissipate heat in high power density systems. In addition, components must be packaged and cooled effectively, which has cost implications, and the technologies are too heavy and require additional structural weight for support.

3.2.9 Strategies for Overcoming Barriers/Challenges

The strategy for overcoming the market and technical barriers must be tailored to the needs of the automobile industry. These needs can range broadly–from those of relatively small 42V systems adequate for a vehicle that would operate in a minimum "start/stop" mode, to moderate-size, high-power systems for use in HEVs and fuel cell vehicles, to large batteries for EVs. They will not be met by a single battery, or even a single chemistry. FCVT continuously reaffirms the performance and cost targets for the full range of these batteries with the USABC and develops hardware for specific applications that can be tested against respective performance targets and used for subsystem benchmarking.

To meet this range of needs, a range of activities take place from hardware development with industrial contractors to mid-term R&D and long-term research. First, FCVT establishes technical requirements in cooperation with industry. Next, batteries available in the marketplace are evaluated against the requirements. If these requirements cannot be met, additional R&D is indicated, which may be in the nature of either immediate-term directed research (applied research), or more long-term exploratory research. The R&D is always directed at overcoming specific technical barriers. The R&D activities leverage the efforts of the whole electrochemical community, including universities, national laboratories, and small and large businesses.

The APEEM effort includes R&D activities in power electronics, electrical machines, thermal control, and integrated APEEM systems:

- Development of power inverters, DC/DC converters, and supporting technologies such as DC bus capacitors.
- Development of advanced permanent magnet motor technologies.
- Development of thermal control technologies and integration of APEEM components and subsystems.

Focus areas include:

- ***Higher temperature electronics.*** The trend in automotive power electronics is toward using higher operating temperatures, making it necessary to investigate higher temperature wide band-gap semiconductor materials such as SiC. These materials would permit higher-junction temperatures reduced switching losses, smaller heat sinks, and a reduced size/weight for power converters.
- ***Multi-output DC/DC converters.*** The trend in automotive power electronics is to use two-stage bidirectional power conversions: DC/DC converters to boost energy storage voltage from approximately 200 to 600 volts (or higher), and DC/AC inverters to drive the traction motor. Fuel cell-powered vehicles will require a bi-directional DC/DC converter to interconnect the fuel cell power high-voltage bus and the low-voltage bus for vehicle auxiliary loads. The fuel cell energy storage subsystem (either battery or ultra-capacitor) operating at a lower voltage, such as 200-300 volts, and uses a bidirectional DC/DC converter to maintain the state of charge. R&D is ongoing to develop innovative designs and demonstrate commercial viability in high-volume production. Technical issues include choice of topology, filtering requirements, switches, switching frequency, thermal systems, and type of magnetic components. Cost, reliability, weight, and volume are critical factors.

- ***Integrated inverters.*** System performance improvement and cost reduction will result from the integration of the motor and inverter, and the power converter and inverter. The future fuel cell hybrid vehicle also requires an electrical motor-driven compressor.

- ***Capacitors.*** Ongoing R&D includes investigating embedded film-on-foil capacitors, glass ceramic capacitors, nano-ceramic dielectric capacitors, and polymer film capacitors. The ongoing R&D is directed toward the reduction of cost, weight and volume, increased temperature rating, decreased equivalent series resistance (ESR), and increased life and reliability.

  DC bus capacitors are essential to prevent ripple currents from feeding back to the power source and to smooth out DC bus voltage variations. Capacitors represent a significant fraction of the inverter volume (up to 60%), weight, and cost. Current electrolytic aluminum capacitors (used below 450 V) have problems related to bulk, high-temperature and ripple current tolerance, and lifetime; and they can also fail catastrophically. Polymer-film capacitors are used for voltages above 450 V and are less bulky, but currently they cannot tolerate high temperatures.

