Status and Prospects for Zero Emissions Vehicle Technology

Report of the ARB Independent Expert Panel 2007

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By

Fritz R. Kalhammer
Bruce M. Kopf
David H. Swan
Vernon P. Roan
Michael P. Walsh, Chairman

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EXECUTIVE SUMMARY

1. Introduction

At the 2003 Zero Emission Vehicle (ZEV) Regulation hearings, the California Air Resources Board (ARB) directed staff to establish an independent expert review panel (Panel) to examine the status of ZEV technologies and to advise the Board. The Panel was constituted in early 2006 and carried out its work between May 2006 and March 2007. The overall objective of the Panel was to provide a thorough and accurate portrayal of the current status of sustainable zero emission vehicle technologies and the prospects for ZEV technology advancement in both the near-and long-term.

The Panel's work consisted primarily of extensive data collection followed by a critical assessment. Summaries of the data and the Panel's assessment are contained in this Final Report.

Starting in early May, the Panel engaged in an intensive effort to gather information on ZEV technology status, key technical issues, current and prospective materials and manufacturing costs and plans for evaluation/demonstration and commercialization of various ZEV and ZEV enabling technologies. This information was collected by soliciting responses to a series of questionnaires that were developed by the Panel, and through visits with key sources, including the leading developers of ZEV enabling technologies and the major automobile manufacturers.

The information collected by the Panel members underwent a thorough, critical assessment by the entire Panel in an effort to fully understand and accurately portray the current and likely near and medium term state of the art. Information from the various sources was compared and contrasted and, where gaps or discrepancies were identified, was followed up with selected sources in an effort to reconcile the information.

The Panel organized its efforts around three main ZEV enabling technologies –energy storage, hydrogen storage and fuel cells. Then, building on current status and prospects for further advances of these technologies and their integration into vehicles, the Panel attempted to forecast the prospects of zero and near-zero emission vehicles.

The Panel's key findings and conclusions are summarized below.

2. Vehicle Energy Storage Systems

The Panel's investigation focused on advanced battery technologies with potential to be fully developed and available for use in Hybrid Electric Vehicles (HEVs), Full Performance Battery Electric Vehicles (FPBEVs) and Plug in Hybrid Electric Vehicles (PHEVs) within the next 5-10 years. The principal findings and conclusions for the main candidate technologies are summarized below, followed by some observations on battery strategy and availability from the Panel's discussions with battery and automobile manufacturers.

A. Nickel Metal Hydride Batteries (NiMH)

High power NiMH technology for HEVs is now mature and mass manufactured in Japan in plants with capacities up to 500,000 systems annually. It is the conclusion of the Panel that high cost remains the greatest challenge for battery and HEV manufacturers, with an estimated cost (price to Original Equipment Manufacturers [OEMs]) of $2,000 for compact and $4,000 for a midsize HEV battery produced at a rate of 100,000 systems per year. These costs appear to account for much of the current price difference between hybrid and conventional vehicles. At a production rate of 1 million systems, battery costs are projected to drop to $1,300 and $2,500, respectively. Competition is expanding but market entry requires large investments for the required fully automated battery manufacturing plants.

Medium power/medium energy NiMH technology has promise to meet the technical requirements for PHEVs with relatively short (e.g., 10-20 miles) nominal electric range. It is the conclusion of the Panel that in mass production, medium power/medium energy NiMH technology's incremental cost over that of HEV batteries, estimated to be about $800-1,200, is probably less than the difference in lifetime fuel costs. However, no substantial efforts to develop or capabilities to fabricate medium power NiMH technology appear to exist.

High energy NiMH technology is still used successfully in FPBEVs manufactured by major automobile manufacturers under the ZEV program. It is the conclusion of the Panel, however, that energy density is fundamentally limited and marginal for FPBEV applications, and costs remain as high as or higher than in 2000 and are unlikely to decline. High energy NiMH technology for possible FPBEV applications has not advanced in recent years.

B. Lithium Ion Batteries (Li Ion)

Li Ion batteries are making impressive technical progress worldwide especially with regard to calendar and cycle life and safety, the areas of special concern for automotive applications. Promising new materials and chemistries are expanding the capabilities and prospects of all Li Ion technologies.

High power Li Ion technology for HEVs appears close to commercialization in the view of the Panel. A variety of materials, manufacturing techniques and companies are competing to achieve the performance and cost goals for this established battery application which increases the probability of technical and market success. Importantly, for HEV applications Li Ion batteries have potentially lower cost than NiMH because they promise to deliver the required power with smaller capacities and lower specific cost.

Medium energy/power Li Ion technology has sufficient performance for PHEVS and small FPBEVs, and it can be expected to meet the life requirements for FPBEVs, in the view of the Panel. Recent test results indicate good potential to also deliver the very demanding cycle life for PHEVs. The projected costs for shorter range PHEV Li Ion batteries are about $3500-4000 in mass production; this is generally less than the fuel cost savings expected over the life of the vehicle. Low volume cell production and prototype battery fabrication is underway in Asia and Europe, and limited fleet demonstrations are underway or planned.

High energy Li Ion technology has sufficient performance for small FPBEVs, and good potential to meet all performance requirements also of midsize and larger FPBEVs with batteries of modest weight (e.g., less than 250-300kg). Cell and battery technology designed for these applications are likely to also meet cycle life goals. It is the conclusion of the Panel, however, that battery cost remains high even in mass production, (probably near the levels projected in

2000), well in excess of expected lifetime fuel cost savings. While high energy Li Ion technology probably will benefit from general progress in Li Ion technology, no efforts seem underway to advance technology designed for FPBEV applications.

Batteries assembled from large numbers (typically, 5,000 or more) of small, high energy Li Ion cells mass-manufactured for laptop computers and other electronic applications are now being used in FPBEVs (and PHEVs) fabricated on a small scale. It is the conclusion of the Panel, however, that such small-cell batteries, although providing early opportunities to demonstrate the technical capabilities of PHEV conversions and modern FPBEVs, have inherently high costs and uncertain calendar and cycle life.

C. ZEBRA Batteries

The ZEBRA (sodium-nickel chloride) battery technology has insufficient power density for HEV and PHEV applications but meets the technical requirements for small FPBEVs. The batteries have been successfully demonstrated in small European FPBEVs, heavy duty vehicles and hybrid buses. The ZEBRA battery is likely to remain the lowest-cost advanced battery because of low materials costs and can be ordered now from its Swiss manufacturer in quantities of 1000s, with rapid expansion of production possible if demand develops. However, the Panel has not seen any automobile manufacturer interest in the battery, probably due to a combination of limited power density and the implications of high temperature operation.

D. Industry Strategies and Perspectives

Battery manufacturers’ positions depend on their current technology capabilities and market positions. Mass-manufacturers of NiMH high power cells and modules for HEV batteries are focused on technology cost reduction and involved in capital-intensive production capacity expansions that assume increasingly competitive HEV mass markets exceeding 1 million vehicles by 2010. FPBEVs are not a target of their NiMH battery technology development efforts, and they consider PHEV battery requirements insufficiently defined to permit an assessment of NiMH technology and market prospects for this new application. No development activities appear underway to explore whether NiMH has technical potential for PHEVs.

Mass-manufacturers of Li Ion cells for consumer products are now engaged in the development of established Li Ion chemistries for HEV applications, with commercialization possible as early as 2008, and a vigorous market competition of technologies and manufacturers is likely to emerge. They do not appear to be pursuing development of Li Ion batteries for FPBEVs or for PHEVs. Li Ion battery costs are considered too high for FPBEVs and government financial incentives are thought unlikely to induce a large number of customers to buy vehicles of limited range. The major impediment to engagement in developing Li Ion batteries for PHEVs appears to be that the PHEV battery requirements are insufficiently defined at this time. GM’s apparent interest in PHEVs (tied to Li ion availability) might stimulate efforts to develop Li Ion technology for PHEV applications. The Panel found no major battery manufacturer interest in high energy Li Ion batteries for FPBEV applications.

Several smaller companies in Europe and Japan have been developing medium and high energy Li Ion technologies, some of them based on advanced materials, chemistries and/or manufacturing techniques. Their strategy is pursuit of limited-volume applications and markets that may be emerging, especially in small Battery Electric Vehicles (BEVs) (including FPBEVs) and more recently also in PHEVs. Several of these companies hold the view that Li Ion-powered PHEVs and small BEVs will be able to attain life cycle cost competitiveness with conventional vehicles in urban fleet applications, and a few have established cell production capacities for hundreds to a few thousands of 10-25kWh batteries per year, sufficient for demonstration fleets. Most of these organizations are owned by large companies but the resources being invested in development and demonstration of batteries are still very modest. While the commercial prospects of BEV- and PHEV-design Li Ion technologies still seem unclear to them, several of these manufacturers noted that development of such technologies was likely to benefit from supported demonstration programs and/or financial incentives.

Automobile manufacturers' positions regarding batteries are determined largely by their extensive efforts to evaluate and advance the HEV-design Li Ion battery system technologies likely to be commercialized within the next few years. Confidence in the readiness of Li Ion batteries for deployment in mass-produced vehicles is growing but some concerns about life and safety remain. Based on their experience with the FPBEVs under the California ZEV initiative, most automobile manufacturers continue to hold the view that FPBEVs will remain niche vehicles, and no efforts to advance battery technologies for FPBEV applications are being supported by them at present. It remains to be seen whether recent announcements by Mitsubishi and Nissan of plans for introduction of BEVs are going to stimulate efforts to develop Li Ion batteries that meet the requirements of these vehicles.

The prospects of PHEVs also were judged negatively by most major automobile manufactures until recently. However, several manufacturers are now active in modeling, designing and evaluating various PHEV architectures and technologies, with consequent attention to candidate battery technologies and their prospects. In the U.S., an effort sponsored by DOE and supported by USABC is now underway with automobile industry expert participation to establish PHEV battery performance, life and cost targets for a planned Research and Development (R&D) program. In Japan the New Energy and Industrial Technology Development Organization (NEDO) is launching an initiative to develop PHEV batteries with the involvement of leading Li Ion battery developers. These initiatives and automobile manufacturers' initiatives such as GM's recently announced plans to offer a PHEV version of the Saturn VUE HEV and to launch the "Volt" PHEV if suitable Li Ion batteries become available are the signals needed by the major battery manufacturers to become engaged with their own resources in the development and manufacture of batteries for PHEVs.

3. Hydrogen Storage Systems

Storing sufficient hydrogen on a vehicle to power it for adequate distance, safely, and at reasonable cost, without an excessive weight penalty has been and remains a serious challenge for the automobile industry and its suppliers. All of the major potential manufacturers of fuel cell vehicles interviewed by the Panel highlighted hydrogen storage to be among the two or three areas of greatest concern, including all of the other cost and technology challenges associated with developing fuel cell systems for consumer vehicles; one manufacturer identified it as the single greatest challenge.

Unlike other major technologies being pursued in support of ZEVs, hydrogen storage technologies have advanced relatively little in recent years. The primary system advancements have been in the area of improving compressed gaseous hydrogen storage and, to some extent, improving liquid hydrogen storage. However, in the last 3 to 4 years, as it became apparent that on vehicle fuel reformers for generation of hydrogen from carbon based liquid fuels were not a viable option, many alternative storage concepts have begun to receive significant research attention. A few concepts (e.g., metal hydrides and carbon nanotubes) that have been investigated at relatively low levels of effort for many years are now receiving increased attention. However, these efforts are fairly young and it is still too early to determine if they will result in technically and economically realistic hydrogen storage system alternatives.

A. Near Term Outlook

In the near term, the dominant form of storing hydrogen onboard light vehicles will continue to be compressed hydrogen gas. With the exception of BMW, every other OEM contacted indicated that this was the only realistic short term choice available and only Honda indicated that they intend to limit the storage pressure to 350 bar. All the other OEMs preferred 700 bar, which will provide storage of over 50% more fuel in the same space envelope and correspondingly provide almost 50% more range. Using 700 bar storage pressure is not, however, without problems. The volumetric density (kWh/L) will be higher but unit energy cost ($/kWh) is also expected to be higher and the gravimetric energy density (kWh/kg) about the same. It may also require either reduced fill rates or pre-cooling of the hydrogen prior to transferring into the vehicle tank to avoid overheating the tank structural materials.

Liquid hydrogen storage is being demonstrated as workable but with limitations. It provides both higher gravimetric and volumetric density advantages over compressed gas storage but has issues with boil off and dealing with cryogenic liquids. It is not likely to be widely accepted by automobile OEMs in the judgment of the Panel.

An important issue with any of the short term hydrogen storage options is the need for widely accepted codes and standards for permanent storage, onboard storage, and all aspects of transferring and transporting hydrogen.

Cost is another important issue, especially for the short term since none of the storage systems are produced in sufficient volumes to allow significant production economies of scale. While none of the OEMs gave specific current or near-term costs for the essentially one-of-a-kind hydrogen storage systems, the Panel estimates them to cost $10,000 or more each for both liquid and compressed gas storage.

B. Longer Term Outlook

For the longer term, some of the alternative storage technologies being researched may prove to be effective. Both solid and liquid carriers are being researched with hydrogen “recharging” being carried out both onboard and off of the vehicle. There don’t appear to be any clear winners at the present among these alternatives and, in fact, none of the researchers who responded to the hydrogen storage questionnaire provided projections for complete system performance or costs. It appears to be too early to make reasonably accurate projections.

C. Conclusions of the Panel

It is the conclusion of the Panel that on-board hydrogen storage is a major challenge for hydrogen fuel cell vehicles. At present, the only technology being demonstrated by the OEMs, with the exception of BMW, is compressed hydrogen gas storage which has problems providing sufficient vehicle range without excessive volume, weight, and cost.

The volume issue can be partially resolved by using 700 bar storage (thus a smaller required volume) and by innovative vehicle design or design modification. Such innovations might include utilization of a long, small-diameter tank running longitudinally where the center “tunnel” is located and/or replacing rear coil springs with leaf springs to increase space available for hydrogen tanks. Thus, depending on the type of vehicle and system efficiency, it seems likely that sufficient compressed hydrogen could be stored on a vehicle to provide a range in excess of 200 miles, perhaps reaching 300 miles or more.

Liquid hydrogen storage technology appears to have advanced sufficiently that, within certain constraints, it could be utilized. The advantages of liquid hydrogen, higher storage density and low pressure, suggest that it also could provide an adequate range.

However, it seems unlikely that either compressed or liquid hydrogen storage systems can meet weight or cost targets, especially for 2015. Using the TIAX estimates for mass-manufactured tanks, the system cost would be about $10 to $12 per kWh for 350 bar systems and $13 to $15 per kWh for 700 bar systems compared to DOE targets of $4 per kWh for 2010 and $2 per kWh for 2015. Assuming that at least 5 kg (165 KWh) of hydrogen will be needed to provide sufficient vehicle range, the cost would be $1650 even with the lowest TIAX tank cost estimate. For liquid storage, the cost would be even higher. There is little expectation that the cost of either of these systems will go much lower even with higher volumes.

The weight outlook is better than the cost outlook. The TIAX projections for weight fraction are slightly over 6% for both 350 bar and 700 bar systems, compared to the DOE targets of 6% for 2010 and 9% for 2015. The pressure tank manufacturers have also indicated that 6%, and perhaps a bit higher weight fraction is within reach. For a 6% weight fraction system to contain 5 kg of hydrogen, the system would weigh about 83 kg (about 183 lb). Neither TIAX nor the tank manufacturers project that the 2015 target of 9% can be met with pressurized hydrogen tanks.

There are many alternative hydrogen storage systems under investigation. Some of the absorption materials being investigated are relatively inexpensive and have shown, at least in the research phases, the capacity to contain well over 6% hydrogen. However, the remainder of the support system could have a huge effect on both cost and weight fraction.

4. Automotive Fuel Cell Systems

Automotive fuel cell technology continues to make substantial progress but is not yet proven to be commercially viable. Technological and engineering advancements have improved, simplified and even eliminated components of the fuel cell system. Progress made since the 1998 ARB fuel cell report include major improvements in the membrane electrode assembly (MEA) and fuel cell stack technologies. The Balance of Plant has a reduced number of components and now uses some parts that are of automotive quality and cost. The fuel cell system has a reduced start time and in-vehicle start-up from a frozen condition has been demonstrated. Great strides have been made in the science of materials and operating characteristics of fuel cells. This increase in fundamental understanding shows promise for solving life, abuse and durability issues for fuel cell systems.

The consensus among the majority of fuel cell system developers is that in order to achieve commercialization there are simultaneous requirements for:

1) Higher MEA power per unit area of fuel cell electrodes (goal of 0.8 to 1.0 W/cm^2)
2) Reduced MEA catalyst cost (goal of total MEA catalyst loading <0.1 to 0.5 mg Pt/cm^2)
3) Longer fuel cell system operating life and increased durability (goal of >5000 hours of

customer use)

4) Proton Exchange Membrane (PEM) materials that are stable and can operate at a higher temperature (above 100^{o}C)
5) Engineering advances

An increase in MEA specific power allows a given fuel cell stack to produce more power and thus achieve a lower $/kW. Nearly every stack cost factor, at a given voltage, decreases in inverse proportion to MEA specific power. The MEA catalyst cost is directly related to the price of platinum. The price of this noble metal is rising due to world wide demand exceeding supply and at current levels it represents a significant barrier to automotive fuel cell commercialization. The life and durability of fuel cells in automotive applications is not yet proven. A life of 5000 + hours in a light duty vehicle type load cycle has not been demonstrated at the cell or stack level. The development of high temperature membranes can potentially reduce the size and complexity of the Fuel Cell Electric Vehicle (FCEV) thermal system and may possibly eliminate the need for stack humidification. Engineering advances and innovation are focused on materials, stack design, and balance of plant to reduce cost and increase life.

Overall, the Panel concludes that at this time no fuel cell developer has achieved the necessary requirements for automotive fuel cell commercialization. The developers are relying on future technological improvements to meet both cost and life goals. Achieving these goals creates some contradictory requirements for the fuel cell system. The Panel believes that these requirements are difficult to achieve separately and because they are interrelated, even more difficult to solve simultaneously. These technological improvements include the development of MEAs that use significantly less catalyst material and that operate at higher specific power and temperature over a longer system life. To simultaneously increase performance, extend life and reduce cost will likely take ingenuity and invention.

Each of the developers believes that the simultaneous requirements can be met but on different time schedules. For example, one major developer’s objective is to compete with the “upper” segment of internal combustion engine (ICE) vehicles in the year 2020 at volumes of 100,000 units per year. Another major developer’s assessment is that a commercially viable fuel cell system would be available in 2010, if a production rate of 500,000 units per year could be realized.

At this time, large conventional suppliers to the automotive industry are not active in fuel cell development and are taking a wait and see attitude. If the market develops, it is conceivable that they will rapidly acquire the technology.

The Panel remains cautiously optimistic regarding the prospects for fuel cell system commercialization. There are still large technical barriers to be solved but these might well be overcome over the next 5-10 years through massive efforts underway at the major fuel cell and automobile manufacturers. However, there are other issues that are beyond the control of any single manufacturer. Wide spread deployment of FCEVs will require continuous strong support and a long term commitment from government agencies in resolving there issues. These include timely availability of adequate and affordable hydrogen refueling, as well as need for a host of sustainable financial incentives to help minimize the capitalization risks of all key stakeholders during the early years of initial commercialization of hydrogen powered FCEVs.

5. Vehicle Integration – Automotive Manufacturers

The status and prospects of vehicle integration of zero emission vehicles (ZEVs) by ten major original equipment automotive manufacturers (OEMs), as well as their advanced technology vehicles (ATVs) that could have synergistic benefits supportive to the introduction of ZEVs, are summarized below. In addition to vehicle technical considerations, vehicle business considerations (e.g., manufacturing cost, capital investment, marketability, etc.) also are addressed, in order to forecast the future prospects, introduction timing, and volume milestones of the ZEV and ATV technologies.

A. Full Performance Battery Electric Vehicles (FPBEVs)

Full Performance Battery Electric Vehicles are defined in this report as BEVs fully capable of high speed U.S. urban/suburban freeway driving.

Despite substantial technology progress, prior efforts to introduce FPBEVs were unsuccessful due to high manufacturing cost (primarily the battery) and limited mass market customer acceptance due to limited range and long recharge time, and there has been little progress since. Specifically, the large batteries required to provide the necessary driving range, as well as an acceptable “cushion”, remain very expensive.

Higher fuel prices and less demanding driving conditions in Japan and Europe provide lower barriers to success and as a result a few OEMs are developing small FPBEVs with Li Ion batteries for these markets, and they may bring them to the U.S. as niche vehicles.

It is the Panel’s opinion that FPBEVs are not likely to become mass market ZEVs in the foreseeable future due to the high cost for the battery not being recoverable with fuel cost savings and limited customer acceptance due to range and recharge time issues.

B. City Electric Vehicles (CEVs)

City Electric Vehicles are defined in this report as BEVs with limited acceleration and top speed (e.g. 50/60 mph) and thus not suitable for high speed U.S. urban/suburban freeway driving, although at present they must meet all Federal Motor Vehicle Safety Standards (FMVSS) requirements. These performance limitations allow a smaller size battery and lower power electric drive system, so that the vehicle can have a lower manufacturing cost and thus be made more affordable to the customer.

Prior efforts to produce CEVs were unsuccessful due to high cost and limited mass market customer acceptance and there has been little progress since. A special CEV FMVSS similar in concept to FMVSS 500 (e.g., restrict CEVs from freeway driving, etc.) may help stimulate development in the U.S.

It is the Panel’s opinion that CEVs are more likely to become future mass market ZEVs in Japan and Europe than in the U.S. due to performance limitations.

C. Neighborhood Electric Vehicles (NEVs)

Neighborhood Electric Vehicles are defined in this report as BEVs capable of top speeds between 20 and 25 mph that meet FMVSS 500 and are limited to roads with posted speeds of

35 mph or less.

NEV technology appears to be commercially successful but has low volume potential due to limited applicability. Also, because they use very simple technology, NEVs have very little synergy with larger BEVs.

It is the Panel’s opinion that NEVs provide no significant technical benefits to future mass market ZEVs due to their simple technology and performance limitations.

D. Hybrid Electric Vehicles (HEVs)

HEVs have no customer compromises and therefore appeal to mass market customers willing to pay a premium. While producers are driving down the costs of electric drive components and systems, high manufacturing cost is still an issue. However, OEMs are introducing many new entries, despite the cost issue, mostly for competitive reasons. Overall, HEV sales volume rises and falls with the price of gasoline – making future growth forecasts uncertain.

It is the Panel’s opinion that HEVs, due to their success, are providing major support to future mass market ZEVs by continuing to stimulate advances in electric drive systems, electric accessories, and battery technologies. Also, they are increasing customer awareness of electric drive technology and the associated benefits.

E. Plug-in Hybrid Electric Vehicles (PHEVs)

PHEVs have no expected customer compromises while promising several benefits to customers and society. The relatively small battery capacity can be fully used daily for maximum customer fuel savings payback of the initial vehicle premium.

Recently, some OEMs have become interested in PHEVs, and GM and Ford have shown concept PHEVs at recent auto shows and other events – which is attracting major media attention and establishing high consumer expectations.

However, definitions and fuel economy/emissions testing standards do not yet exist and need to be agreed upon. Also, All Electric Range (AER) could have a major impact on manufacturing cost, as well as capital investment requirements if unique and more powerful electric drive systems are necessary, and therefore AER could have a significant impact on the early success of the technology.

Despite the fact that recent auto show PHEVs appeared to require new platforms, it may be more likely that OEMs will want to derive early PHEVs from existing HEVs in order to minimize capital investment and the associated business risk. For the same reason, blended AER, as opposed to EV mode, may be more likely in early products.

It is the Panel’s opinion that PHEVs have the potential to provide significant direct societal benefits and are likely to become available in the near future. They may foster future mass market BEVs by stimulating energy battery development and conditioning mass market customers to accept plugging in.

F. Fuel Cell Electric Vehicles (FCEVs)

FCEVs are considered the ultimate solution by several OEMs with massive R&D efforts underway. However, simultaneously achieving performance, durability and cost objectives with FCEVs continues to be very difficult.

The cost, weight, and volume of adequate vehicle hydrogen storage and availability of a hydrogen infrastructure are major issues.

Plug-in series hybrid FCEVs operating "steady state" have potential to simultaneously achieve performance, durability and cost objectives.

It is the Panel's opinion that with the past rate of success and the massive intellectual and financial resources being devoted to this technology, FCEVs continue to be a promising candidate for a future mass market true ZEV.

G. Hydrogen Internal Combustion Vehicles (H2ICVs)

H2ICV technology is not widespread and is only being pursued by two OEMs – BMW and Ford. This technology entails fairly simple conversions of conventional powertrains, with relatively low manufacturing costs and capital investment requirements. However, the hydrogen issues are the same for infrastructure and worse for onboard storage than for FCEVs. Also, while they have very low emissions, H2ICVs are not true ZEVs.

It is the Panel's opinion that H2ICVs could provide minor benefits to future mass market ZEVs (FCEVs), limited to onboard vehicle hydrogen storage and hydrogen infrastructure, but the Panel also cautions that if the relative incentives change there could be a shift in resources away from FCEV development to fund H2ICVs.

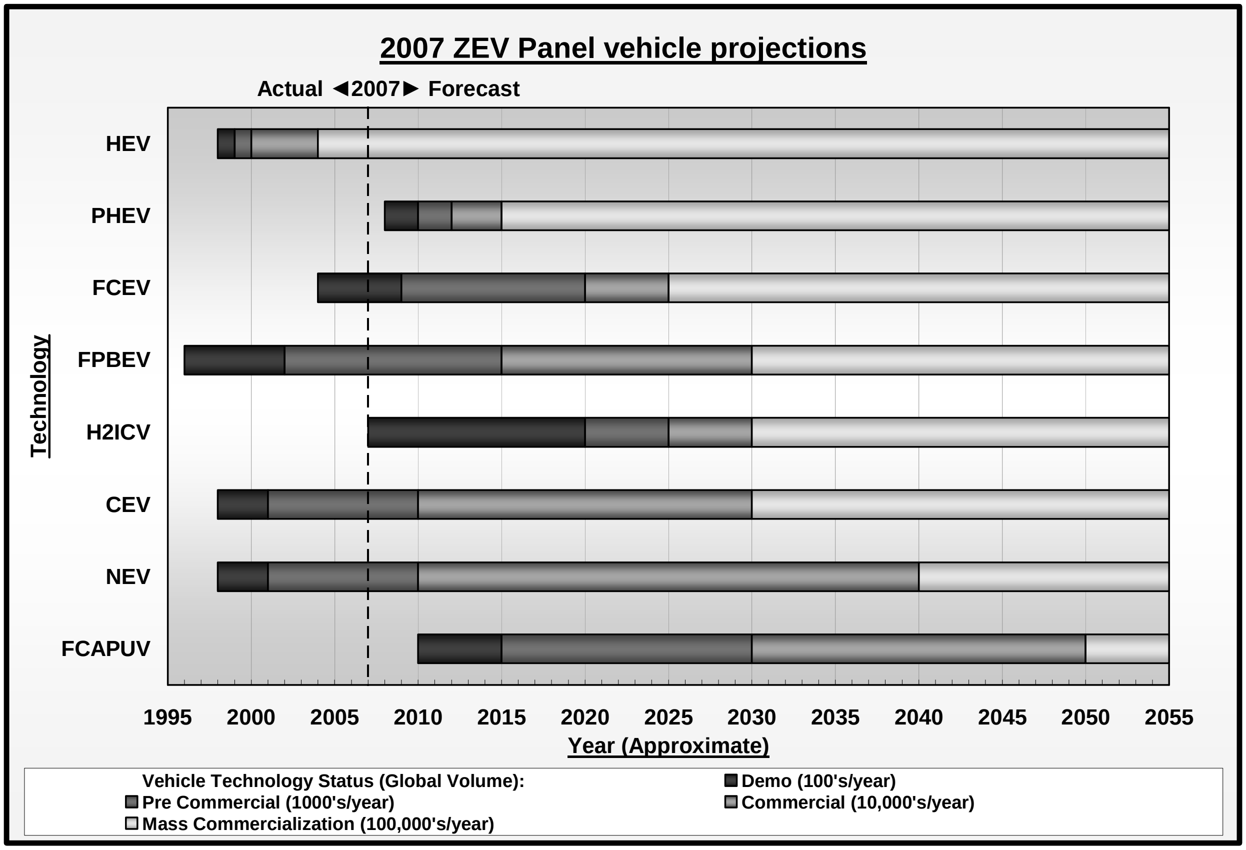
H. Fuel Cell Auxiliary Power Unit Vehicles (FCAPUVs)

FCAPUV technology is not widespread and is only being pursued by one OEM – BMW. The Hydrogen Proton Exchange Membrane (PEM) system in a H2ICV is the most likely application but this is operationally different from a FCEV.

It is the Panel's opinion that FCAPUVs are unlikely to provide any significant benefits to future mass market ZEVs.

6. Overall Conclusions: The Prospects of ZEVs

The bottom line question posed to the Panel by the ARB was "what is the approximate timeframe in which the Panel expects the various ZEV and ZEV enabling technologies to achieve the Demonstration stage (100s of vehicles per year), Pre-Commercialization (1000s of vehicles per year), Early Commercialization (10,000s of vehicles per year) and finally Mass Commercialization (100,000's of vehicle per year). Of course, a precise answer to this question is very difficult as it depends upon many factors which are impossible to foresee at this time. The chart below reflects the Panel's consensus projection on global volumes, based on today's automotive environment, including the present ZEV regulations, and barring any sudden and unanticipated major trigger events (e.g., scientific breakthroughs, trends and actions such as further major increases in gasoline taxes (U.S.) and/or reduced gasoline availability driven by major disruptions in petroleum supply, increasingly dramatic evidence of climate change, war, terrorism, etc.):



The Panel suggests that these time projections while necessarily uncertain regarding the exact years of implementation carry somewhat greater confidence in the relative timing of these technologies for the reasons outlined in this report and briefly summarized here:

> *The Panel's projection is that PHEVs with modest energy storage capacity will be derived from HEVs and will proliferate rapidly, stimulating further development and cost reduction of energy batteries and leading to commercially viable PHEVs and, in the longer term, FPBEVs. While PHEVs will continue to grow rapidly, as they have no functional limitations, FPBEVs will grow more slowly due to customer acceptance of limited range and long recharge time. NEVs are commercially viable now and will continue to grow, but will grow slowly due to limited functionality. CEVs will become commercially viable in Japan and Europe in the not too distant future due to lower hurdles for BEVs to overcome. CEVs may be offered in the U.S. as energy batteries continue to mature, but growth will be slow due to functional limitations of BEVs in general, and the specific limitations of CEVs, especially urban freeway driving. The intense effort on FCEVs will result in technically capable vehicles by the 2015 to 2020 time frame, but successful commercialization is dependent on meeting challenging cost goals and the availability of an adequate hydrogen infrastructure. If that happens, FCEVs will grow rapidly, followed by some H2ICVs, and some H2ICVs with FCAPUs.*

As a long term ZEV outcome, the Panel can envision plug-in hybrid FCEVs, powered by sustainable electricity for shorter trips and sustainable hydrogen for longer trips.

Glossary of Terms, Abbreviations and Symbols:

APU	auxiliary power unit
ARB	Air Resources Board (California, CARB)
ATPZEV	Advanced Technology Partial Zero Emission Vehicle
BEV	battery electric vehicle
CEV `	city electric vehicle
CH2	compressed hydrogen
CNG	compressed natural gas
CO	carbon monoxide (contributor to air pollution)
CO2	carbon dioxide (greenhouse gas)
Cold FTP	driving schedule conducted in 20°F ambient temperature (part of fuel economy label value for 2008 MY vehicles)
Combined	vehicle fuel economy – prior to 2008 MY: harmonic average of FTP and HFET weighted 55/45% respectively; can be applied to adjusted values or unadjusted values ("C-H", "M-H")
Consumption	vehicle fuel consumption – quantity of fuel or energy consumed divided by distance traveled (e.g., litres/100 kilometers, Wh/mile)
CVT	continuously variable transmission
CY	calendar year
DOD	depth of discharge (battery)
DOE	United States Department of Energy
DOT	United States Department of Transportation
Economy	vehicle fuel economy – distance traveled divided by quantity of fuel or energy consumed (e.g., miles/gallon, miles/kWh)
EDF	Electricitè de France
Efficiency	output energy divided by input energy, expressed as a percentage
EPA	United States Environmental Protection Agency
EPRI	Electric Power Research Institute
ETS[1]	electrical traction system (direct current to torque out)
EV	electric vehicle
FC	fuel cell
FCAPU	fuel cell auxiliary power unit
FCAPUV	fuel cell auxiliary power unit vehicle
FCEV	fuel cell electric vehicle
FCPS[1]	fuel cell propulsion system (hydrogen fuel in to torque out)
FCS[1]	fuel cell system (fuel cell stack + balance of plant for H2, air, coolant supply)
FPBEV	full performance battery electric vehicle
FMVSS	Federal Motor Vehicle Safety Standards
FTP	Federal Test Procedure; UDDS followed by first 505 seconds of UDDS ("FTP75", "EPA75")
GVWR	gross vehicle weight rating
H2	hydrogen
H2ICV	hydrogen internal combustion vehicle
HC	hydrocarbons (contributors to air pollution)
HEV	hybrid electric vehicle
HSS[1]	hydrogen storage system
HFET	Highway Fuel Economy Test (dynamometer driving schedule)
ICE	internal combustion engine

ISO	International Organization for Standardization
Label	vehicle fuel economy – prior to 2008 MY: city label = FTP x 0.9; highway label = HFET x 0.78 (“window sticker”)
LEV	low emission vehicle
LH2	liquid hydrogen
LHV	lower heating value (for calculating energy content of fuels used in vehicles)
Li Ion	lithium ion (battery)
Mass-Market	buyers that make up the majority of the (automotive) customer base, primarily interested in price/value/convenience, not hobbyists/enthusiasts
METI	Japanese Ministry of Economy, Trade and Industry
MY	model year
n/a or n.a.	not available (at publication of report)
NEV	neighborhood electric vehicle
NHTSA	National Highway Traffic Safety Administration (part of DOT)
NiMH	nickel-metal hydride (battery)
NOx	oxides of nitrogen (contributors to air pollution)
NREL	National Renewable Energy Laboratory (part of DOE)
OEM	original equipment automotive manufacturer
Panel	2006-2007 ZEV Technology Review Expert Panel (contractors to ARB)
PEM	polymer electrolyte membrane, or proton exchange membrane (fuel cell)
PbA	lead-acid (battery)
PHEV	plug-in hybrid electric vehicle
RESS[1]	rechargeable energy storage system (battery, ultra capacitor, flywheel, hydraulic)
SAE	Society of Automotive Engineers
SC03	driving schedule with air conditioning operating and 95°F ambient temperature (part of fuel economy label value for 2008 MY vehicles)
SMUD	Sacramento Municipal Utility District
SOC	state of charge (battery)
SULEV	super ultra low emission vehicle
TBD	to be determined (before finalizing report)
UDDS	Urban Dynamometer Driving Schedule (“LA4”, “city test”)
UEV	utility electric vehicle
ULEV	ultra low emission vehicle
US06	driving schedule containing aggressive acceleration and high speeds (part of fuel economy label value for 2008 MY vehicles)
USABC	United States Advanced Battery Consortium
USCAR	United States Council for Automotive Research
VESS	vehicle energy storage system (section 3)
VFCS	vehicle fuel cell system (section 4)
VHSS	vehicle hydrogen storage system (section 5)
V2G	vehicle to grid (discharging electric vehicle battery energy into electric grid)
VOC	volatile organic compound (contributor to air pollution)
ZEV	zero emission vehicle

1. ISO term (electric vehicles)

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MAIN REPORT

1. Introduction

At the 2003 Zero Emission Vehicle (ZEV) Regulation hearings, the California Air Resources Board (ARB) directed staff to establish an independent expert review panel (Panel) to examine the status of ZEV technologies and to advise the Board. The Panel was constituted in early 2006 and began work in May 2006. The overall objective of the Panel is to provide a thorough and accurate portrayal of the current status of sustainable zero emission vehicle technologies and the prospects for ZEV technology advancement in both the near-and long-term. The Expert Panel is not considering specific changes to the ARB ZEV Regulation but rather is focused on providing independent advice on the status of technologies.

2. Work Program and Process

In many ways the Panel is similar to previous panels which have been asked to provide independent expert advice to the Board (Kalhammer 1995, Kalhammer 1998, Kalhammer 1999, Anderman 2000) but with a notable distinction regarding the breadth of the scope of the study. Rather than focusing on one technology, i.e., fuels cells or batteries, this study broadly reviews all ZEV, near ZEV and partial ZEV technologies.

Special emphasis in this review is on timing and cost projections from the technology developers and OEMs. In particular, the Panel was asked to address the following questions:

- When will ZEVs achieve a level of automotive-industry technical maturity necessary for deployment at the following U.S. industry-wide production levels:
    - 100’s (demonstration),
    - 1,000’s (pre-commercialization),
    - 10,000’s (early commercialization), and
    - 100,000’s (commercialization)?
- What are the projected manufacturing costs at each of the above production levels?
- Does the deployment of ZEV technologies in Advanced Technology (AT) non-ZEVs accelerate the development and affordability of these components so that ZEVs can be deployed sooner? At what sales volumes does each of these AT “bridge” technology vehicles continue to provide significant improvement in the performance and affordability of components needed for ZEVs?

The Panel’s work was organized into four key tasks:

A. Acquisition of information

From early May into December, the Panel was engaged in an intensive effort to gather information on ZEV technology status, key technical issues, current and prospective materials and manufacturing costs and plans for evaluation/demonstration and commercialization of various ZEV technologies. ZEV technology topics which the Panel emphasized included:

- On-vehicle hydrogen storage technologies

- Automotive Fuel cell technologies (both vehicle & vehicle APU) and including balance of plant (BOP) components.
- Batteries (both power and energy)
- Electric drive systems, and
- Automotive platform issues:
    - Transition from low volumes to mid-high production volumes
    - Ground-up VS conversion ZEV design considerations,

For application in:

- Fuel Cell Vehicles (FCVs),
- Battery Electric Vehicles (BEVs), and
- Advanced Technology non-ZEVs, including:
    - Plug-in hybrids, &
    - Hydrogen combustion engine vehicles

This information was collected by soliciting responses to a series of questionnaires that were developed by the Panel (See Appendices A, B, C, D and E) and through visits with all of the key sources, including the leading developers of the components as well as the major OEMs. A listing of companies or organizations visited is contained in Appendix F. Multiple site visits took place with some companies and many companies and organizations were asked follow up questions after the visits were completed.