- ***High-energy magnets.*** The unacceptably high cost of permanent magnet motors is due to the high cost of magnet materials, magnet manufacturing, and rotor fabrication. More powerful magnets would help motors maintain high torque for more efficient operation. Additionally, improved magnetic materials would result in improved motors with reduced size and weight, increased durability and reliability, and reduced cost. Ongoing R&D is directed toward:

  - Developing high performance permanent magnets for motors with internal permanent magnet rotors;
  - Reducing the manufacturing cost of permanent magnet traction motors; and
  - Achieving high performance and reliability for bonded magnets. Research is being conducted on polymer-bonded particulate magnets with the objectives of increasing the useful operating temperature from 150°C to 200°C and decreasing the cost to about 25 percent of its current price of approximately $90/kg.

- ***Traction Motors.*** The strategy to address barriers for traction motors includes R&D to develop advanced interior permanent magnet motors and for combustion engine and fuel cell hybrid vehicles. Induction motors are widely available but cannot meet the FreedomCAR requirements of cost, weight, volume, and efficiency, and, because the technology is mature, additional improvements are unlikely. A permanent magnet motor has the highest power density but does not have a sufficient constant power speed range, and its costs are too high. Switched reluctance motors are potentially the lowest-cost candidate, but have significant problems related to high torque ripple, noise, and low power factor.

The R&D is focusing on improved interior permanent magnet motors:

- Combining reluctance and magnetic torque components,
- Accomplishing field weakening and enhancement,
- Reducing cost through use of less expensive materials, and
- Providing high efficiency over a wide constant power speed range.

- ***Thermal Control.*** Current marketplace combustion engine hybrid vehicles use a 60-70°C cooling system for APEEM independent of 105°C engine coolant. In future combustion engine hybrid vehicles it may be possible to simplify vehicle systems (and reduce the weight, volume and cost) by using a single 105°C cooling loop. Such an approach would, however, impose more severe temperature constraints on the power electronics and motors. The thermal systems R&D effort is investigating thermal solutions for a range of cooling temperatures–60-70°C for the separate cooling loop system, to 80-90°C for proton exchange membrane fuel cells, to 105°C for single cooling loop combustion engine hybrids.

  Focus areas for thermal systems include:

  - System modeling and analysis to understand cooling requirements and to aid in setting cooling performance targets;
  - Investigating gas cooling and multiphase liquid cooling regimes;
  - Enhancing heat transfer coefficients;
  - Developing low thermal resistance materials and designs; and
  - Managing motor thermal systems.

3.2.10 Tasks

To implement this approach, specific tasks, provided in Tables 3.2-8 through 3.2-11, have been identified under the battery development, applied battery research, long-term exploratory research, and other research activities.

Within the battery development activity, FCVT works closely with the automotive manufacturers through the EES Technical Team in carrying out all of the technical tasks, particularly in the development area. The tasks planned in development are shown in Table 3.2-7.

Within the applied battery research activity critical, cross-cutting barriers which impede the adoption of technologies close to commercialization get addressed. Tasks specific to it are presented in Table 3.2-8.

Within the long-term exploratory research activity, which consists of research on new electrochemical systems having the potential to meet the technical targets, the emphasis is on understanding fundamental processes and limitations and using this knowledge to develop new and improved materials and components. This work requires a steady, focused, long-term commitment. Baseline systems for exploratory research are defined to help maintain a level of cohesiveness and provide continuous focus to the investigators. Specific task details are shown in Table 3.2-10.

Certain other energy storage R&D activities supported by FCVT (not exclusive to one of the preceding activities) are listed in Table 3.2-11 These include the modeling of thermal properties, development of battery and full system models, and participation in Small Business Innovative Research (SBIR).

A description of each APEEM technical task, with estimated duration and the associated technical barriers, is provided in Table 3.2-12.