B. Critical assessment

The information collected by the Committee members underwent a thorough, careful and critical assessment in an effort to fully understand and accurately portray the current and likely near term state of the art. Information from the various sources was compared and contrasted and where gaps or discrepancies were identified was followed up in an effort to reconcile the information.

It is important to note, however, that at the end of the day the assessment relied as it had to on the data provided. While a great deal of new (at least to the Panel) and valuable information was provided, some questions and requests for information remained unanswered in spite of numerous requests. Where possible, the Panel provided interpretation and in some cases extrapolation from the information it received to support its projections and assessments.

C. Reports at Public Meetings

The Panel presenting a status report of the panel's work at ARB's ZEV Technology Symposium in September of 2006 and is preparing to provide the Panel's conclusions directly to the Board at a 2007 hearing.

D. Final Report

The Panel's key findings and conclusions are documented in this Final Report. Sections of this report were circulated in draft form to most information sources to assure accuracy and to prevent the inadvertent inclusion of information given to the Committee in confidence.

3. Vehicle Energy Storage Systems

A. Background and Scope

Energy storage is fundamental to electric, hybrid electric and plug-in hybrid electric vehicle operation, and it has proven instrumental to achieving efficient practical operation of fuel cell vehicles. The prospects for large-scale introduction of these vehicles and realization of their zero/near-zero emission benefits are tied closely to the availability of energy storage systems that provide high performance, are durable and safe, and meet severe cost constraints.

Systematic efforts to meet these demanding requirements through development of improved batteries have been undertaken repeatedly for more than thirty years. Since the early 1990s, the United States Advanced Battery Consortium (USABC) has led a large cooperative government-industry program to develop more advanced battery technology, first for electric vehicle applications and since the mid-1990s for hybrid electric vehicles. In 2000, the Battery Technical Advisory Panel (BTAP 2000) chartered by the California Air Resources Board reviewed progress and assessed the status of nickel metal hydride (NiMH) and lithium ion (Li Ion) batteries, the two energy storage technologies that had received much of the USABC development support and were considered the most promising choices for full performance battery electric vehicle (FPBEV) and hybrid electric vehicle (HEV) applications.

The BTAP 2000 panel concluded (Anderman, 2000) that NiMH batteries were likely to meet the power and endurance requirements for FPBEVs. However, batteries limited to an acceptable fraction of EV total weight would limit FPBEV range on a single battery charge to approximately 75 to 100 miles in real world driving. The cost of such a battery was estimated to exceed approximately $10,000 if produced at the level of 10-20k battery systems per year, $7,000 in mass production (100k or more systems per year). Li Ion batteries were seen to meet power requirements at reduced weight and thus to offer promise for increased FPBEV range. However, Li Ion technology appeared handicapped by inadequate calendar life (typically only 2-4 years) and by sensitivities to abuse tests intended to simulate battery safety behavior. Moreover, Li Ion battery cost was projected to be even higher than that of NiMH batteries; at least until substantially less expensive battery materials and mass production were achieved.

The BTAP 2000 panel also observed that leading advanced battery developers were achieving rapid progress in developing high power NiMH battery technologies for the hybrid electric vehicles under development at several OEMs. HEV battery technology advancement was seen to benefit directly from the years of FPBEV battery development. Conversely, the successful commercialization of HEVs was expected to lead to continued improvements of advanced battery technologies, including technologies for possible future FPBEV applications.

Six years later, high power NiMH batteries are commercially produced in Japan on a large scale for the rapidly growing numbers and types of HEVs, and high power Li Ion battery technologies of much improved endurance are emerging from companies in Japan, Europe and North America. Several of these are being considered for commercial introduction in HEVs possibly beginning in 2008, and advances in battery chemistry and technology are rekindling interest in Li Ion batteries for BEV propulsion. At the same time, the emergence of the plug-in hybrid electric vehicle (PHEV) as a partial ZEV option and possible bridge to more competitive BEVs and fuel cell-electric vehicles (FCEVs) is creating substantial interest in batteries with energy and power characteristics intermediate to those of FPBEV and HEV batteries.

Because these positive developments bear directly on the prospects of ZEV and near (including partial) ZEV technologies, an assessment of battery status and prospects is one of the key tasks established for this Panel by the California Air Resources Board. The Panel decided to center its assessment of vehicle energy storage systems on lithium ion batteries that promise to meet the energy storage requirements of FPBEVs, PHEVs and FCEVs. Nickel metal hydride battery progress and prospects for PHEV applications also were assessed, as were a limited number of battery technologies with significant near- and/or longer-term promise to meet ZEV requirements.

Among candidate technologies, the emphasis was on those now in low volume production or, at least, available from laboratory pilot facilities and tested in prototype or experimental vehicles. In the Panel's view, advanced batteries that have not reached this stage are unlikely to be available in commercial quantities in the nearer term.(e.g., within the next 3-5 years), However, information is presented on one battery type that is in an earlier state of development but might have longer term potential especially for FPBEV applications if successfully developed.

To the extent possible, up to date technical information and cost projections were obtained from manufacturers and developers of candidate battery technologies. This information base was supplemented with pertinent information obtained from expert individuals and groups at OEMs, National Laboratories and private organizations active in advanced battery testing and evaluation.

The Panel's review of vehicle energy storage systems is organized in four main subsections. In Section 3.B, the energy storage functions, technical requirements and cost constraints for electric and hybrid (including fuel cell hybrid and plug-in hybrid) electric vehicles are discussed to provide context for the subsequent review and assessment of candidate battery technologies. Section 3.C summarizes the battery technical information collected by the Panel. Prospective costs of candidate batteries are discussed in Section 3.D, and Section E reviews candidate manufacturers and the availability from them of batteries for ZEV, near-ZEV and partial ZEV applications. Finally, Section 3.F summarizes the Panel's overall assessment of ZEV and near-ZEV battery status and prospects, and it presents information on the strategies and views of battery and OEMs pertinent to the prospects of ZEV and near-ZEV batteries.

B. Vehicle Energy Storage Requirements

The primary functions and capabilities provided by the storage systems of electric vehicles and the main types of hybrid electric vehicles are summarized in Table 3-1.

Table 3-1: Vehicle Functional Capabilities Provided by Energy Storage

Vehicle Type	Functional Capabilities
Micro HEV	Automatic start and stop *plus* regenerative braking
Mild HEV	Micro HEV capabilities *plus* power assist to vehicle IC engine
Full HEV	Mild HEV capabilities *plus* electric launch
Plug-in HEV	Full HEV capabilities *plus* electric range with grid-charged electricity
FPBEV	Exclusively electric propulsion power *and* energy (grid-charged)

With increasing vehicle functional capabilities the vehicle energy storage system needs to deliver increasing amounts of electric power and energy. These increases are determined almost entirely by the vehicles' *incremental* capabilities (see Table 3-1), as shown in recent analyses of mid-size HEV architectures (Deiml, 2005) and PHEV designs (Duvall, 2001).The energy storage system of fuel cell hybrid electric vehicles provides additional functions but the performance requirements are generally similar to those of full HEVs.

The following discussion of energy storage requirements is limited to full (fuel cell) HEVs, FPBEVs and PHEVs, the vehicle types that operate as ZEVs all or part of the time.

1. Performance

Table 3-2 summarizes the energy storage power and energy requirements derived from the analyses of, Deiml and Duvall, respectively, with the assumptions given in the footnotes and discussed below. They are generally consistent with the goals established by the United States Advanced Battery Consortium (USABC) and by the FreedomCar Program for FPBEV and HEV batteries, respectively, see also Section 6.A.i (2) further below.

Table 3-2: Vehicle Energy Storage System Performance Requirements

EDV Type	Weight (max. kg)	Peak Power (min. kW)	Power Density (min. W/kg)	ES Capacity (min. kWh)	Energy Density (min. Wh/kg)
Full HEV	50[1]	40[1]-60	800-1200	1.5-3 [0.7][2]	30-60
Plug-in HEV[3]	120	65[4]; 50[5]	540[4]; 400[5]	6[4]; 12[5]	50[4]; 75[5]
FPBEV	250	50[6]; 100[7]	200[6]; 400[7]	25[6]; 40[7]	100[6]; 160[7]

[1] Data taken from Deiml (2005)

[2] Minimum energy required to perform the electric launch function

[3] PHEV data derived from Duvall (2001) are considered preliminary

[4, 5] Requirements for midsize passenger PHEVs with nominal electric ranges of 20 and 40 miles, respectively

[6, 7] Requirements for small and midsize FPBEVs, respectively, with weight, performance and accommodations comparable to similar size ICEVs

For full HEVs, battery capacities need to be several times larger (see Table 3-2) than the minimum energy required for vehicle electric launch because energy must be delivered at high power that reduces available energy. Also, on occasion the battery must provide energy repeatedly within relatively short periods during which insufficient battery charge is restored by the engine and regenerative braking.

For PHEVs, the required battery capacities are substantially larger than for full HEVs; actual capacity will be determined by the specified nominal electric ranges. During normal PHEV operation the battery is being discharged continuously until its state of charge (SoC) has declined to a predetermined level. When that level is reached, the PHEV control system switches vehicle and battery operation to the HEV (“charge-sustaining”) mode. In that mode, the PHEV battery is subject to small swings in SoC, generally less than 50Wh, or less than 1% of capacity even for a 6kWh PHEV battery (Table 3-2). PHEV batteries must meet peak power requirements even at the lowest SoC they experience, often set at 20% SoC to prevent excessively deep discharges that could compromise battery life.

FPBEVs need much larger battery storage capacities for practical driving ranges, and the highest practical gravimetric and volumetric energy densities are desired for acceptable battery weight and volume. Because of the larger weight of FPBEV batteries, gravimetric power densities can be lower than for other advanced technology vehicle batteries yet still enable sufficient battery peak power. However, as with PHEV batteries peak power must be sufficient to meet vehicle minimum power requirements down to low SoCs (e.g., 20%). Another key requirement for all advanced-technology vehicle applications is that batteries meet peak power and storage capacity requirements at the lowest operating temperatures they experience in practical applications.

Table 3-2 makes clear that full HEV applications pose the most demanding requirements for high *power* density of batteries while FPBEVs demand the highest possible *energy* density. Battery designs for different PHEVs must be optimized for intermediate but different levels of power and energy. The common driver for these requirements is the desire to minimize battery weight, volume and cost.

2. Life

a) Cycle Life

Batteries deteriorate in operation due to the cumulative changes of the structure and composition of key battery *cell* components caused by charge-discharge cycling. Battery cycle life – the number of cycles before battery performance has degraded to a predetermined level – is a measure of a battery's ability to withstand these changes. The key requirement for the cycle life of HEV, BEV and PHEV batteries is that they retain a high fraction (often taken as 80%) of their original power and energy delivery capabilities over the life of the vehicle. In the past, a nominal vehicle life of 10 years was used to set battery cycle life requirements. More recently, USABC has adopted a 15-year life goal for its battery development program, consistent with the 15-year life requirement established by the California Air Resources Board for ZEV technologies.

Batteries for HEV applications must tolerate a large number of shallow charge-discharge cycles because of the numerous power assist, braking and recharge events that occur over the vehicle life. BEV batteries, on the other hand, must be able deliver a large number of deep discharge-full recharge cycles to maximize the vehicle miles delivered by the battery over its lifetime. In addition, they must tolerate the many recharges imposed by regenerative breaking, but because individual recharges are very small (typically less than 0.2% of capacity) for a single braking event, their effect on battery life can normally be neglected.

PHEV batteries are deep-discharged like BEV batteries, but they are expected to experience a larger number of deep cycles because their smaller capacity is likely to be used more often. PHEV batteries must be able to sustain a large number of shallow charge-discharge cycles although fewer than HEV batteries, but only a fraction of these cycles occur at low SoC (e.g., 20%), and SoC swings will be less than 1% of capacity. The stresses imposed by these cycles (and those at higher SoCs) are much less than those on HEV batteries and thus are unlikely to limit PHEV battery life.

Table 3-3 summarizes approximate cycle life requirements for HEV, PHEV and FPBEV batteries.

Table 3-3: Battery Cycle Life Requirements[1]

Vehicle Type	Deep Cycles		Shallow Cycles
	Energy[2] (MWh)	Number[3] @80%DoD	Number[4] @ 50Wh[5]
Full HEV	n.a.	n.a.	200k [300k]
PHEV-20	~12 [~17]	2400 [3500]	fewer than full HEV
PHEV-40	~17 [~25]	2300 [3400)	fewer than full HEV
Battery EV	~32[6]	1000 [1500]	fewer than full HEV

[1] for battery operation over a 10-year life [15-year life and total energy delivery requirements in brackets]

[2] energy delivered by battery over its life time in form of deep discharges

[3] number of equivalent 80% DoD cycles to be delivered by battery over its life time
[4] number of shallow cycles to be delivered by battery over its life time
[5] maximum energy to be delivered by battery in single pulse
[6] for mid-size FPBEV with 40kWh battery discharged to 20%SoC

The cycle life requirements for HEV and FPBEV batteries were developed by USABC from analyses of representative vehicle driving patterns. The PHEV battery deep cycling requirements shown in Table 3-3 were derived (Duvall 2001) from the statistical distribution of the daily distances driven by U.S. automobiles, under the assumptions that PHEVs are operated to maximize daily use of propulsion energy from the battery, and that PHEV batteries are fully recharged after each day of operation. From these inputs, the total DC electric energy delivered by the batteries over a 10 year (respectively 15 year) period shown in Table 3-3 can be determined. Dividing these totals by the maximum battery capacities used (80% of 6kW and 12 kWh, respectively) results in the equivalent numbers of 80% depth-of-discharge cycles to be delivered by the batteries over their service life, see Table 3-3.

PHEV can also be operated in the so-called “blended” (EV-HEV) mode where the internal combustion engine is allowed to turn on in response to power demand above a preset level while the battery continues to be discharged until 20% SoC is reached. In the blended mode, the battery will experience fewer deep cycles over 10 and 15 years than in the strategy to maximize use of electricity. Thus, the deep cycling requirements shown in Table 3-3 for PHEV batteries are conservative, even more so because batteries are unlikely to be discharged to 20% SoC every day, and the amount of energy delivered by a battery over its life increases as the depth of discharge decreases.. As discussed in the Battery Technologies subsection below, this effect is observed with both Li Ion and NiMH batteries and can benefit the cycle life of both, PHEV and FPBEV batteries.

b) *Calendar Life*

Batteries also can deteriorate through undesirable chemical reactions between battery cell materials, whether the battery is being cycled or not. The general effect of these reactions is to degrade one or more of the cell’s functional components and thereby the battery’s energy storage and/or peak power performance. Battery degradation processes are specific to the type of battery and the materials used in it. They tend to be complex and their control through choice of appropriate designs, materials and operation is almost always difficult. The challenges and prospects of achieving the 10-15 year calendar life essential for cost/economic viability is discussed in Section 3.3, with emphasis on the life prospects of lithium ion batteries.

3. Safety

Batteries present potential hazards if the energy they store and the chemicals they contain are released rapidly and in an uncontrolled way outside the battery containment. Depending on the specific battery chemistry, such releases can be caused by shorting, sustained and/or rapid overcharging or excessive heating of batteries. These abuses can occur only if the generally hierarchical electric, thermal and mechanical controls used to assure the safety of batteries in BEV, HEV or PHEV applications fail.

The maximum amount of energy dissipated as heat in a battery by a short circuit is determined by the maximum (electrochemical) energy storage capacities required for the specific application, independent of technology. These capacities range from about 1 kWh for a partially charged HEV battery to about 40kWh for a fully charged FPBEV battery. The corresponding energies are the equivalent of approximately 1/40 to at most 1 gallon of gasoline. As long as there is no rupture of battery cells by the heat generated in a short circuit or no propagation of cell rupture through the battery, shorting is not normally a truly hazardous abuse of batteries although it can damage the battery.

Excessive overcharging of most types of batteries can result in gas evolution within battery cells, rupture of pressure release devices and release of gases, some of them flammable. For some battery types, overcharging can cause progressive heating and a thermal "runaway" condition of continued heat evolution even after the triggering event is terminated. However, if the battery materials react only with each other inside the battery enclosure, heat release is limited to the amount above.

The maximum amount of heat that can be released by a battery is given by the total heat of combustion of all battery components. That heat is different for different battery types but generally exceeds the electrochemical energy content of a battery several times. However, this heat is released only through exposure of all battery materials to air and their subsequent complete combustion, an event that is exceedingly unlikely unless the entire battery is immersed in a hot fire. Even in that event, combustion and heat release would likely be gradual rather than explosive because of the gradual penetration of air and propagation of combustion into the densely packed battery cells.

Different battery technologies differ substantially in the mechanisms, materials and energy amounts involved in uncontrolled releases of energy and chemicals. Specific considerations pertaining to safety of the battery technologies reviewed by the Panel are presented in Section 3.C further below.

4. Costs

The high costs of batteries have been one major impediment to the introduction of electric vehicles. Even the far smaller batteries of commercially available hybrid electric vehicles contribute substantially to their cost increment over conventional vehicles. High battery costs also are among the chief concerns surrounding the prospects of plug-in hybrid electric vehicles. Cost constraints are, therefore, a central consideration in the assessment of candidate battery technologies, and they continue to be key drivers in the development and commercialization of advanced batteries for ZEV and near-ZEV applications.

Table 3-4 summarizes cost goals established by USABC and the FreedomCAR program for the development of advanced FPBEV and HEV batteries, respectively. The table also includes a preliminary cost goal that is currently being discussed for PHEV batteries.

Table 3-4. Battery Cost[1] Goals

Vehicle Type	Battery Rating	Production Rate (Batteries/year)	Specific Capacity Cost[2] ($/kWh)	Specific Power Cost [3] ($/kW)
FPBEV	40 kWh	25k	<150 [< $6,000]	n.a.
HEV	25--40 kW	100k	n.a.	<20 [< $500 – $800]
PHEV	(10 kWh)	(100k)	(<300) [< $3000]	n.a.