Table 3.2-8. *Tasks for the Battery Development Area*

Task	Title	Duration & Barriers
1	Establish/revise targets and continue to assess candidate technologies that have the potential to meet FreedomCAR requirements. • Establish and maintain technical targets for the 42-V system, HEV, EV, FCV, and heavy-duty hybrid batteries. • Pursue the continuous evaluation of available technology. Evaluate new technologies and commercial products as they become available, and combine data from these studies with similar data from other development contracts to identify areas for additional R&D. • Assess technologies based on the results of current benchmark testing and a thorough review of other available data. If the assessment is positive, begin development with an established manufacturer, potentially to support application to heavy-duty hybrid vehicles	144 months Barriers A,B,C,D (Begin 1Q 1999)
2	Continue to support cost reduction programs of lithium ion batteries for power assist applications. Develop ultra-capacitors for stop/start and mild power assist. Issue solicitation to assess and develop lithium based systems for high energy including plug-in hybrid applications. • Initiate plans with a major developer to develop a full HEV 40kW Li ion battery meeting all FreedomCAR targets, including safety. • Continue investigations with a qualified developer to establish the feasibility of a Li-ion/gel polymer system. • Focus on addressing lithium/sulfur isolation issue through the development of new processes to protect the lithium anode. Evaluate these processes; choose one developer to continue development of the most promising technology. • Initiate a contract with a major ultra-capacitor developer to dramatically reduce the cost and increase the energy density of ultra-capacitors.	96 months Barriers A,B,C,D *(Begin 1Q 2003)*

Table 3.2-9. Tasks for Applied Battery Research		
Task	**Title**	**Duration & Barriers**
3	Screen Materials, Study Power Fade, Study Overcharge, Improve Abuse Tolerance, and Develop Advanced System • Rapidly screen and evaluate new materials from vendors using advanced diagnostic techniques to determine if they meet performance and life targets. Disseminate results to the battery community through formal reports and quarterly reviews. • Apply a range of diagnostic techniques to a group of cells aged to various degrees in order to pinpoint the cause of power fade in cells for high-power applications. • Expose cells designed specifically for high-power applications to overcharge and high-temperature conditions to increase understanding of the chemical processes occurring that may result in thermal runaway and cell failure. • Evaluate additives, coatings, and new active materials designed specifically to mitigate the effects of exposure to overcharge and/or high temperatures. • Define an advanced electrochemical system through advanced electrolyte modeling, anode screening and development, and electrochemical testing and diagnostics.	168 months Barriers A,B,C,D (Begin 1Q 1999)
4	Develop Accelerated Life Testing Protocols, and Evaluate Enhanced Quality Control • Validate and publish a robust Accelerated Life Testing protocol that will provide the battery industry with a statistically accurate prediction of cell life within a short time period.	144 months Barriers B,C *(Begin 1Q 1999)*

Table 3.2-10. Tasks for Long-Term Exploratory Research		
Task	**Title**	**Duration & Barriers**
5	Define Baseline Chemistry, Assemble and Test Baseline Cells, Conduct Diagnosis and Modeling, and Synthesize and Evaluate Novel Materials • Review the baseline and exploratory systems every 2 to 3 years and revise them as needed to provide direction and cohesiveness to investigators • Assemble materials acquired from the Anodes, Electrolytes, and Cathodes areas or from outside sources into laboratory cells and test them (Cell Development group) • Examine virgin materials, as well as materials from uncycled and cycled cells, to determine failure mechanisms (Diagnostics group). Model the baseline systems and optimize the design of each system for applications where each system is more likely to meet performance targets. Model growth of the surface-electrolyte interface layer, structural changes during cycling, and ohmic losses due to poor particle-to-particle contact (Modeling group) • Synthesize novel materials offering the possibility for improved cell performance, life, or cost (Anodes, Electrolytes, and Cathodes group). Research on polymers may shift to gels where significant cost savings can be achieved.	144 months Barriers B,C,D (Begin 1Q 2001)