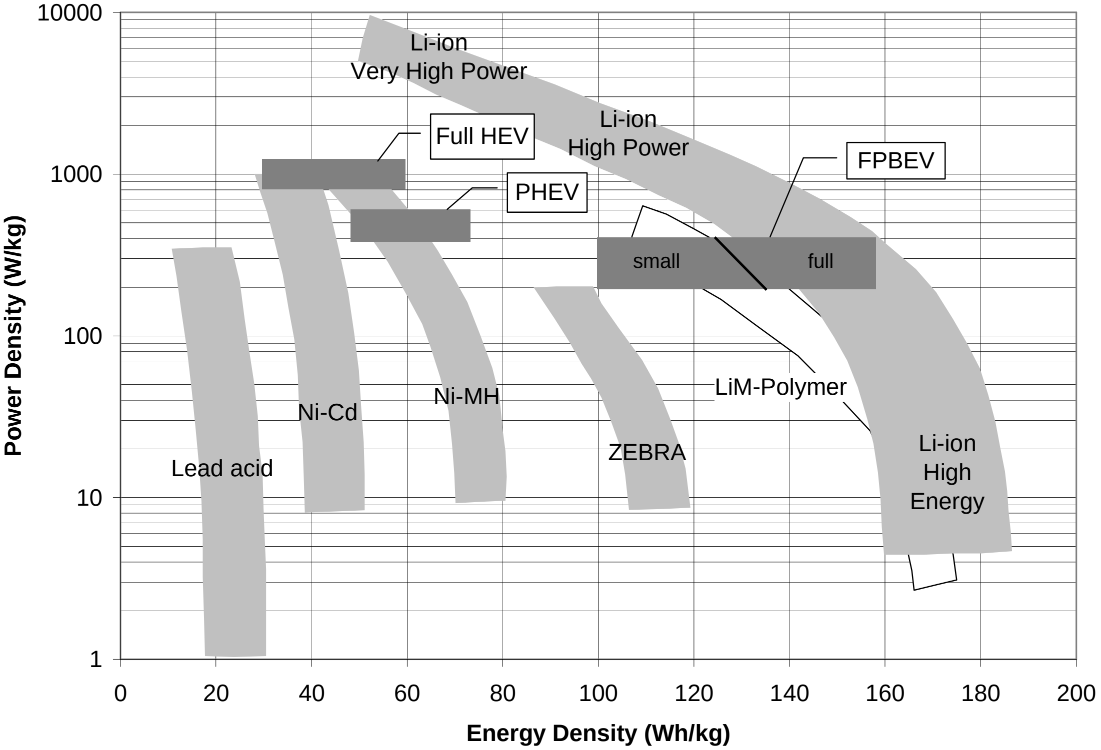
[1] selling Price to OEMs
[2] in brackets: cost goals for complete batteries of rated energy storage capacity
[3] in brackets: cost goals for complete batteries of rated peak power capability

No detailed derivation of the battery cost goals shown in the table has been published. However, the assumption underlying the goals of USABC and the FreedomCar program is that, if achieved, battery costs would permit market introduction of FPBEVs and HEVs.

C. Battery Technologies: Status and Prospects

Only a few battery types have the potential to meet the combination of power and energy density requirements for full HEVs, PHEVs and FPBEVs, as illustrated in Figure 3-1.

Figure 3-1: Potential of Battery Technologies for HEV, PHEV and EV Applications



The figure shows (as rectangular domains) the approximate ranges of energy and power densities required for the batteries of the various advanced-technology vehicles, see Table 3-2. It also includes the general relationship between gravimetric power and energy densities for the battery types used or being considered for automotive applications. These so-called Ragone plots show that, for each type, batteries designed for high power densities have substantially lower energy densities than batteries optimized for high energy (FPBEV designs).

Whenever the performance domain for a specific vehicle type is below and to the left of the "Ragone" performance characteristic for a particular battery type in Figure 3-1, properly engineered versions of that battery type can be expected to meet vehicle power and energy requirements. The figure indicates that only lithium ion batteries can be designed to meet the performance requirements of small and midsize FPBEVs, all types of PHEVs, and full HEVs. As discussed further below, all other battery types either have restrictions with respect to their ZEV and partial ZEV applicability, or they require compromises with respect to battery weight and vehicle performance.

1. Lithium Ion Batteries: Characteristics

a) Cell Chemistry and Composition

As the lightest metal and most electronegative element, lithium is the most attractive negative electrode (anode) material for high energy batteries. However, high reactivity with water and with the solvents used in organic battery electrolytes prevented the use of lithium in rechargeable batteries until two important discoveries were made about 15 years ago: lithium can be inserted ("intercalated") electrochemically in carbon "host" materials, and a protective layer forms at the interface of the lithium-containing carbon with the organic electrolyte solvent when a cell is charged for the first time. Remarkably, this complex solid-electrolyte interface (SEI) layer prevents further attack of the electrolyte by lithium but allows passage of lithium ions during charge-discharge cycling. The host material forming the negative electrode in Li Ion cells is made from special grades of graphite and/or coke. Mixed with binders, these carbons are deposited on thin copper sheets that serve as conducting supports.

A variety of materials can be paired with carbon-based negatives in battery cells using organic electrolytes. Mixed with carbon for increased conductivity and with binders, these materials are deposited on thin aluminum sheets as conducting supports. Currently established positive electrode materials are listed in Table 3-5 and reviewed below in the context of current Li Ion battery technology.

Active Material Chemical Formula (discharged state)	Storage Capacity (mAh/g)	Nominal Voltage (Volt)	Stability at High T and SoC	Stability against Dissolution	Active Material Cost Range ($/kg)	Active Material Cost Range ($/kWh)
$LiCoO_2$	145	3.6	fair-good	very good	30-40	57-75
$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$	160	3.6	fair-good	very good	28-30	~50
$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	120 (200)	3.6 (3.9)	good	good[1]	22-25	~55 (~30)
$LiMnO_2$	100	3.9	very good	fair	8-10	~25
$LiFePO_4$	150	3.3	very good	very good[1]	16-20	~35

[1] when chemically stabilized

$LiCoO_2$. Lithiated cobalt oxide is the main component of the positive electrodes in Li Ion cells produced on a very large scale for consumer product applications. It has good storage capacity for lithium ions, adequate chemical stability and good electrochemical reversibility but is relatively more expensive per kWh of storage capacity than other oxides and thus not a good candidate for automotive applications of Li Ion batteries that are under severe cost constraints.

Li $(Ni_{0.85}Co_{0.1}Al_{0.05})_2$. Commonly termed NCA, this lithiated mixed oxide of nickel, cobalt and aluminum has become accepted for prototypical HEV, FPBEV and PHEV batteries. It approaches the favorable characteristics of $LiCoO_2$ at lower per-kWh costs.

Li $(Ni_{1/3}Co_{1/3}Mn_{1/3})$ O_2. Often termed NCM, this lithiated mixed oxide of nickel, cobalt and manganese is potentially less expensive than NCA. It can be charged to two cell voltage levels. At the higher voltage (e.g., 4.1-4.2 Volts), NCM yields excellent storage capacity and relatively low per-kWh cost but tends to degrade through dissolution of manganese; at lower voltage, capacity is substantially less and per-kWh cost is higher but stability appears adequate.

$LiMnO_2$. Lithium manganese spinel (denoted LMS in the following) is more stable than cobalt oxide and nickel oxide-based positives in Li Ion cells because the spinel crystal structure is inherently more stable and has no or little excess lithium ions in the fully charged state. Thus, it provides very little lithium for undesirable lithium metal deposition on the negative electrode in overcharge. Also, the threshold of thermal decomposition of the charged (lithium-depleted) material is at a considerably higher temperature than that of other positive electrode materials. Despite its lower specific capacity, the expected substantially lower per-kWh cost will make LMS attractive if the efforts to stabilize the material against electrochemical dissolution of its manganese content are successful.

$LiFePO_4$. Lithiated iron phosphate (olivine), denoted LFP in the following, is now being used successfully as a potentially lower cost positive electrode material. Due to its lower electrochemical potential, LFP has less tendency to oxidize the electrolyte solvent and thus is more stable, especially at elevated temperatures. Doping is used to increase the conductivity and stability of this promising material.

It is reasonable to assume that yet other materials will prove practical and may offer specific advantages in terms of cell voltage, electrochemical reversibility, chemical stability, and/or low cost.

The electrolyte used in Li Ion battery cells is a solution of a fluorinated lithium salt (typically $LiPF_6$) in an organic solvent, enabling current transport by lithium ions. Separators are usually microporous membranes made of polyethylene or polypropylene. Because of the low conductivity of organic electrolytes, adequate cell and battery power can be realized only with electrodes and separators that are much thinner than those used in aqueous-electrolyte batteries. The need for thin electrodes has made spiral winding of positive electrode-separator-negative electrode composites the preferred method for Li Ion cell fabrication, but flat cell configurations packaged in soft plastic (often matallized) enclosures are now gaining acceptance.

b) Advantages and Challenges

A key attraction of lithium-based batteries is the high cell voltage, the direct result of the highly negative potential of lithium. With currently used mixed oxide positives, Li Ion cell operating voltage range is approximately 2.75 to 4.2 volts. The nominal (average) discharge voltage is about 3.6 volts, and most of the usable cell capacity is delivered between 4.0 and 3.5 volts. With iron phosphate positives, the nominal cell voltage is about 3.4 Volts.

The high cell voltage is the fundamental reason for the high specific energy of Li Ion cells and batteries. High cell voltage also results in a smaller number of cells for a battery of given voltage, for reduced fabrication costs and increased reliability. The second basic advantage of the Li Ion electrochemistry derives from the small size of lithium which permits reversible electrochemical intercalation of lithium atoms into carbon-based negative electrodes with little structural stress and strain. Similarly, the very small lithium ion is readily and reversibly incorporated into a variety of host oxides that form the positive electrode. These characteristics are responsible for maintaining the integrity of both electrodes during charge-discharge cycling, a key requirement for long cycle life especially in deep-discharge cycling. As discussed further below, key technology advantages of Li Ion batteries are high power density and energy efficiency due to thin-cell construction and low self-discharge rate.

The main challenges encountered in the development of Li Ion technologies for practical applications also derive from the highly negative potential of lithium. It is a powerful driving force not only for the effectiveness of lithium as a negative electrode but also for its chemical reactivity within the cell. Only the formation of an SEI prevents continued, uncontrolled reaction of lithium with the electrolyte solvent and enables the controlled discharge and recharge of Li

Ion cells and batteries. Once formed as a protective thin layer, the SEI must be stabilized chemically and kept from growing thicker because of the associated irreversible declines of cell capacity (through loss of lithium) and of peak power (through growth of cell resistance). Proper choice of electrolyte solvents and additives, and keeping cell temperatures below approximately 45-50℃, are very important for stabilization of the SEI and achievement of practical calendar and cycle life.

Another key challenge is the sensitivity of Li Ion cells to overcharge that can result in chemical decomposition of positive electrode materials and the electrolyte, and/or in the deposition of metallic lithium at the negative electrode. These processes damage the cell and can result in hazardous conditions, including gassing and release of flammable electrolyte solvent vapors if the cell safety seal is breached by excessive gas pressure. To avoid overcharge, Li Ion batteries require accurate voltage control of every cell, unlike nickel metal hydride and other aqueous electrolyte batteries that can tolerate significant amounts and rates of overcharge.

Accurate and reliable control of cell voltage and temperature thus are critical requirements for achieving long life and adequate safety of Li Ion batteries for all uses, but especially so for automotive applications with their demands for very long battery life and high levels of safety.

2. Lithium Ion Batteries: State of the Art

a) Performance and Life

For more than a decade, prospective manufacturers have been developing Li Ion batteries for electric vehicles. A number of these efforts were terminated when the initiatives to introduce electric vehicles were abandoned earlier in this decade. However, some programs continued and resulted in the development of high or medium energy/medium power Li Ion technologies. Although none of these are commercially available as yet, a few have reached low-volume production of cells and in-vehicle evaluation of prototype batteries. Key characteristics of these technologies are summarized in Table 3-6 and reviewed below. Prospective costs and availability of batteries for EV and PHEV applications are discussed in subsections 3.D and 3.E further below.

Table 3-6. Status of Li Ion High Energy/Medium Power Cell and Battery Technologies

Manufacturer	JCS[1]	GAIA	LitCEL[2]	Lamilion[3]	Kokam[4]
Cell (Designation)	VL 45E/41M	HE/HP Series	EV Type	EV Type	HE/HP
Positive Electrode (Matl.)	NCA	NCA	LMS	NCM+LMS	NCM
Voltage (Volt)	3.6	3.6	3.85	3.6	3.7
Capacity (Ah)	45/41	60/45	50/33	13	100/40
Energy Density (Wh/kg)	150/136	150/105	136/142	>150	163/135
Energy Density (Wh/L)	314/286	380/284	270	270	340/285
Peak Power Density[3] (W/kg)	664/794	~900/~1500	1500	1300	~700/~1250
Power/Energy Ratio (1/h)	4.4/5.8	~6/~14	7.7	8.7	~4.3/~9
Cycle Life (Cyc. @% DoD)	>3200 (80)	~1000 (70)	~1000	>1400(100)	~3000
Calendar Life (years at RT)	>12	n.d.a.	n.d.a.	~10	>10
Development Status	LVP[5]	LVP	LVP	LVP	LVP
Battery (Application)	EV/PHEV	EV/PHEV	EV/PHEV	Small EV	EV/PHEV
Storage Capacity (kWh)	~24/15	22+/8.1	20/7.6	9.2[6]	~30/~5
Energy Density (Wh/kg)	90/94	115/74	118/117	~60 (~90[7])	~110/~100
Energy Density (Wh/L)	145/80	165/130	194/n.d.a.	n.d.a.	n.d.a.
Peak Power (kW)	55/87	50+/80	155/60	62	130/47
Peak Power Density (W/kg)	210/540	~250/730	912/917	~400 (620[8])	~490/~940
Power/Energy Ratio (1/h)	2.3/4.6	~2.2/~10	7.7/7.8	6.7	~4.3/~9.4
Weight (kg)	265/160	200/110	170/65	150 (100[5])	265/~50
Development Status	LVP; IVE[6]	LVP; IVE	LVP; IVE	LVP; IVE	LVP

[1] JCS is a joint venture of Johnson Controls, Inc. and SAFT

[2] Litcel is a wholly owned subsidiary of Mitsubishi; Litcel data are for 4-cell module; cells use stacked electrode construction and liquid electrolyte

[3] Lamilion is wholly owned by NEC

[4] Kokam cells use laminate of polymer electrolyte-separator film with electrodes

[5] low volume production

[6] two parallel strings of 96 cells in series

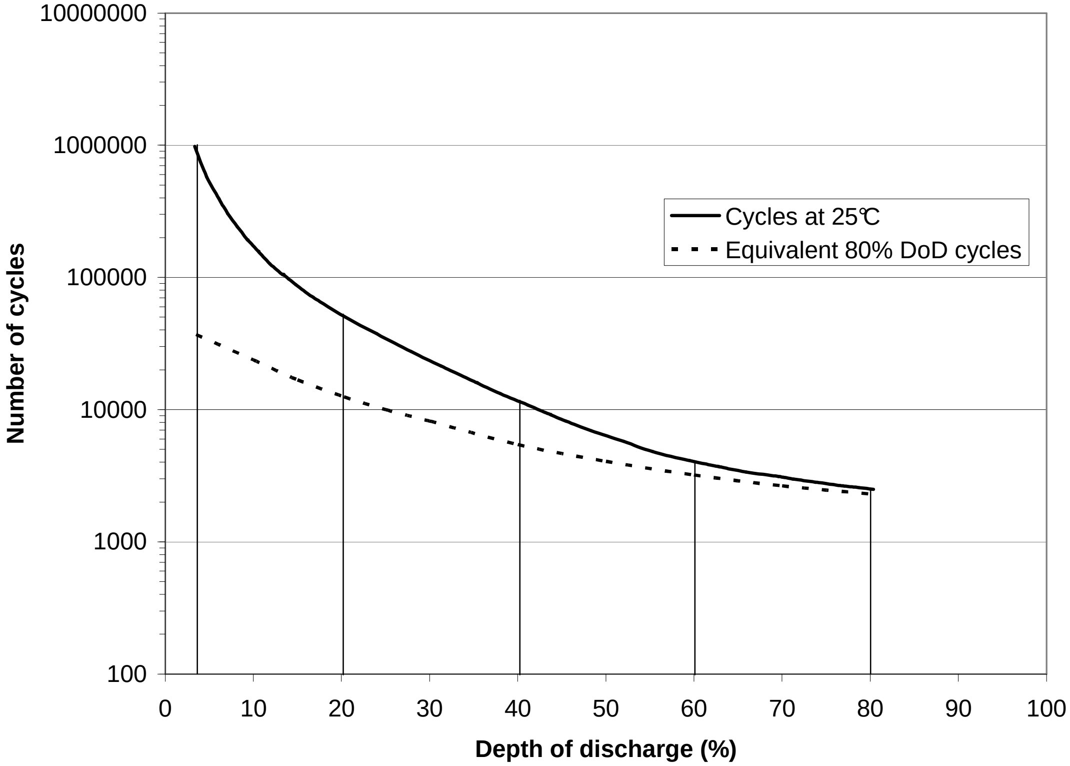
[7] near term goal

[8] in vehicle evaluation

The table indicates that current high energy cell designs achieve energy and power density levels of at least 150Wh/kg and 650W/kg. 20-30kWh batteries using such cells can attain energy densities of around 100kWh/kg and power densities in the range of 250-350W/kg or above sufficient for small or even full performance EV applications at acceptable battery weights (see Table 3-2). Also, medium power Li Ion cells in the appropriate size range enable construction of 7.5-15kWh batteries with energy densities above 70Wh/kg and power densities in the 500-900W/kg range, readily meeting the PHEV battery performance requirements shown in Table 3-2.

Table 3-6 includes data on cycle and calendar life, two of the remaining concerns about the readiness of Li Ion batteries for vehicle applications. The more than 3000 deep cycles achieved by SAFT and claimed by Kokam indicate the potential of large Li Ion cells for very long cycle life. This potential is documented in Figure 3-2 which shows cycle life achieved by SAFT for different depths of discharge.

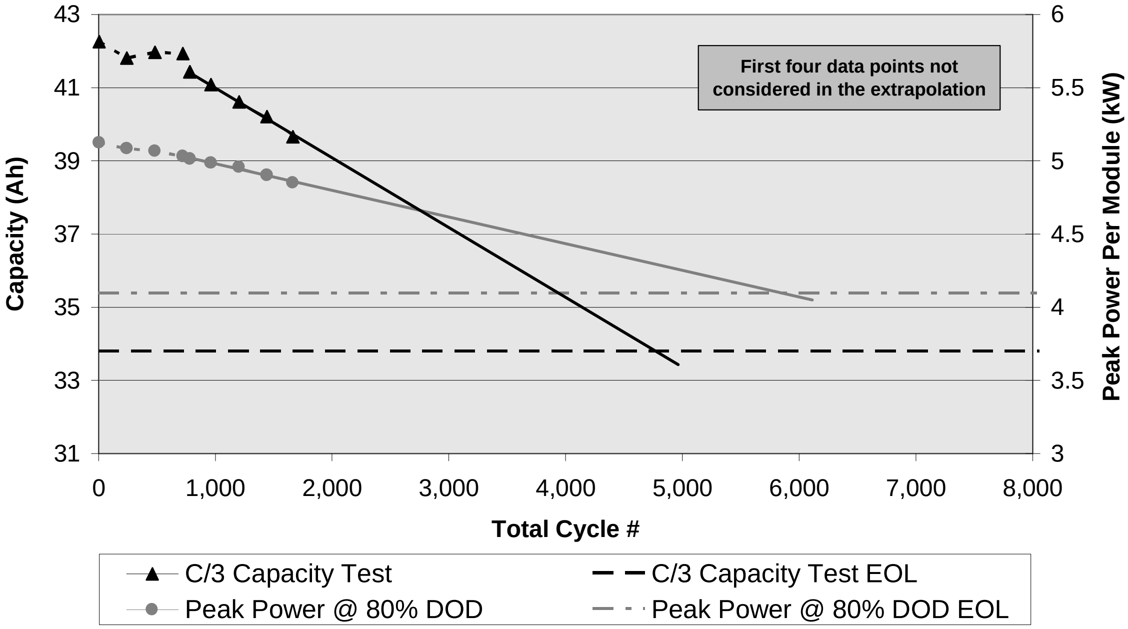
Figure 3-2: Deep Discharge Cycle Life of Li Ion High Energy Cell Technology



Included in the figure (see dotted line) is the total energy delivered by the cell over its lifetime, expressed as the equivalent of 80% DoD cycles on the same scale. Importantly, not only the actually achieved lifetime cycles but also the number of equivalent 80% DoD cycles increase progressively with decreasing depth of discharge. For example, if discharged consistently to 40% DoD (half of the maximum energy available from BEV or PHEV batteries in normal use), the battery cell under test yielded about 12,000 cycles, the energy equivalent of 6,000 cycles at 80% DoD, Thus, the lifetime energy delivered at 40% DoD is twice the energy delivered by a battery cycled at 80%DoD, and this ratio increases with decreasing DoD. This cycle life-extending effect is expected to be significant for BEV and PHEV batteries that are likely to experience a substantial number of partial discharges in practical operation.