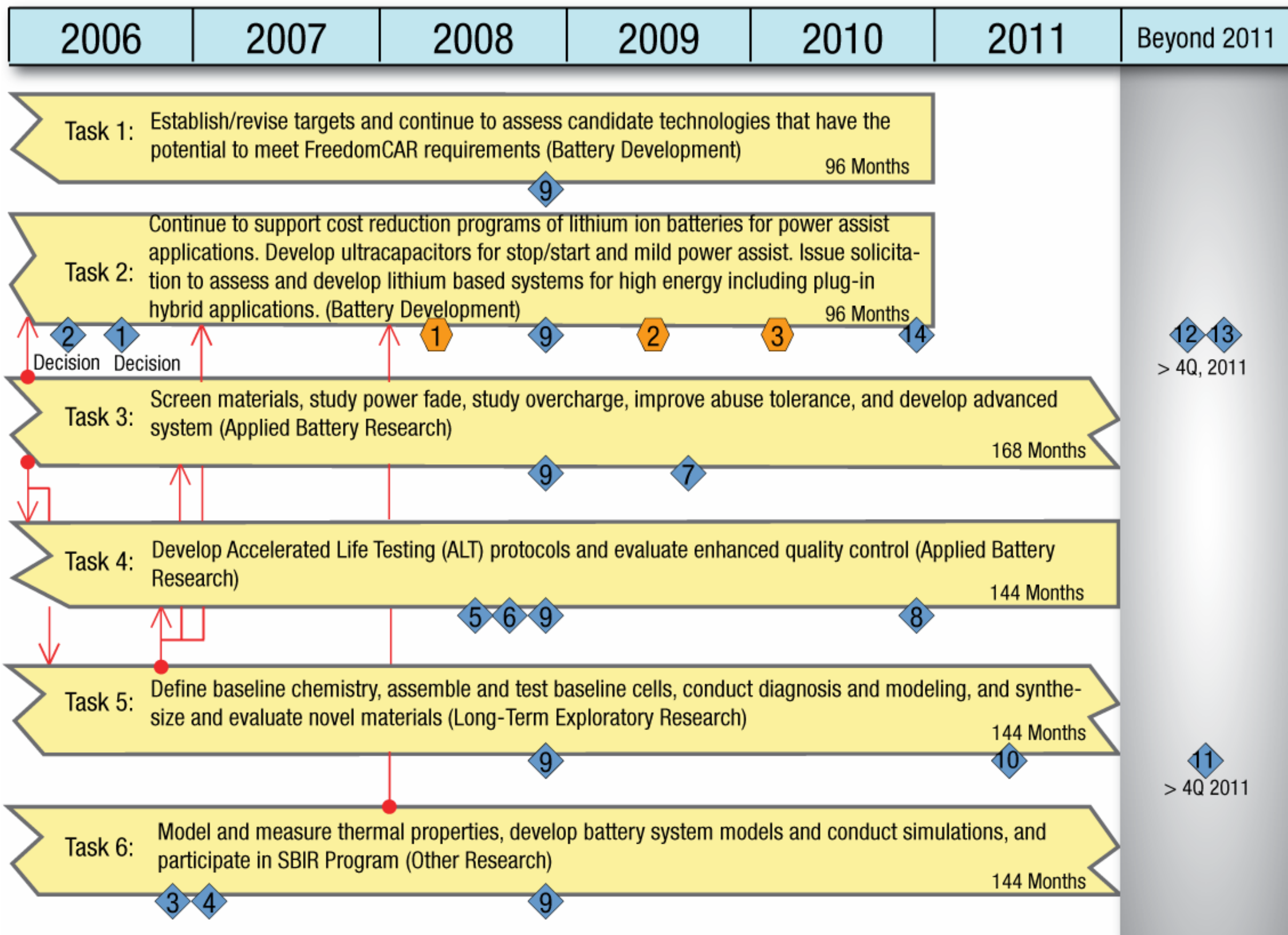
Table 3.2-11. *Tasks for Other Research*		
Task	**Title**	**Duration & Barriers**
6	Model and Measure Thermal Properties, Develop Battery System Models, Conduct Simulations, and Participate in the SBIR Program • Measure thermal characteristics of batteries. Model the thermal performance of batteries and use computer-aided design tools to develop configurations with improved thermal performance. • Task engineers to work with battery developers to improve and validate energy storage models for system simulations, for use in optimization studies and target analyses for different platforms and vehicle types. • Prepare SBIR topics on innovative technologies with a reasonable chance of technical success and market penetration. Publish topics, review proposals, and make grants to the best proposals.	108 months Barriers B,C *(Begin 1Q 2002)*