Ongoing tests of JCS VL41M (medium energy design) multi-module assemblies at the EV and battery test facility of the Southern California Edison Co. (SCE) confirm the excellent deep cycling potential of Li Ion batteries, as illustrated in Figure 3-3 provided by SCE.

Figure 3-3. Storage Capacity and Peak Power of JCS VL41M Modules
(cycled in simulated PHEV mode)

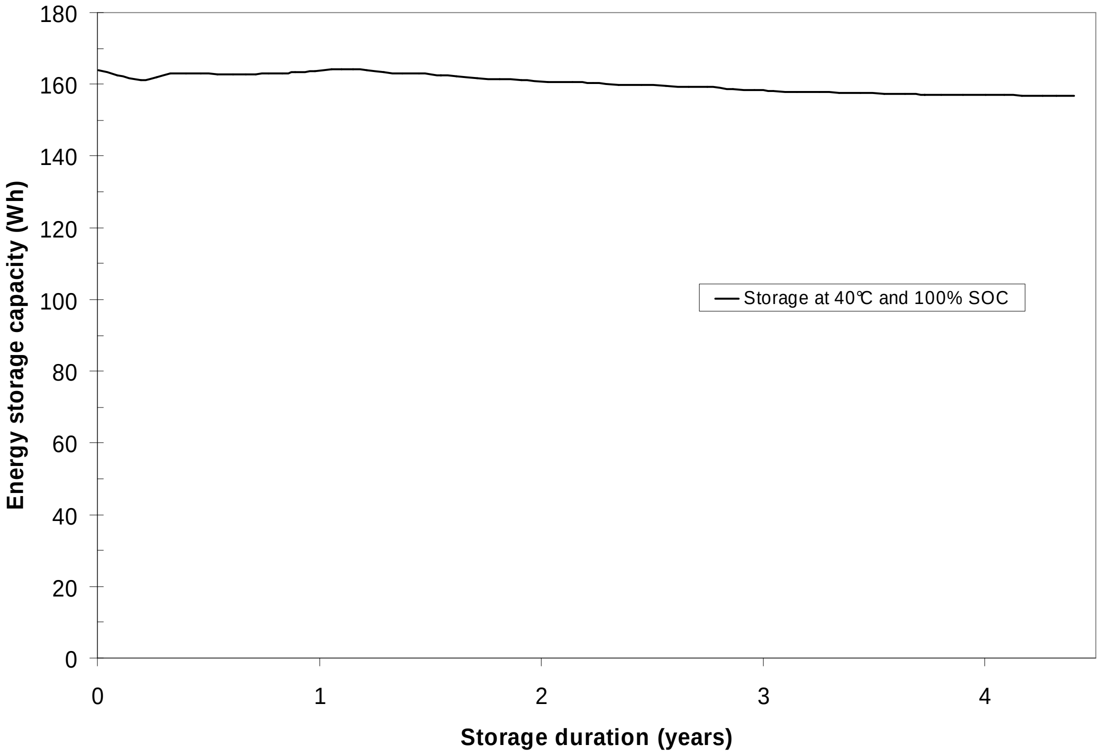


After more than 1500 cycles between 100% and 25% SoC, battery storage capacity and peak power capability each have declined by less than 6%. If the linear degradation rate of storage capacity (dark lines and left axis in Figure 3-3) continues until capacity has declined by 20%, the nominal end of life (EOL), the battery will have delivered approximately 4800 deep cycles. The extrapolation of peak power degradation (gray lines and right axis) to a 20% decline results in a projected life of 5800 deep cycles.

These test results are noteworthy not only because of the projected long cycle life but because the battery modules were cycled in a test mode that simulated one type of operation that might be experienced by the battery of a PHEV. That test cycle comprises discharging the fully charged battery to approximately 25% SoC through a series of consecutive portions of INRETS Urban I cycles in approximately 1.2 hours, followed immediately by operating the battery in the charge sustaining (HEV) mode for 1.4 hours with the same modified INRETS I cycles. This is followed by a 15 minute rest period, a full recharge in approximately 3 hours, and another rest period of 1 hour. The complete cycle most likely provides less engine assist, as well as shorter rest periods and a more rapid recharge compared with practical applications. Thus, the test cycle very likely is more stressful for the battery than its operation in a PHEV. The SCE data represent the first substantive evidence that properly designed Li Ion batteries have good prospects to meet the cycle life requirements posed by PHEV applications.

The calendar life of state-of-the-art high energy Li Ion technology also is much improved over the 2-4 years that were typical and a major concern five years ago. This progress is illustrated in Figure 3-3 obtained from JCS.

Figure 3-3: Calendar Life of Li Ion High Energy Cells at 40ºC



As shown in the figure, the storage capacity of a Li Ion high energy design cell decreased less than 5% in more than four years of storage at 40°C when fully charged (100% SoC), the most demanding condition. The slope of the capacity vs. storage time relationship suggests that 20% capacity loss would not be reached for another 12 years if the capacity loss rate did not accelerate. Since that assumption cannot be made with complete confidence, battery developers test calendar life at substantially higher storage temperatures for which end-of life occurs within 2-4 years. Results from accelerated cell life testing were presented to the Panel; they indicate that calendar life of Li Ion high energy cells and batteries should attain 15 years if battery cell temperature is kept below approximately 45°C and the *average* state of charge below 50%.

Table 3-7 presents performance and life data for high power/medium energy Li Ion cell and battery technologies that are currently under test for HEV applications. Only cell technologies for which manufacturers provided the most important technical data are included in the table. Little information on complete batteries was made available to the Panel, probably because of the impending commercialization of Li Ion HEV batteries by several manufactures. Li Ion high power cell and battery developments are underway also at other manufacturers (especially in Asia), but the Panel considers the cell data in Table 3-7 sufficient to permit a technical assessment of Li Ion high power battery technologies.

Table 3-7 includes a promising Li Ion high power technology in a smaller cell size that has been commercialized by A123Systems for power tool applications. The expectation is that the basic technology can also be developed into larger cell sizes of higher power density for HEVs, an application for which it is well suited because of the safety advantages of iron phosphate-based positives.

Table 3-7. Status of Li Ion High Power/Medium Energy Cell and Battery Technologies

Manufacturer	JCS	Matsu-shita	Hitachi VE	Kokam[1]	GAIA	A123 Systems
Cell (Designation)	VL7P		Gen 2	UHP	HP	MI 26650
Positive Electrode (Matl.)	NCA	NCA	n.d.a.	NCM	NCA	LFP[2]
Voltage (Volt)	3.6	3.6	3.4	3.7	3.6	3.3
Capacity (Ah)	7	7	5.5	7.2	7.5	2.3
Energy density (Wh/kg)	67	92	n.d.a.	114	84	110
Power Density (W/kg)	1800	3400	n.d.a.	2600	1500	~2000
Power/Energy ratio (1/h)	27	37	n.d.a.	23	18	~20
Power Density (W/L)	3525	n.d.a.	n.d.a.	4900	3750	~4000
Cycle Life (shallow cycles)	>400k	n.d.a.	>750k	n.d.a.	n.d.a.	>240k
Cycle Life (cycles/DoD)	n.t.[3]	(>1000)	n.t.	~3000/80	1000/60	7000/100
Calendar Life(years@RT)	>20	n.d.a.[4]	n.d.a.	>10	n.d.a.	>15
Development Status	LVP[5]	n.d.a.	n.d.a.	LVP	LVP	CP[6]
Battery (Application)	HEV	HEV	HEV	HEV	HEV	Power Tool
Storage Capacity (kWh)	2	3	~1	2.6	2	n.d.a.
Peak Power (kW)	50	90	47	52	25	2.1
Peak Power Dens. (W/kg)	1110	2100	1900	1850	n.d.a.	n.d.a.
Power Density (W/L)	1110	n.d.a.	2100	n.d.a.	n.d.a.	2200
Energy Density (Wh/kg)	44	70	42	93	n.d.a.	n.d.a.
Power/Energy Ratio (1/h)	25	30	45	20	12.5	n.d.a.
Weight (kg)	45	43	22.5	~28	n.d.a.	n.d.a.
Development Status	PP[7]	D[8]	PP	LVP	n.d.a.	n.d.a.

[1] cells use folded and stacked laminate of polymer electrolyte-separator film with electrodes
[2] lithium iron phosphate (modified)
[3] not tested; [4] no data available
[5] low volume production; [6] commercial production; [7] pilot production; [8] development

Even smaller Li Ion cells of the type used in consumer electronic products are being used for developmental PHEVs and FPBEVs in the form of batteries that consist of several thousand cells connected in parallel and in series. This approach takes advantage of Li Ion cells that are available now since they are being produced in very large numbers and sold at competitive prices for laptop computers. However, it raises questions regarding the reliability, safety and ultimately achievable cost of “small-cell” batteries. Several such batteries and some of the questions surrounding their use in FPBEVs and PHEVs are discussed in Appendix H.

The comparison with Table 3-2 shows that all of the Li Ion high power cell technologies included in Table 3-7 – and no doubt others not shown for lack of detailed data – meet the battery performance requirements of full HEVs. Also, available shallow cycling test data indicate (Table 3-7) that high power Li Ion cell designs can be expected to meet HEV battery shallow cycle life requirements (see Table 3-2). This is consistent with the capability of *high energy* Li Ion cells to achieve very large numbers of shallow cycles (for example, 500k at 5% DoD, see Figure 3-2). The achievement of 7000 complete discharge (100% DoD) cycles claimed by A123Systems for its technology is yet another indication of the deep cycling capability of Li Ion chemistries and technologies.

The calendar life of high power Li Ion battery cells is expected to have the same basic dependence on temperature as high energy cell designs since several of the high power cell technologies use the same basic chemistry as larger cells and thus are subject to the same kind of degradation processes. The Panel was shown experimental data that confirm this expectation. Because high power cells for HEV applications are operated around 50% SoC most of the time, a 15 year calendar life should eventually be attainable if thermal management can keep battery operating temperatures below approximately 45℃.

As with high energy Li Ion technologies for BEV and PHEV applications, a key technical question that continues to confront high power HEV-design Li Ion batteries is whether they can meet the very high levels of safety required for vehicles operated on public roads. Information bearing on this question is discussed below.

b) Safety

Assurance of battery safety is critical for the prospects of Li Ion batteries for HEV, PHEV and EV applications. Li Ion battery safety is tied directly to the avoidance or strict control of those processes in Li Ion battery cells that, if uncontrolled, can release dangerous amounts of energy, flammable gases and/or toxic chemicals into the battery environment. These processes include electrochemical overcharging of battery cells and the ensuing reactions of the chemical species formed during overcharge, and chemical reactions of the organic electrolyte/solvent with one or both electrodes. Under normal operating conditions of cell voltage and temperature, these processes are either precluded through cell-level voltage control (overcharge) or occur at very low rates that do not constitute safety risks.

Concerns about Li Ion battery safety thus can be limited to the response of cells and batteries to “abuse”, either electrical/electrochemical (shorting, high rate and extensive overcharging), thermal (heating to temperatures above the cell tolerance limit) and/or mechanical (destruction of physical integrity). Abuse tolerance testing has become part of cell development as well as battery design and engineering efforts. The degree of tolerance to various abuses is serving as a relative measure of safety as well as a guide to the development of adequately safe Li Ion cells and batteries. The procedures most commonly used in Li Ion abuse testing were developed with U.S. DOE funding under the USABC and FreedomCar programs (Unkelhaeuser, 1999) and are now widely accepted.

Results of systematic abuse testing of small commercial Li Ion cells following these procedures show that sustained high rate/high voltage overcharge and massive shorting of some Li Ion cell types can cause thermal runaway that is accompanied by cell-internal gas evolution, cell venting, and (if triggered by sparks) burning of vented electrolyte solvent. However, these conditions can be created only if the standard, multiple levels of protection devices (voltage-sensitive and pressure-driven switches to interrupt current, current-sensitive and temperature-activated fuses, cell balancing electronics) are removed. Continued external heating above 150ºC (approximately 300ºF) also resulted in thermal runaway for the particular Li Ion technologies tested.

Table 3-8 summarizes the abuse behavior of a high power Li Ion cell designed for HEV applications and of a prototype battery designed for small electric vehicles.

Table 3-8. Results of Abuse Testing of JCS Li Ion Technologies

Test	HEV Cell [1](VL7P)	EV Battery[2] (VL45E Modules)
Mechanical Crushing	No event	No event
Perforation (Nail Test)	Smoke (venting)	n.a.
External Short Circuit	No event	No event
Overcharging (High Rate)	Smoke (venting)	No event
Over discharging	No event	No event
Overheating (External Heat)	Smoke (venting)	n.d.a. [3]
Fuel Fire Immersion (890ºC)	Flame	Flame (low rate combustion)
Water Immersion	No event	No event

[1] All tests started at 100% SoC and performed according to USABC Test Procedures,
With all safety devices disabled; similar cell abuse test results have been reported by other manufacturers
[2] Battery-level abuse tests followed USABC Procedure except with safety devices enabled
[3] No data available

Even these severe abuses did not result in catastrophic failures of single cells, and only the immersion in a hot fire resulted in combustion of gases vented from a cell. No releases of gases or toxic chemicals from the containment were observed under the battery test conditions in which the cell, module and battery-level protection systems were enabled.

It is important to recognize that, although the chemistries of the cells and batteries used in these experiments and other tests (including in-vehicle operations).are similar to the chemistries used in Li Ion laptop batteries, cell and battery designs are substantially different. Even more important, batteries for HEV, PHEV and BEV applications have sensors of voltage, pressure and temperature used in multiple, independent controls that prevent or terminate unsafe battery conditions of the type that resulted in a number of laptop battery fires..

The high level of safety achieved for current Li Ion technology is attested to by the experience with more than 200 electric and hybrid vehicles that were equipped with FPBEV-design or HEV-design Li Ion batteries and road tested in California, Europe and Japan over the past five years. No significant safety issues were encountered in these tests.

While Li Ion technology representing the state of the art of several years ago has proven safe in on-road vehicle testing, R&D is continuing to further enhance battery life and safety, as part of extensive worldwide efforts to advance all aspects of Li Ion cell and battery technology.

3. Li Ion Technology Advances and Prospects

A remarkable feature of the Li Ion battery concept is that a number of different materials can function as positive electrodes to “host” lithium ions. Similarly, several different materials work as negative electrode hosts for elemental lithium. Together with a choice of several salt-organic solvent electrolytes, this characteristic gives rise to a large number of possible Li Ion cell chemistries. Several of these have been developed into practical cell and battery technologies with the favorable performance, life and safety characteristics discussed above. It is likely that ongoing, extensive R&D will result in further advances of one or more of these characteristics.

Among recent chemistry advances are several that have become part of state-of-the-art technologies. These advances include:

- Modifications of manganese oxide-containing positive electrode materials such as NMC and LMS, to increase the *chemical* stability of these structurally stable and thus inherently safer materials that also are potentially less expensive than NCA;

- "nanostructured" (highly disperse) doped iron phosphate (olivine) positive electrodes that operate at lower positive potential and exhibit reduced reactivity with electrolyte solvents at elevated temperatures, to eliminate the danger of thermal runaway;
- nanonstructured graphite and other carbon-based negative electrode materials that permit high rate intercalation of lithium atoms during rapid and/or low-temperature charging, to minimize formation of highly reactive and potentially hazardous metallic lithium at the negative electrode surface;
- various additives to electrolytes and/or electrodes, to stabilize the SEI and/or electrode composition and structure, thus increasing cell life and safety;
- polymer (gelled) electrolyte-separator films that when laminated to the electrodes permit simplified, more flexible manufacturing of folded or stacked cell structures and that reduce venting of combustible solvent vapor when cell seals are breached by overpressure.

Currently making the transition to state-of-the-art technology is nanostructured lithium titanate to serve as a new negative electrode material for Li Ion batteries instead of the universally used carbon-based electrodes. This replacement results in a new, fundamentally different and safer cell chemistry in which ions are the only lithium species involved in the positive *and* negative electrode reactions. No SEI is present or needed for the functioning of the cell. In conjunction with the titanate electrode's nanostructure, these characteristics have already been shown to result in the capability for very high charge and discharge rates and tolerance of exceptionally large numbers of deep cycles.

For applications such as HEVs that require very high levels of power density, efficiency, lifetime cycles and safety in a small battery, the advantages of Li titanate-based cells might well balance the lower energy density and higher cost that must be expected for this chemistry because its cell voltage is approximately 1.3-1.5 Volts lower than that of Li Ion cells with lithium-in-carbon negatives. In practice, this reduction in energy density potential is partially offset by the fact that cells with lithium titanate negatives do not require an excess of lithium to make up for the lithium lost irreversibly in the initial formation of the SEI layer. Further, batteries with titanate-based Li Ion cells are likely to require less of the reserve capacity needed to make up for the slow loss of energy and power capacities due to the aging of the SEI layer in carbon-based cells.

Yet more advanced concepts still await full development and evaluation in Li Ion cell and battery technology for HEV, PHEV and/or BEV applications. Examples include liquid or polymeric *inorganic* electrolytes that are not flammable and thus inherently safer. Another potentially important advance is the discovery of an electrolyte salt that is oxidized reversibly at the positive electrode to form a chemical species that can be reduced at the negative electrode. If such a "redox shuttle" is reversible at a potential just above that of a fully charged positive electrode, it can prevent cell overcharging without causing significant self discharge. If successfully developed and incorporated into Li Ion technologies, any of these advances will improve the safety performance of Li Ion technologies even further.

New materials continue to be explored as negative and positive electrodes in Li Ion cells. Some of these materials -- for example, recently reported silicon oxynitride negatives that do not contain any of the relatively heavy transition metals -- exhibit not only good electrochemical performance but much higher specific capacities than established materials. If proven to work as electrodes in practical Li Ion cells, new high-capacity positive and negative materials could lead to significant increases in energy density over that of established Li Ion chemistries. While it is premature to quantify these improvement prospects, it is noted here that a just a 50%

increase of positive and negative capacities would increase the gravimetric energy density of a state-of-the-art 20-30Ah cell from around 150Wh/kg to approximately 180Wh/kg, with a similar percentage increase in volumetric energy density (Wh/L). Future battery technology based on such materials as well as on advances in cell designs and battery packaging should readily meet the performance goals for FPBEVs.

However, the R&D, engineering development and technology validation efforts required to move basic advances from the laboratory into commercial battery technology are likely to take at least five to ten years, depending on the extent of the attendant changes in Li Ion chemistry, cell design and/or battery operation.

4. Nickel Metal Hydride Batteries: Characteristics

a) Chemistry, Advantages and Limitations

The nickel metal hydride (NiMH) battery uses a hydrogen-absorbing alloy as the negative electrode, nickel oxide as the positive electrode, an alkaline electrolyte, and a separator made from porous polyolefin material. The NiMH cell voltage is a relatively low 1.2 Volt.

The key to the practicality of NiMH batteries was the discovery of nickel-based alloys that retain their structural integrity over a large number of charge-discharge cycles during which hydrogen is absorbed into, and released from, the alloy crystal lattice. Only a few alloys offer this characteristic at hydrogen pressures that can be managed in sealed battery cells, as well as sufficient resistance to corrosion by the caustic electrolyte used in NiMH cells. After many years of development, alloys of the general composition AB_5 (where A denotes an alkaline earth metal such as lanthanum and B stands for nickel) have emerged as the preferred composition of negative electrodes.

Before being used in NiMH batteries, the nickel oxide electrode demonstrated ruggedness and very long cycle as well as calendar life in nickel cadmium batteries. Its long life derives in good part from the minimal structural changes occurring during charge-discharge cycling during which nickel hydroxide is converted reversibly into nickel oxide–hydroxide and back to nickel hydroxide.

The main advantage of the NiMH battery is its basic potential for long cycle and calendar life. Another favorable feature is the high conductivity of the caustic electrolyte that permits high power densities to be achieved without going to very thin and thus more expensive cell structures. Other advantageous characteristics include overcharge tolerance of cells properly engineered to permit recombination (reduction) at the negative electrode of oxygen evolved at the overcharged positive electrode, and safety even under abuse conditions. All of these advantages derive from the use of an aqueous electrolyte and the relatively low cell voltage.

The main technical limitation of NiMH batteries – modest specific energy – also derives from the low cell voltage. Another disadvantage is that oxygen evolution at the positive electrode is thermodynamically favored over charging. Positive electrodes thus must not contain any of the many substances such as iron that can catalyze oxygen evolution. Even so, oxygen evolution occurs near the end of charge, and this effect increases markedly with temperature. Although recombination of this oxygen at the negative electrode can keep cell gas pressure within acceptable limits, this process reduces charging efficiency and releases appreciable heat. Higher temperature also increases corrosion of the negative alloy by the electrolyte. The associated loss of electrolyte and loss of hydrogen through the cell enclosure limit the ultimately achievable NiMH cell and battery calendar life.

Maintaining cell temperature below approximately 45-50℃ through effective thermal management (especially during charging), keeping charging rates (especially at high states of charge) as low as practical, and limiting the extent and frequency of overcharging are the chief challenges for automotive applications of NiMH batteries.

5. Nickel Metal Hydride Batteries: State of the Art

a) *Performance and Life*

NiMH batteries have demonstrated high reliability and long life in automotive applications, beginning with their use as EV batteries in several thousand vehicles built and leased or sold by major automobile manufacturers under the provisions of the California Air Resources Board ZEV regulation. However, to enable driving ranges of just 75-100 miles for typical compact and midsize cars, batteries were shown to need capacities of around 30kWh and more. With a representative gravimetric energy density of 50-55Wh/kg, a complete NiMH battery of 30kWh weighs between 540 and 600kg, adding almost 40% to the weight of a conventional vehicle. This weight greatly exceeds the goals set for FPBEV batteries (see Table 3-2) and tends to disqualify NiMH batteries for application in full-performance BEVs.

The technical status of high energy NiMH batteries, with one example of the few available technologies shown in Table 3-9 (left column), has changed relatively little over the past five years. The Panel believes that this reflects lack of automobile and battery manufacturer interest in FPBEVs and in NiMH batteries for this application. The modest energy density of NiMH batteries is an inherent limitation unlikely to yield much improvement even if development efforts were continued.

Table 3-9. Characteristics of Nickel Metal Hydride Battery Technologies

Manufacturer	JCS	Varta[1]	Electro Energy	PEVE	Sanyo	Cobasys[2]
Cell Type	High Energy	Medium Energy	Medium Energy	High Power	High Power	High Power
Configuration	Prismatic	Prismatic	Bipolar	Prismatic	Cylindrical	Prismatic
Capacity (Ah)	100	40	30	6.5	6	8.8
Module (Application)	FPBEV	PHEV[3]	PHEV[4]	HEV	HEV	HEV
Weight (kg)	18.6	~35	130	1.2	1.14	2.4
Voltage (Volt)	12	48	220	7.2	7.2	12
Peak Power (kW)	3.6	8.75	~50	1.35	1.31	2.64
Power Density (W/kg)	195	250	~400	1130	1150	1100
Power Density (W/L)	405	n.d.a.[5]	~1000	2750	n.d.a.	2200
Storage Capacity (Wh)	~1200	1920	6500	47	43	106
Energy Density (Wh/kg)	65	57	~50	39	37	43
Power/Energy Ratio (1/h)	3.0	4.5	~8	29	31	26
Cycle Life (50Wh DoD)	n.t.[6]	n.t.	n.t.	>150k	~300k	.140k
Cycle Life (80% DoD)	>2000	(>3000)	>1000	n.t.	n.t.	n.t.
Calendar Life (years)	>8	n.d.a.	>10	>8[7]	>8	n.d.a.
Development Status	LP[8]	LP	P[9]	CP[10]	CP	LP

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[1] Varta is owned by Johnson Controls and part of JCS

[2] website data (not updated)

[3] block of ten 4-cell modules; [4] bipolar stack of ~180 cells
[5] no data available; [6] not tested; [7] inferred from warranty period
[8] limited production; [9] prototype; [10] commercial production;

A positive observation about the capabilities of high energy NiMH battery technology can be derived from experience with the aging fleets of NiMH-powered BEVs remaining from the ZEV initiative. It is showing that even the NiMH technology of more than five years ago is capable of very good cycle and calendar life, often exceeding the cycle life goals set by USABC.

Varta's technology is a more recent design that is being used successfully in prototype hybrid buses and a prototype PHEV version of the DaimlerChrysler "Sprinter" van. Module packs of approximately 2kWh capacity are showing 100% capacity retention after nearly 2000 deep cycles in testing at the electric vehicle and battery test facility of the Southern California Edison Co. Although power capability has declined somewhat, extrapolation of the rate of decline to 20% capacity loss indicates a capability for more than 3000 lifetime cycles of 80% DoD under simulated PHEV operation.

The development of bipolar (stacked-electrode) high energy NiMH battery technology by Electro Energy is an interesting advance in NiMH technology. The technology's high gravimetric and volumetric power density (Table 3-9) is characteristic of bipolar designs and meets not only FPBEV but also PHEV battery power density requirements (see Table 3-2). Its energy density, although still falling short of the performance requirement for FPBEV applications, promises to meet the less stringent PHEV requirements. The Electro Energy battery technology still needs to demonstrate consistent long term reliability of the critical peripheral cell seals, the key issue with bipolar battery designs in the past.

NiMH high power batteries have enabled the introduction of the Toyota Prius and Honda Insight as the first practical and affordable hybrid electric vehicles, as well as the successful extension of the HEV concept to a growing number and diversity of models. Key to this success was the development of NiMH cell and battery designs with the characteristics summarized in right half of Table 3-9 above. The comparison with Table 3-2 shows that NiMH high power technologies meet the performance required for application in full HEVs, even if the module-level power and energy density data in Table 3-9 are reduced by 30% (typical for HEV-size batteries) to arrive at battery-level performance data. The technologies also promise to meet the cycling and calendar life requirements for HEV applications, as attested to by the 8-10 year warranties provided to HEV owners.

b) Safety

Nickel metal hydride batteries present no significant safety issues under normal operating conditions. Occasional brief cell venting can occur as a result of uncontrolled overcharging or charging at excessive rates and/or temperatures, but this has little safety impact. Even events caused by abnormal conditions are relatively mild although they can lead to damage or failure of NiMH batteries. Continued uncontrolled overcharging of NiMH cells will eventually lead to opening of the pressure relief valves that are standard features of NiMH battery cells. The evolving gases (primarily oxygen; on prolonged overcharge also some hydrogen) can carry some of the alkaline battery electrolyte mist with them, but the amount will be limited because cells will shut down after sufficient loss of electrolyte.

Mechanical destruction of the battery, should it occur in a severe accident, could cause leaks of the non-flammable caustic electrolyte. Such leaks will be modest and slow because the amount of electrolyte is quite limited, and much of it will remain in the pores of separators and electrodes.

6. NiMH Technology: Advances and Prospects

Through the developments of the past decade, high power NiMH cell and battery technologies meeting the performance requirements for application in full (and other) HEVs have reached technical as well as manufacturing maturity. They are now mass-produced by two Japanese battery manufacturers, as discussed further below. Continued efforts to improve high power NiMH technology, driven by the desire to further increase specific power and enable reductions of battery capacity, volume and costs, are underway. Further improvements will continue to have commercial importance but are likely to be incremental only.

Transfer of high power NiMH technology advances to the development of medium power, medium energy NiMH technology could lead to batteries that meet performance requirements for PHEVs with nominal electric ranges of 20 miles or less. However, this type of transfer does not appear to have been attempted, probably because of the relatively recent emergence of interest in PHEVs. In view of the poor prospects of NiMH for substantial increases in energy density and cost reduction (see below), there is little incentive for seeking technology improvement and application in small or larger full performance BEVs.

7. Other Candidate Batteries: ZEBRA

Although the ZEBRA (sodium-nickel chloride) battery strictly speaking does not meet the peak power requirements for application in full performance BEVs, PHEVs and HEVs (see Table 3-2), the battery has demonstrated its usefulness in several hundred small BEVs as well as in a number of buses and other heavy vehicles. The technology, its prospective cost and its manufacturing status have, therefore, been reviewed by the Panel and are discussed below as well as in subsections 3.E and 3.F.

a) Chemistry, Advantages and Limitations

The ZEBRA battery is based on the discharge reaction $2Na + NiCl_2 \rightarrow Ni + 2\ NaCl$; in the charging reaction, this reaction is reversed. In the practical realization of the ZEBRA battery cell discharge process, liquid sodium (Na) is electrochemically oxidized to sodium ions. These migrate through the wall of a ceramic tube (surrounded by the liquid sodium) that contains nickel chloride and liquid sodium-aluminum chloride with a conducting carbon wick. At the positive electrode, nickel chloride is reduced to form nickel metal (as powder) and chloride ions. Chloride ions combine with sodium ions to form sodium chloride that is precipitated in the aluminum chloride. Cell operating temperatures in the range of 270-350℃ (520-660℉) are required to keep the sodium as well as the sodium-aluminum chloride electrolyte liquid, and to enable sufficient sodium ion conductivity of the beta-alumina ceramic tubes.

ZEBRA batteries present difficult challenges but also have unique advantages; both derive directly from the battery's cell chemistry and construction. A key characteristic is high temperature battery operation that requires start-up heating and effective thermal insulation to prevent significant thermal energy loss. It also requires tolerance of the ceramic tubes and their seals to occasional freeze-thaw cycles of the cells. On the other hand, high temperature operation facilitates battery cooling (a critical requirement and challenge for both Li Ion and NiMH batteries), and it makes operation of the insulated ZEBRA battery independent of either high or low environmental temperatures.

The development of ceramic tubes capable of conducting sodium ions and unaffected by the corrosive sodium-aluminum chloride electrolyte was the breakthrough that enabled use of liquid sodium in a battery. Because no corrosion or other side reactions occur within a ZEBRA battery cell, it has potential for excellent calendar as well as cycle life. In combination with the modest total weight of the battery active materials, the relatively high cell voltage of 2.58 Volts gives the ZEBRA battery high energy density, comparable to that of complete Li Ion batteries.

Unlike Li Ion batteries, ZEBRA batteries tolerate substantial amounts of overcharge and of cell reversal. ZEBRA batteries also tolerate a significant number of individual cell failures because they normally result in shorted cells and continued operability of the battery albeit at a slightly lower capacity. A major advantage compared to other advanced battery types is low materials cost. Finally, ZEBRA batteries can be recycled simply and completely by immersion in electric furnaces for stainless steel production, with credits for the nickel content covering all recycling costs including transportation.

The most serious drawback of the ZEBRA technology is its rather modest peak power density of approximately 180W/kg (battery level). This characteristic limits the power even of BEV-design ZEBRA batteries, and it tends to disqualify the technology for HEV and PHEV applications. Together with questions about the practicality of high temperature battery operation, this limitation has kept the technology from being accepted as a serious candidate for EV applications, especially by U.S automobile manufacturers.

b) State of the Art

Table 3-10 summarizes the current state of development of the ZEBRA battery technology. All data are for complete batteries including thermal insulation, the battery box, and the battery management system. The comparison with Table 3-2 shows that ZEBRA batteries are well matched to the energy storage requirements and battery weight constraints posed by smaller electric vehicles although peak power must be considered marginal. Nevertheless, a small but growing number of small BEVs are being equipped with ZEBRA batteries and used successfully in regular European traffic situations, typically delivering 75-100 miles on a single battery charge.

Table 3-10. Characteristics of MES-DEA ZEBRA Batteries

Cell (Type)	ML8P	ML3P	ML3C
Configuration (shape)	cruciform	cruciform	cruciform
Capacity (Ah)	25	38	32
Battery (Application)	Small EV	EV	Hybrid Bus
Battery Type	Z21-310-ML8P-50	Z5-278-ML3P-78	Z37-620-ML3C-32
Weight (kg)	137	184	203
Voltage (Volt)	310	278	619
Storage Capacity (kWh)	15,5	21.2	19.8
Energy Density (Wh/kg)	113	115	100
Energy Density (Wh/L)	173	181	154
Peak Power (kW)	23,7	32	36
Power Density (W/kg)	179	179	179
Power Density (W/L)	264	273	276
Power/Energy Ratio (1/h)	1,5	1.5	1.8
Cycle Life (80% DoD)	1000	1000	1000
Calendar Life (years)	15	15	15
Development Status	CP	CP	CP

ZEBRA batteries meet the energy density requirements for smaller full performance battery electric vehicles and PHEVs. However, battery peak power falls short of PHEV requirements and would have to be assisted by a high power device (ultracapacitor, or small very high power battery) in meeting vehicle power requirements. The type of system performance and cost analysis required to judge the prospects of ZEBRA battery-battery hybrid energy storage systems was beyond the scope of this report.

ZEBRA batteries have already demonstrated attractive deep cycle and calendar life. In laboratory tests of battery modules, 3500 80% DoD cycles were achieved, and long term testing of complete ZEBRA batteries in vehicles show retention of full (100%) of battery capacity after delivery of 1350 deep cycles over five years, with only modest degradation of peak power over the same number of cycles.

c) Commercial Status and Prospects

ZEBRA batteries are produced commercially by the Alternative Energy Division of MES-DEA in Stabio, Switzerland, a manufacturer of electric vehicle components. MES-DEA acquired the ZEBRA technology and pilot plant facilities for its production from AABG, a joint venture of Daimler Benz (Germany) and the Anglo American Corp. (South Africa) in 1999. In 2001 MES-DEA built a new plant that combines all ZEBRA battery production operations, from processing of raw materials to the manufacture of the battery hermetic enclosure and the integration of the required thermal and electric management systems.

The plant’s current production rate is around 1000 batteries per year of approximately 20kWh capacity. Production capacity will increase to 1500 batteries (approximately 30 MWh) per year in 2007, and equipment is currently being installed for 4000 units per year. On-site expansion of plant capacity to about 30,000 batteries (600 MWh) per year is a possibility given development of sufficient demand. A new “green field” ZEBRA battery plant could be built and put in operation in about three years. The market strategy of MES-DEA is to manage risk by developing and commercializing ZEBRA batteries for several independent applications in the transportation and stationary power sectors.

At present, ZEBRA batteries are used in limited numbers of electric and hybrid-electric buses, vans and light duty vehicles worldwide. In practical demonstrations, ZEBRA battery-equipped small BEVs had similar or lower AC electric energy consumption compared to BEVs equipped with NiCd batteries, attesting to the low thermal losses of the ZEBRA battery. Current initiatives include fabrication and sale by MES-DEA of 100 BEVs based on the Renault Twingo small car, provision of batteries for approximately 100 Smart city car conversions to be produced, sold and serviced by DaimlerChrysler, and supply of batteries for commercial milk delivery vans purpose-built as BEVs for use in the inner City of London.

Currently, ZEBRA batteries cost approximately $600/kWh if purchased in quantities of about 250 batteries per year. Based on detailed cost analyses of all battery materials and manufacturing operations, MES-DEA projects a selling price of around $150-200/kWh for batteries produced at an annual rate of 100,000 complete systems. (See also section 3.D below.)

8. Longer-Term Possibilities: The Lithium-Sulfur (Li-S) Battery

The lithium-sulfur electrochemical couple has the highest theoretical energy density among known battery systems. In principle, therefore, the Li-S battery is a candidate for a high-capacity energy storage system that might give electric vehicles the ranges needed for universal acceptance. Despite sustained albeit limited R&D efforts over the past 10-15 years to exploit this potential, no viable Li-S technology has emerged. However, claims are now being made that the very difficult problems surrounding the development of practical Li-S batteries are being solved. The Panel therefore decided to include Li-S batteries in the scope of its inquiry, as a possible longer term candidate for ZEV applications.

a) Chemistry, Advantages and Limitations

The Li-S battery is based on the discharge reaction $2Li + S \rightarrow Li_2S$; in the charging process, this reaction is reversed. The theoretical energy density of the Li-S battery active materials is nearly 3000Wh/kg, far higher than that of all other candidate batteries for ZEV applications. Although only a fraction of the theoretical energy density can be realized in practical batteries (for Li Ion cells about 25-30% of a theoretical 640Wh/kg) because of the weight of the other materials needed in a battery, a reasonable goal for the Li-S battery appears to be 350-400Wh/kg. At this energy density, a 60kWh battery would weigh less than the 250kg battery weight constraint for full performance electric vehicles (Table 3-2) and would give an FPBEV a range of 200 miles or more.

However, the use of metallic lithium and elemental sulfur in a battery presents a number of difficulties. Compared to other battery negative electrodes, metallic lithium is more expensive to process because of its reactivity with moisture and air, and it is more difficult to recharge from organic electrolytes. Also, the presence of substantial amounts of metallic lithium makes it considerably more difficult to assure battery safety, especially under abuse conditions. In addition, elemental sulfur is an insulator that can be made to work as a battery electrode only by mixing it intimately with substantial amounts of an inert conductor such as carbon. Finally, the Li-S cell discharge reaction proceeds through a series of lithium polysulfide intermediates with decreasing sulfur content. Polysulfides are partially soluble in organic electrolytes, with two undesirable consequences: increase of the cell resistance due to increased electrolyte viscosity, and self discharge of cells through polysulfide-based species acting as redox shuttles that constitute a cell-internal electrochemical short.

b) Status and Prospects

Sion Power appears to be the only organization currently engaged in Li-S development. According to information provided to the Panel by Sion, major progress has been achieved over the past five years in resolving the issues with the Li-S electrochemical system. Most important, a stable SEI layer can now be formed at the metallic lithium-electrolyte interface that largely suppresses reaction of lithium with the electrolyte and prevents polysulfide shuttle species from reaching the lithium negative while at the same time passing Li ions. Also, the negative electrode is produced by vapor deposition of Li into a structure that helps retain the original electrode shape and functionality despite the well known tendency of lithium to deposit in the form of dendrites during charging. Dendrite growth and cell shorting also is suppressed by chemical reaction of dendrites with the polysulfide species.