Table 3.2-12. *Tasks for Advanced Power Electronics and Electric Machines*		
Task	**Title**	**Duration & Barriers**
7	Power Electronics • Develop integrated motor/inverter drive systems with emphasis on cost, density, reliability, and efficiency. • Develop improved inverter/converter architectures and topologies to allow faster switching and enhanced performance. • Develop improved packaging concepts, focusing on component integration with improved thermal systems. • Develop improved low-cost dielectric materials, and improved capacitors with high-temperature, high-current capabilities, low equivalent-series resistance, and long operating lifetimes. • Develop advanced multi-stage DC/DC converters suitable for combustion-engine and fuel cell vehicle applications.	96 months Barriers A,D,E
8	Electric Motors and Generators • Develop advanced motor materials and manufacturing processes to reduce costs. • Develop lower cost magnet materials without sacrificing performance. • Develop advanced interior permanent magnet motor	96 months Barriers A,D,E
9	Thermal Systems • Develop advanced thermal systems for internal combustion engine vehicles and fuel cell vehicles, including the inverter, motor, and other APEEM subsystems. • Perform systems analysis of dynamic electric-drive-vehicle system using analysis and computer models incorporating power electronics, motors, and thermal systems to determine performance/cost trade-offs for drive systems.	96 months Barriers A,D,E
10	Fuel Cell Hybrid Requirements • Address the goals and targets for the transition pathway from ICE Hybrids to Fuel Cell Hybrid Vehicles for components and subsystems.	36 months Barriers B,C,D,E

3.2.11 Milestones & Decision Points

The task-level milestones for the Hybrid and Electric Propulsion subprogram for the next several years are shown in the following network charts.