Based on these advances, Sion Power has been able to develop small, rechargeable cells in plastic enclosure with the following specifications:

Voltage Range	Cell Size (Configuration)	Energy Density	Energy Density	Max. Rate Discharge	Power Density
2.5 → 1.7 Volt	2.2(Ah) (prismatic)	>350(Wh/kg)	>350(WH/L)	~4(A)	~600 (W/kg)

Achieving a practically usable gravimetric energy density of more than 350Wh/kg, a value that greatly exceeds the energy densities of every other practical battery type, is an important achievement. Volumetric energy density and (gravimetric) power density, on the other hand, are comparable to the corresponding values for high energy Li Ion cells (Table 3-6). The currently achieved cell life of around 100 deep cycles is expected to increase to about 300 cycles which might be sufficient for the applications currently being targeted (military and space small power; consumer electronics). Sion Power is projecting further significant increases in energy and power density, but extracting more of a Li-S cell's energy tends to shorten cycle life.

To date, Sion Power has built a number of battery systems consisting of up to 500 small cells, for evaluation by the military. The investor-owned company is now in the process of raising funds to build its first commercial battery facility in the U.S., with the goal to have a plant producing small cells operating in the first quarter of 2008. Sion's product roadmap also includes development of cells and batteries in capacities suitable for BEV and PHEV applications. Prototype 25Ah cells are scheduled to be available in early 2007 and prototypes of complete battery systems a year later.

For electric vehicle applications, envisioned by Sion Power for Li-S batteries in the longer term, 1000-1500 deep cycles would be needed, and with a required 2500-3500 deep cycles PHEVs are even more demanding. It remains to be seen whether such long cycle life is possible with Li-S batteries that do not have the fundamental potential for long life offered by "host"-type electrodes with their minimal structural changes during charge-discharge cycling. At the current stage of development, it must be considered highly uncertain whether fully developed Li-S batteries would be able to meet the cycle life requirement for FPBEV (much less PHEV) applications.

Sion has provided preliminary cost estimates for BEV-design Li-S battery modules produced at early and full commercial production rates. These estimates are about 1/3 higher than the projections for high energy Li Ion battery modules and would make Li-S batteries too expensive for FPBEV applications except in instances where users would be prepared to pay a substantial price premium for the extended range capability that might be provided by such batteries..

D. Battery Costs

The prospects of battery electric and plug-in hybrid electric vehicles for capturing significant markets will depend in large measure on the costs of their batteries. While the cost of the smaller batteries used in fuel cell hybrid electric vehicles will be a less critical factor, the prospective high overall cost of FCHEVs provides a strong motive to minimize the cost of these batteries as well.

FPBEV battery costs were assessed in the BTAP 2000 Panel report and found to substantially exceed the goals for commercialization. The technology advancements and fuel price increases over the past five years now call for updates not only of battery costs but also of the overall economics – and, thus, cost constraints – for FPBEVs and their batteries. For HEV batteries, cost information is generally not available because of the emerging market competition. PHEV batteries are only now moving into development and pilot-level fabrication. As a consequence, their prospective costs in volume production, although most likely falling between those of FPBEV and HEV batteries, are not well understood.

In the following, the year 2000 battery cost background is updated and expanded with cost information obtained by the Panel from battery developers and prospective manufacturers, with emphasis on the cost of batteries suitable for FPBEV and PHEV applications. Because this information was made available on a confidential basis, the report does not identify the battery manufacturers that provided cost data. Also, since this data was neither complete nor consistently framed, the Panel supplemented the manufacturers' data with cost information from other sources and used its own judgment in combining and extrapolating cost information. The battery cost information so developed is compared further below with battery cost goals and with the value of the fuel cost savings achieved by HEVs, PHEVs and FPBEVs compared to conventional ICE vehicles.

1. Lithium Ion Battery Costs

The Panel collected Li Ion battery cost information from a number of manufacturers. This information came in several different formats, ranging from specific costs for cells to the costs of multi-cell modules (usually with module-level electric/electronic controls) and of complete batteries, and it covered several different cell chemistries as well as a range of cell and battery capacities all of which can be expected to affect costs.

To enable comparisons of manufacturers' data and to develop its own Li Ion battery projections, the Panel first converted the manufacturers' data to module-level specific costs using the scaling factors in Table 3-11. These factors are averages of the corresponding factors directly provided by some manufacturers, or derived from cell-, module- and/or battery-level specific costs made available for the same technology.

Table 3-11. Scaling Factors for Li Ion Technology Specific Costs:
From cells to modules and batteries

Battery Size (kWh)	Cell → Module	Module → Battery	Cell → Battery
40-45	1.03	1.2	1.24
20-25	1.04	1.25	1.3
12-15	1.05	1.33	1.4
7	1.07[1]	1.42[1]	1.52[1]
2	1.1	1.5	1.65

[1] Interpolated

The module specific costs thus derived were then normalized to the same approximate cell size (40-45Ah) and battery capacity (20-25kWh), the capacities for which a majority of the cost data were made available to the Panel. The factors used for this normalization are shown in Table 3-12 below; they were derived empirically from the cell-, module- or battery-level specific costs provided by the same manufacturer for different cell and/or battery capacities and averaged over the few manufacturers from which this information was available. (For a given cell size, these scaling factors turned out to the closely the same, whether derived from cell-, module- or battery-level specific costs.) The increase of specific costs with decreasing cell size (for a given chemistry) expressed by the factors in Table 3-12 is due to a combination of factors, primarily the increasing contributions of inactive cell materials and manufacturing to total cell costs. Because cells for vehicle applications are designed for increasing specific power levels as the application changes from FPBEVs to PHEVs and HEVs, the scaling factors also reflect the fact that cell and battery specific costs increase substantially with increasing power-to-energy ratios.

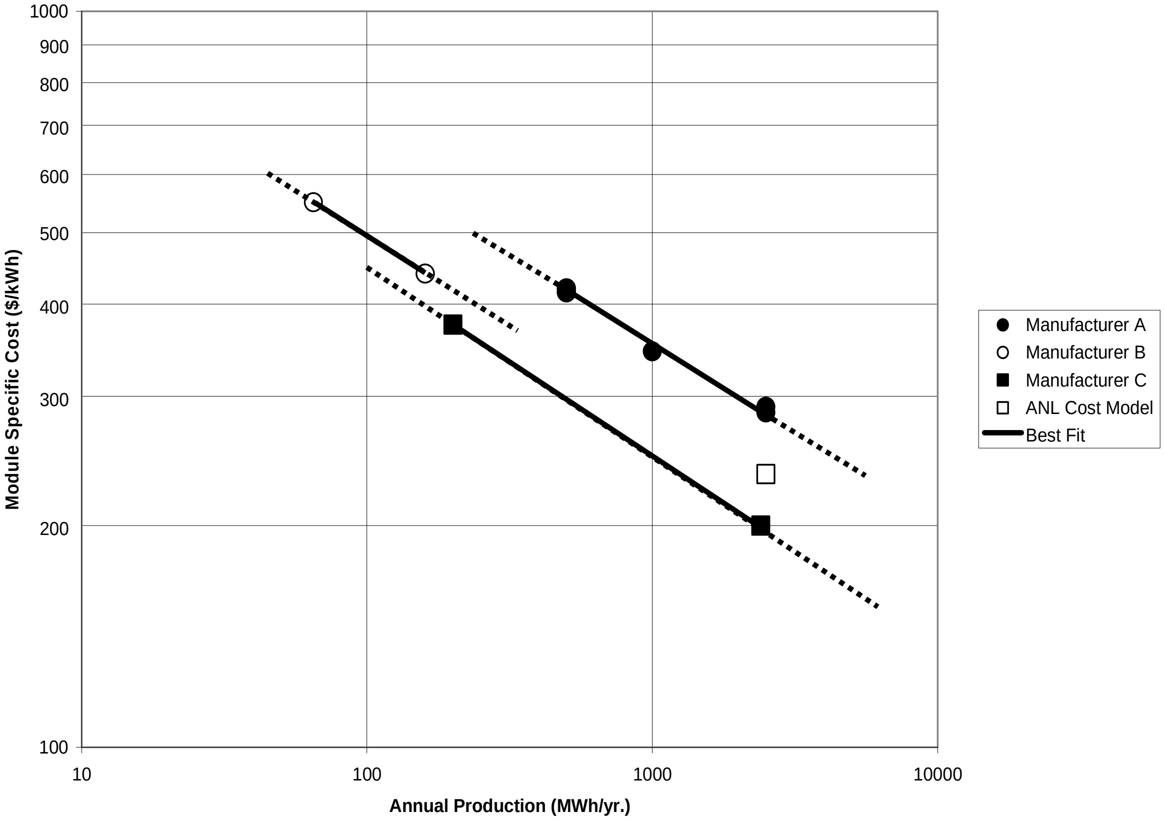
Table 3-12. Scaling Factors for Li Ion Technology Specific Costs:
From larger to smaller cell sizes

From Cell Size (Ah)	To Cell Size (Ah)	Factor	From Cell Size (Ah) to 45 Ah	Factor
120	60	1.20	120	1.35
60	30	1.27	60	1.12
60	45	1.12[1]	**45**	**1.00**
45	30	1.14[1]	30	0.88
30	15	1.33	15	0.66
15	7	1.40[2]	7	0.47

[1] interpolated; [2] extrapolated

The cost projections provided by manufacturers, normalized to the specific costs for modules of approximately 45 AH cells by application of the factors in Tables 3-11 and 3-12, are plotted in Figure 3-4. The figure uses total annual battery capacity (in MWh per year) as the measure of annual battery production considered the most appropriate by battery manufacturers.

Figure 3-4. Li Ion Module Specific Cost Projections



The Panel also developed an independent check of its module specific cost methodology and projections using the results of a series of cost calculations made available by Dr. Paul Nelson with support of ANL. These detailed calculations started with complete bills of materials for several chemistries, cell sizes and power density requirements, and they built up costs to the cell, module and battery levels through addition of the appropriate costs for materials, labor and overhead. The normalized module specific cost derived from Dr. Nelson's ANL cost model is included in Figure 3-4.

Figure 3-4 indicates a substantial spread in module specific costs even after applying the Panel's cost normalizing approach to manufacturers' cost data. These differences are due to differences in presently used materials and manufacturing methods as well as to different assumptions made when material and manufacturing costs are projected to production levels well beyond those currently practiced. For example, the manufacturer identified as "C" in Figure 3-4 used generally (but not systematically) lower materials costs that, if adjusted, would remove more than half of the difference to the module specific cost projections provided by manufacturer "A".

Taking these differences into account, the Panel considers ranges of \$340-420/kWh (500MWh/year production rate) and \$240-280/kWh (2500MWh/year) representative of manufacturers' specific cost projections for Li Ion modules using 45Ah high energy-design cells. These production rates correspond to annual production of 20,000 and 100,000 batteries of 25kWh capacity for small FPBEVs, or approximately 80,000 to 400,000 batteries of about 7kWh for a midsize PHEV-20.

Using the midpoint of the Li Ion module specific cost ranges above, and applying the cost scaling factors from Tables 3-11 and 3-12, the module specific and battery total costs for HEVs, PHEVs and FPBEVs summarized in Table 3-13 were calculated. The Panel recognizes that its approach – to estimate module and system costs for a range of cell and battery sizes from the specific cost of a single module type using a series of scaling factors – represents a simplification that cannot fully account for specific differences in cell, module and battery design and manufacturing features and costs. Clearly, a more sophisticated cost model, verified by comparisons with detailed materials, engineering and manufacturing cost studies, would be desirable for more confident projections of battery costs. However, in absence of such a model, and given the importance of cost projections to its assessment of advanced technology vehicles, the Panel proceeded with this approach. Confidence in its general validity comes from the fact that the projections given in Table 3-13 are generally consistent with the limited directly comparable data provided by manufacturers. The few projections the Panel received from automobile manufacturers also are broadly consistent with the costs in the table.

Table 3-13. Projected Costs of Li Ion Batteries

Vehicle Type	Battery Capac. (kWh)	Cell Capac. (Ah)	500MWh/year 20k Batteries/year			2500 MWh/year 100k Batteries/Year		
			Product. Rate (MWh/y)	Module Cost (\$/kWh)	Battery Cost (\$)	Product. Rate (MWh/y)	Module Cost (\$/kWh)	Battery Cost (\$)
FPBEV	40	120	500	285	13,680	2500	195	9,285
			800	255	12,240	4000	175	8,395
Small EV	**25**	**45**	**500**	**380**	**11,875**	**2500**	**260**	**8,150**
			20			**100**		
PHEV-40	14	45	500	380	7,075	2500	260	4,850
			280	435	8,350	1400	300	5,585
PHEV-20	7	30	500	435	4,305	2500	295	2,750
			140	595	5,190	700	405	4,025
PHEV-10	4	15	500	575	3,265	2500	395	2,240
			80	880	4,990	400	605	3,445
Full HEV	2	7	500	805	2,420	2500	550	1,650
			40	1,465	4,395	200	1,010	3,025

For each application, the table lists module specific and battery total cost projections for limited production rates (left half of table) and in mass production (right half). For each of these two levels of commercialization, cost projections are given for *capacity* production rates (MWh/year, upper numbers) and for *battery* production rates (batteries/year, lower numbers).

A key point to take from the cost projections in Table 3-13 is the substantial increase of module specific costs with decreasing cell size. For example, at the same MWh production rate, module specific cost increases around 50% when going from a cell size appropriate for a FPBEV to one suitable for a PHEV-20, and it nearly doubles when going from PHEV-20 to full HEV modules. The corresponding percentage increases are even higher for *battery* specific costs (not shown in Table 3-13) because the factor for scaling module to battery specific costs increases significantly with decreasing battery size, see Table 3-11. This is explained by the fact that balance-of-plant cost factors such as the battery management systems, hardware and enclosure contribute an increasing percentage of cost as battery size decreases.

One important consequence is that the differences in the costs of batteries for the different vehicle types are substantially less than the differences one would calculate from a strict proportionality of battery cost with capacity. For example, at the same *battery capacity* production rate (in MWh/year), the cost of a complete 40kWh FPBEV battery is estimated to be less than six times the cost of a 2kWh battery for a full HEV while the capacity ratio is 20. The effect is even more dramatic when comparing battery costs for the same *number of vehicles and battery systems* because of the much larger MWh capacity production rates (scale benefits) for FPBEV batteries: in that case, the cost of a FPBEV battery is projected to be only about three times HEV battery cost.

As another example, at the same mass production rate (100,000 systems per year), a PHEV-20 battery is projected to cost only around $1000 more than a full HEV battery, despite its 3.5-fold larger storage capacity. For a PHEV-10 battery, the difference of its cost to that for a full HEV battery is projected to be less than $500. This has direct implications for the life cycle cost competitiveness of PHEVs compared to HEVs, as is discussed in section 4 below.

Several other observations on the prospective costs of Li Ion batteries for ZEV and near-ZEV applications are pertinent. In the nearer term, the costs projected for the large batteries needed for full performance BEVs are likely to remain high, with little change from those projected by the BTAP 2000 Panel six years ago. The analysis also projects rather high costs for high power Li Ion batteries, for example approximately $3000 for a 2kWh HEV battery produced at an annual rate of 100,000 systems. This represents an important motivation for battery developers/manufacturers to obtain the highest possible power densities from HEV-design Li Ion batteries and thus reduce capacities as close as possible to the minimum energy (approximately 0.7kWh, see Table 3-2) required for full HEV applications. Caveats for this approach are that the cost reductions will be less than proportional to capacity reductions for the reasons discussed above. Also, capacity reductions will increase the average depth of discharge and the power densities experienced by batteries in HEV operation both of which tend to shorten life.

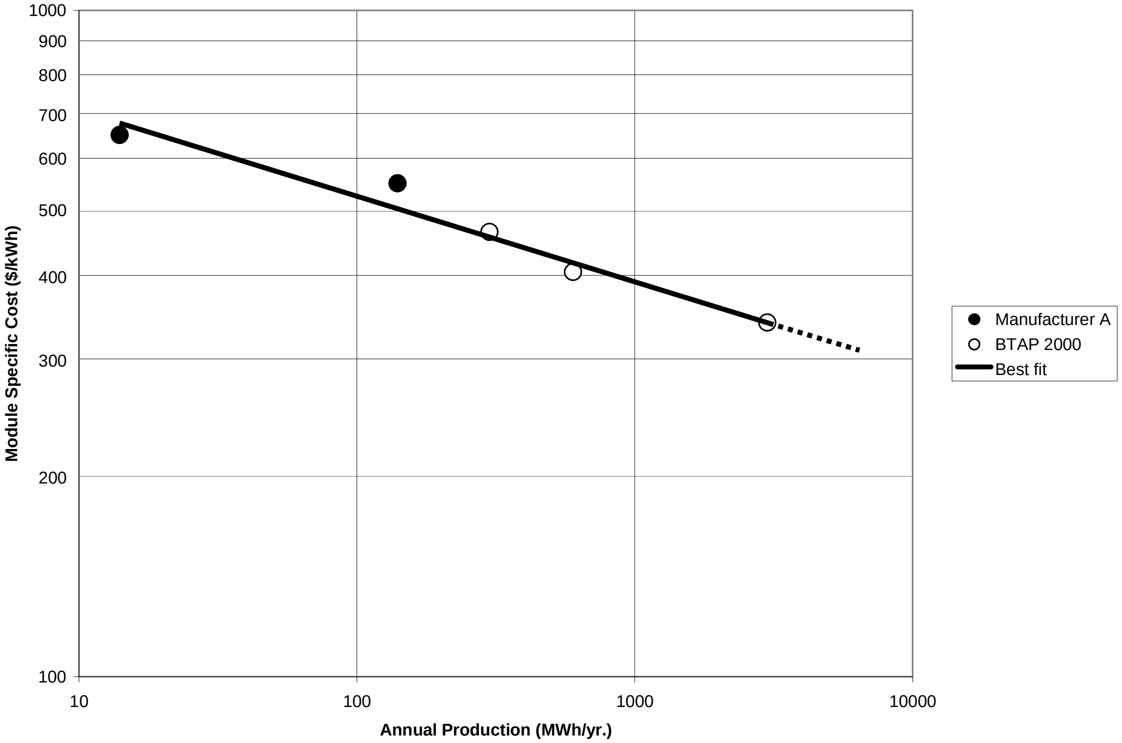
In the longer term, there appear to be good prospects for reduction of Li Ion battery costs for all applications through a combination of approaches that are likely to include development of new electrode materials with lower costs and/or higher capacities, cost reductions of inactive cell materials (especially separators and electrolyte salts) through improved and larger-scale production processes, lower costs of balance-of-system components, and advanced large-scale manufacturing processes, The magnitude of this cost reduction potential cannot be assessed at this time. As an example, however, just the combination of a 50% increase in specific capacity (mAh/g) and 50% reduction in cost ($/kg) of the active materials from those underlying the nearer term projections would reduce Li Ion module specific costs by about 20%.

2. Nickel Metal Hydride Battery Costs

Figure 3-5 shows the few indicators of NiMH module specific costs available to the Panel. They include projections obtained by one of the Panel members in 2003 (corrected for the higher nickel price and lower value of the US dollar in 2006) from a low-volume manufacturer of medium energy/medium power NiMH batteries. For comparison purposes, Figure 3-5 also includes projections of module-level specific costs for NiMH FPBEV batteries obtained by the BTAP 2000 Panel. (The original BTAP 2000 cost projections were increased by 10% to allow for inflation since the year 2000, and by the addition of $40/kWh to account for an approximate doubling of the nickel price since then.)