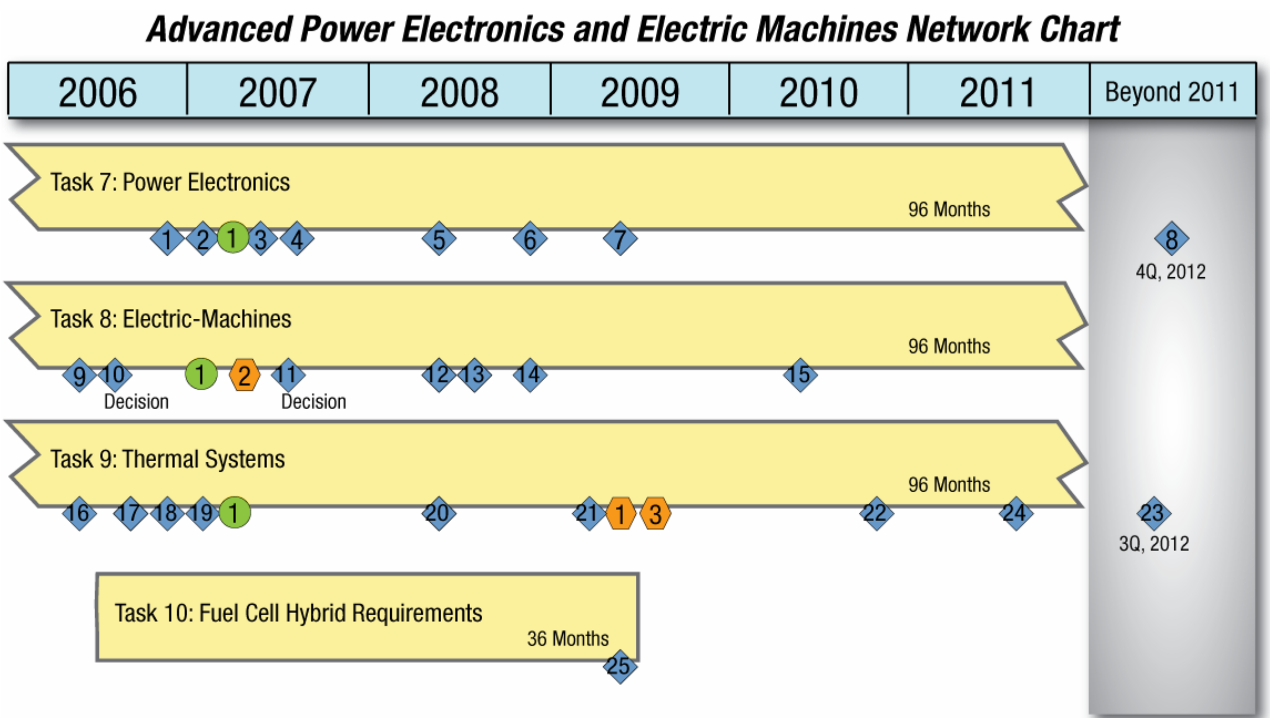
Energy Storage Group Network Chart



Legend

Milestone	Milestone	Technology Program Output
1. **Decision.** Determine if Li-ion polymer battery meets life requirements 2. **Decision.** Determine is Li-S battery meets cycling requirements 3. Validate improved battery thermal control system 4. Validate experimental hardware for battery preheating 5. Validate performance against requirements for hybrid fuel cell vehicle battery targets 6. Evaluate hardware for ultracapacitor and battery combinations for hybrid and fuel cell vehicles	7. Validate $20/kW for high power batteries 8. Validate low-cost, energy-efficient thermal management system 9. Reaffirm all technical targets with the FreedomCAR tech teams 10. Synthesize materials that satisfy plug-in hybrid performance requirements 11. Identify possible high-energy couples that satisfy life requirements for electric-vehicle applications 12. Develop batteries for plug-in hybrids 13. Develop batteries for electric vehicles. 14. **Decision.** Evaluate merits of renewing USABC Cooperative Agreement	1. Analysis and test performance data on 42V/Ultracapacitors (to Vehicle Systems Analysis and OEMs) 2. Performance data and lighium ion battery prototypes (to Vehicle Systems Analysis, Heavy Hybrid Vehicles Subprogram and OEMs) 3. Candidate technologies for development in support of plug-in and electric vehicles applications (to Vehicle System Analysis, USABC and OEMs)

Figure 3.2-3. Network Chart for Energy Storage Group



Legend

Milestone	Milestone	Technology Program Output
1. Receive Ballard DC/DC converter deliverables for testing and evaluation	13. Complete build and evaluation of high speed (1500rpm) reluctance IPM motor with field enhancement/weakening	1. Integrated inverter/motor to meet FreedomCAR goals to Vehicle Systems Analysis
2. Hardware delivery of high temperature AIPM	14. Complete evaluation of optimized HSUPM motor achieving ½ size reduction of THII Prius	2. Prototype internal PM motor to Vehicle Systems Analysis
3. Completion of 55kW SiC inverter with high temp packaging	15. Complete build and evaluation HSUPM motor/generator with integrated inverters and thermal cooling system	3. Thermal-management system to Vehicle Systems Analysis
4. Validate improvements in inverter packaging methods with dual inverter	16. Complete jet impingement modeling tool for single and two phase cooling systems	**Supporting Input**
5. Receive high temp, high capacitance improved capacitors for testing and evaluation	17. Complete validation testing of floating loop	1. Fuel cell performance characteristics from HFCIT
6. Completion of cascade inverter build and test, resulting in inverter size reduction to 1/3 of Semikron 2005 inverter	18. Complete prototype inverter with low resistance IGBT	
7. Complete build and evaluation of high temperature multilevel converter system with bidirectional DC/DC converter and 50kW inverter	19. Complete system analysis and specifications for air-cooled inverter/motor	
8. Complete build of optimized DC/DC converter for use in FC vehicles	20. Produce first generation of carbon nanotube TIM	
9. Completion of Phase 1 of industrial motor project	21. Complete analysis and modeling of jet impingement with nano-particle enriched fluids	
10. **Decision.** Verify that developments in field-weakening techniques help attain technical targets for PM motors	22. Produce first generation of carbon nanotube to replace solder for die connection	
11. **Decision.** Validate contribution of developments in magnet materials to technical targets for motors	23. Complete prototype air cooled system	
12. Receive Industrial RFP awardee motor for testing and evaluation	24. Complete prototype inverter using carbon nano-tube heat spreaders, nano-particle working fluids and carbon nano-tube die joint	
	25. Establish APEEM requirements for fuel cell vehicles	

Figure 3.2-4. Network Chart for Advanced Power Electronics and Electric Machines

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