Fitting a straight line to the data in Figure 3-5 supports the projection of $430/kWh and $350/kWh as the specific costs of 40Ah high energy design NiMH modules produced at rates of 500MWH/year and 2500MWh/year, respectively. Using these costs, and assuming that the scaling factors for Li Ion technologies (Tables 3-11 and 3-12) are applicable, the projected costs summarized in Table 3-14 were estimated. This assumption is considered reasonable because material costs, cell designs and manufacturing methods for Li Ion and NiMH batteries with spiral-wound cells are quite similar.

Figure 3-5. NMH Module Specific Cost Projections



As expected from the consistency of the few newer NiMH cost data available to the Panel with the BTAP 2000 cost projections (see Figure 3-4), NiMH battery cost projections show little change from 2000 and thus remain high. The cost factor method employed by the Panel to estimate the specific costs of smaller NiMH cell sizes results in rather high costs of NiMH batteries for full HEV applications, even in mass production (e.g., 100,000 systems per year, see Table 3-14). The projected cost of approximately $1500/kWh (nearly $2,000 for 1.3kWh) for a mass-produced NiMH HEV battery explains the extensive efforts of established manufacturers to further increase power density and thus reduce the minimum battery storage capacity needed to provide the required power and energy. Significant for the life cycle economics of PHEVs is that the incremental cost of a NiMH PHEV-10 battery over a full HEV battery is less than $800; for a PHEV-20 battery, the difference is about $1,200.

Table 3-14. Projected Costs of NiMH Batteries

Vehicle Type	Battery Capac. (kWh)	Cell Capac. (Ah)	500MWh/year 20k Batteries/year			2500 MWh/year 100k Batteries/Year		
			Product. Rate (MWh/y)	Module Cost ($/kWh)	Battery Cost ($)	Product. Rate (MWh/y)	Module Cost ($/kWh)	Battery Cost ($)
FPBEV	40	120	500	320	15,360	2500	260	12,500
			800	300	14,285	4000	240	11,430
Small EV	**25**	**45**	**500**	**430**	**13,440**	**2500**	**350**	**10,500**
			20			**100**		
PHEV-40	14	45	500	430	8,005	2500	350	6,520
			280	520	9,680	1400	375	6,980
PHEV-20	7	25	500	490	4,305	2500	400	3,720
			140	595	5,200	700	460	4,275
PHEV-10	4	12	500	650	3,700	2500	530	3,015
			80	820	4,990	400	675	3,830
Full HEV	2	6	500	805	2,420	2500	740	2,110
			40	1,320	4,395	200	1,030	3,090

The comparison of Figures 3-4 and 3-5 and of the tables derived from them indicates that, for the same application and production rate, NiMH batteries are likely to cost more than Li Ion batteries. Further, the cost advantage of Li Ion is projected to grow with increasing production volume (steeper “cost learning” curve), primarily because most manufacturers’ projections assume significant future cost reductions for the key materials used in Li Ion batteries. On the other hand, the prospects for cost reductions of NiMH batteries below the numbers in the Table 3-14 do not seem promising since nickel costs (the major materials and battery cost factor) may well continue to rise.

3. Zebra Battery Costs

MES-DEA, the manufacturer of ZEBRA batteries, has published its projection of ZEBRA battery costs for different annual production volumes. This information, discussed and basically confirmed with the Panel, indicates that ZEBRA batteries of approximately 21kWh can be ordered now in quantities of 250 complete systems at a cost (price to OEM) of $12,’750 per battery, corresponding to approximately $600/kWh. For production in quantities of 10,000, 20,000 and 100,000 batteries per year, battery specific costs are projected by MES-DEA to be $335/kWh, $275/kWh and $200/kWh, respectively. These costs fully account for all cost factors, including amortization of plant investment, warranties and profit. They are judged by the Panel to have good credibility because not only the basic battery technology but the complete manufacturing technology and the manufacturer’s plans for expansion of capacity appear well established.

The current and projected ZEBRA battery costs are substantially lower than the costs of all other advanced battery technologies, including Li Ion and NiMH batteries of similar capacities produced in comparable quantities. The main reason appears to be the lower cost of the materials from which the ZEBRA battery is manufactured: ordinary salt, nickel (in quantities well below those needed per kWh of NiMH battery), aluminum chloride, and aluminum oxide. MES-DEA estimates the specific cost of these materials as $60/kWh of ZEBRA battery capacity. The materials specific cost for NiMH and Li Ion batteries, on the other hand, are unlikely to decline below $100/kWh.

4. Battery Costs and Propulsion Energy Cost Savings

Comparisons of the projections in Tables 3-13 and 3-14 with the cost goals in Table 3-4 above suggest that, even in mass production, the costs of Li Ion and NIMH batteries exceed the goals for FPBEVs and HEVs substantially. On the other hand, Li Ion and NiMH batteries designed for PHEV applications -- especially for PHEVs with shorter electric ranges -- appear able to meet or approach the preliminary cost goals, probably because these new goals already reflect the recent escalation of motor fuel prices that have increased the economic value of higher fuel efficiencies and of the cost savings from displacement of petroleum-based fuels with electricity.

Under these circumstances, higher first costs of advanced-technology vehicles are likely to become more acceptable to vehicle owners, and some or all of the acceptable cost difference can be allocated to the battery. It is appropriate, therefore, to compare battery cost projections not only with historic cost goals but with the value of the fuel cost savings enabled by the batteries of ZEVs and near (including partial) ZEVs. Underlying this direct comparison is the key assumption (frequently made, also in Section 6 of this Report) that the costs of mass-produced ZEVs and advanced-technology vehicles *minus* battery will be approximately the same as the cost of a complete ICE vehicle of comparable performance and accommodations.

Table I-1 in Appendix I lists the net present values (NPVs) of the fuel cost savings realized by HEVs, PHEVs and BEVs relative to conventional ICE vehicles, calculated with the assumptions noted in the appendix. A number of observations can be derived from comparisons of the cost projections in tables 3-13 and 3-14 with the fuel cost savings NPVs:

- Net present values of fuel cost savings generally exceed currently accepted battery cost goals. Specifically, for HEVs, the NPV substantially exceeds cost goals in every scenario used to calculate these NPVs. For PHEVs and FPBEVs, NPVs exceed battery cost goals in all but the conservative near term scenario.

- For full hybrid electric vehicles (HEVs), the fuel cost savings NPV approximately matches the projected cost of a mass-produced Li Ion battery and approaches the cost of a mass-produced NiMH battery in the least favorable (the conservative near term) scenario. In all other scenarios, the costs of mass-produced Li Ion and NiMH battery costs are significantly less than fuel cost savings NPVs.

- For a PHEV-20, the costs of mass-produced NiMH batteries are almost 50% higher than the NPV in the least favorable scenario, but Li Ion battery costs exceed NPV by only 15%. In all other scenarios, the cost of mass-produced batteries are below NPVs, substantially so in the favorable long term scenario. In the favorable near term and unfavorable longer term (“middle”) scenarios, NPVs approach the cost of Li Ion and NiMH batteries produced even in pre-commercial quantities.

- For all but the conservative near term scenarios, fuel cost savings NPVs exceed battery costs by larger amounts for the PHEV-20 than for the full HEV. That is, a PHEV-20 has lower life cycle costs than a HEV because the substantially lower per-mile cost of electricity more than compensates for the higher cost of the PHEV battery.

- For a PHEV-40 vehicle, NiMH and even Li Ion battery costs exceed the fuel cost savings NPV significantly in the least favorable scenario. Li Ion costs are near or below NPVs in all other scenarios, NiMH costs only in the favorable long term scenario. For batteries produced in early commercialization quantities (20,000 systems per year), costs are in the range of NPVs only in the most favorable scenario. The fuel cost savings NPV approximately matches the projected cost of a mass-produced Li Ion battery and approaches the cost of a mass-produced NiMH battery

- Finally, for small and midsize full performance electric vehicles (FPBEVs), the costs of mass-produced Li Ion (25kWh and 40kWh) batteries exceed the NPVs of fuel cost savings in all but the favorable longer term scenario. In the middle scenarios, battery costs are about 15% above NPVs. On the other hand, mass-produced ZEBRA batteries for small BEVs cost less than fuel cost savings NPVs in all except the least favorable scenario.

E. Battery Manufacturers: Technology and Availability

This section summarizes information collected by the Panel on the development and commercialization status and plans of prospective manufacturers of the battery technologies reviewed in Sections 3.C and 3.D. The focus is on companies that were visited by Panel members or that provided key staff for off-site meetings with the Panel. The section also summarizes information received in response to the Panel's battery questionnaires (see Appendices A and B) and through follow-up contacts with organizations not visited by the Panel. Companies are listed in alphabetical order.

A123Systems (A123) is an investor-owned U.S. company formed in 2001 and located in Watertown, MA. The company develops and manufactures Li Ion batteries that use proprietary iron phosphate (LFP) positive electrode technology based on initial developments of MIT. Structurally and chemically stable LFP positives provide excellent safety and long life, even at elevated temperature, and the nanostructured (highly disperse) electrodes enable high charge and discharge rates, a prerequisite for high power applications. Technical details confirming these capabilities were presented by A123 staff at recent conferences, including EVS-22 and the September 2006 ZEV Symposium of the California Air Resources Board.

A123Systems owns and operates several Li Ion cell manufacturing plants in Asia and the U.S. that according to A123 meet stringent manufacturing quality standards. The company successfully developed and commercialized 2.2Ah type 26650 Li Ion cells and modules for power tools, a new and very promising application for Li Ion technology. A123 is now engaged in the development of higher-power cells for application in HEVs. In pursuit of this goal, the company received $30 million in investments in early 2006 and a $15 million contract from USABC for development of advanced HEV batteries in December 2006.

Altair Nanotechnologies (Altairnano) is an investor-owned, NASDAQ-listed U.S. materials company headquartered in Reno, NV. Altairnano is specializing in development and commercialization of pigments based on titanium oxide (TiO_2). In 2000, the company initiated development of lithiated TiO_2 into a new negative electrode material for Li Ion batteries, to replace the universally used graphitic and/or amorphous carbon electrodes. The advantages of eliminating elemental lithium from Li Ion battery -- inherently higher safety, lower resistance and better reversibility of this new Li Ion chemistry -- were discussed in section 3.3, above. For applications such as HEVs that require very high levels of power density, efficiency, lifetime cycles and safety in a small battery, these advantages might well balance the lower energy density and higher cost that must be expected for this chemistry because of its lower cell voltage of approximately 2.5 V

Altairnano occupies a 100,000 square foot facility of offices, laboratories and manufacturing areas in Reno, NV, that includes a pilot plant for titanium dioxide nanoparticle production. An experienced battery technology team acquired by Altairnano developed a 2.5V Li Ion cell technology with the company's nano-titanate negatives and using a soft cell packaging technique. Prototypical battery modules with such cells were first fabricated in September 2006 and demonstrated in a complete 35kWh battery pack powering a Korean-manufacture SUV converted to electric drive by Phoenix Motorcars. Altairnano has developed an 11Ah cell for a 35kWh battery to be fabricated in 2007 and evaluated in BEV conversions fabricated by Phoenix Motorcar. DOE awarded Altair Nano a $2.5 million contract for continued technology improvement through materials optimization and extension of battery cell operability to a wider range of temperatures. An initiative to evaluate the Altairnano technology in PHEV conversions is in negotiation.

Electrovaya is a small investor-owned technology development company with headquarters in Toronto, Canada, and manufacturing facilities in Toronto and in Saratoga Springs, NY. The company's four groups focus on development, engineering, manufacturing and applications of Li Ion battery technology. Electrovaya's 156,000 sq.ft. manufacturing facilities have a current Li Ion cell production capacity of 5 MWh/month that is being expanded to 10 MWh/month (120 MWh/year) which will be among the largest Li Ion production capacities in North America. The company's Li Ion technology products include flat, large area batteries that provide laptop computers with extended running times, and portable power systems for astronauts. In these developments, Electrovaya has demonstrated the design flexibility of its technology and the company's capability to develop, engineer and fabricate complete power system based on that technology.

Key elements of Electrovaya´s proprietary technology include use of nanostructured active materials, a highly conducting "SuperPolymer" electrolyte and Z-folding cell construction, to achieve high conductivity and charge/discharge rate capabilities. The technology can utilize all positive and negative electrode materials commonly used in Li Ion cells. In addition, Electrovaya has developed its own proprietary positive electrode material and manufacturing process to the pilot plant level. This material is claimed to exceed the specific capacity of established positive materials by 40-70% and to enable cell energy densities exceeding 200Wh/kg. Based on this cell technology, Electrovaya`s 750Wh, 15V module achieves energy densities of 150Wh/kg (gravimetric) and 260Wh/L (volumetric). The company claims calendar life exceeding seven years as well as a high level of safety due to use of very stable electrode materials. UL approval for the technology has been obtained on the cell, module and battery level.

Electrovaya is now positioning itself for the anticipated expansion of Li Ion battery markets in the transportation sector. For ZEV applications, it has 750Wh/50Ah and 1.4kWh/90Ah modules that are used in complete BEV batteries. These include an 80kWh system for delivery vans being evaluated in a fleet demonstration program. The company has established the capability for development and engineering of complete, Li Ion battery-based electric drive systems including integrated battery management, high-efficiency motor and motor control technology, and the software needed to control the system.

Electro Energy, Inc. (EEI) is a battery technology, engineering and manufacturing organization headquartered in Danbury, CT. Founded in 1992. EEI invested more than a decade and $30 million in the development of a bipolar nickel metal hydride battery technology while meeting its customers' needs with EEI's proprietary battery technologies and systems. The patented NiMH bipolar technology is claimed by EEI to be lighter, more efficient, longer lasting and less expensive, and have a greater range of applications, than other NiMH technologies. One basis of this claim is the fundamental fact that bipolar batteries of "stacked" cells have simpler design, fewer parts, lower resistance and more uniform current distribution than the generally employed monopolar cell designs. The second basis is EEI's claim to have solved the known difficulty of integrating many individual cells into a stack with seals that endure conditions in the cell over the life of the battery.

EEI has developed the technology to the laboratory prototype stack and battery level and is accumulating experience with experimental batteries, including a 6kWh, 220V battery (see Table 3-6) used to convert a Prius HEV to operation as a PHEV. Over the next two years, EEI expects to advance this technology to commercial readiness for conversion of HEVs to PHEV operation.

GAIA Accumulatorenwerke (GAIA) is a subsidiary of Lithium Technology Corp. (LTC), a publicly traded US company largely owned by a Dutch venture capital firm. GAIA's business is Li Ion technology development and production, currently on a limited-scale for military and developing commercial applications including transportation and stationary power, in a 170,000 sq.ft. facility in Nordhausen, Germany. LTC's business includes assembly of complete batteries from GAIA cells, R&D support for GAIA, and limited production of prismatic cells.

GAIA's Li Ion technology uses well established cell materials and designs: NCA positive and graphite negative electrodes, conventional electrolyte compositions and standard separators. Cell construction is by spiral winding of electrodes made by a proprietary extrusion process. This process has potential to reduce production cost, simplify scale-up, and reduce environmental impact. A variety of cell types are manufactured, ranging from high power 7.5Ah cells to high energy cell designs with 120Ah and more capacity. GAIA also has developed a battery management system based on master control and "slave" modules for electric and thermal management of individual Li Ion modules. This system is produced in limited numbers and used in complete batteries supplied by GAIA/LTC. In volume production, the cost of such a system is expected to be around $2 per cell in the battery.

Cell production capacity currently is approximately 4000Ah/day, or about 4 MWh/year, corresponding for example to 200 batteries of 20kWh for a small FPBEV. Based on the expected demand of niche markets, a 10-fold scale-up will be implemented at the Nordhausen facility within a year. A production plant representing another 10-fold scale-up could be built on site within less than 2 years if justified by demand.

Experimental transportation applications of GAIA Li Ion cell technology include a 2kWh/25kW battery for a Smart-based HEV, a 8kWh (45Ah cells) battery for a small series PHEV with 50 miles electric range, a similar battery for an experimental PHEV of an automobile manufacturer, and a 25kWh/200kg battery for a BEV converted from a Daihatsu small car by Innosys, a small Dutch company. All of these batteries use air cooling, considered adequate because of the very low impedance, low heat generation and good heat dissipation of GAIA cells. The Innosys BEV has a nominal range of 250km (about155 miles), with actual ranges falling between 150-300 km (about 95-190 miles), depending on conditions and drivers. GAIA executive management foresee lifecycle cost competitiveness of volume-manufactured, Li Ion battery-powered small BEVs with conventional ICE cars in Europe.

GS Yuasa (GSY) was formed in 2004 by merging GS (formerly Japan Storage Battery Co.) and Yuasa, battery companies with similar history, size and battery products. A joint venture company with Sanyo produces small (type 18650) Li Ion cells for consumer electronic products but price competition is severe in that market. Li Ion technology in larger cell sizes has been developed, and 40 and 80 Ah cells are now in limited-scale production (roughly 1 MWh/year) for special applications, including leveling of electric train peak loads, automated guided vehicles (more than 1000 systems on order), stand-by power and other industrial applications. These cells use lithium manganese spinel-based positives and other established cell materials. Cells are assembled into multi-cell modules that include their own battery management units, with cells making up 90% of module weight. Air cooling is considered adequate for discharge rates up to 5C.

For the emerging power tool application of Li Ion batteries, GSY has developed technology based on lithium manganese spinel positives, polymer (gelled) electrolyte and laminated cell construction; cell life is limited to around 3 years because of slow electrolyte solvent loss through the plastic cell enclosures.

Under the Japanese NEDO (Government-funded) battery R&D program, GSY developed 10Ah Li Ion cells and a 0.3kWh prototype module for HEV applications. A battery using these modules would meet the program's power and energy density targets of 1800W/kg and 70Wh/kg, respectively; these targets are somewhat more demanding than the USABC targets, see Table 3-2. GSY also is participating in the new NEDO program to develop Li Ion technology suitable for PHEV applications.

Hitachi Vehicle Energy (HVE) was established in 2004 as a joint venture of Shin Kobe Electric Machinery, Hitachi and Hitachi Maxell, to develop, manufacture and market Li Ion batteries for HEV and other applications. The venture's Li Ion battery capability is based on the competency and technology established by Shin Kobe during the preceding decade which included development of Li Ion modules and batteries for BEV and HEV applications. One of the developments, the Li Ion battery used in BEVs based on the Nissan Tino compact van, has demonstrated more than 6 years of service life.

Efforts are ongoing at HVE to improve the power density and energy density of modules and batteries for light vehicle (electric bike and scooter) and HEV applications. HVE 1.8kWh Li Ion high power batteries currently are under test in 20 FedEx vehicles that use a HEV drive train developed by Eaton.

HVE's high power Li Ion technology is considered ready for industrialization. The key for commercial success will be the development of manufacturing processes capable of large scale production of high quality cells, modules and battery systems at competitive costs. HVE expects to see Li Ion batteries introduced in HEVs in 2008, with mass production (e.g., 100,000 system per year) to begin in 2010. In the meantime, battery cell materials, designs and manufacturing are being advanced.

Hitachi Vehicle Energy is a participant in the NEDO-sponsored program to develop a 3kWh Li Ion battery that meets the targets for the energy storage system of fuel cell vehicles. HVE also may participate in the new NEDO program to develop a PHEV battery, but the targets for that program have not yet been set.

JCI-SAFT Power Solutions (JCS) is a joint venture of Johnson Controls, Inc., the world's largest manufacturer of lead acid automotive batteries, and SAFT, a French company with established leadership in nickel cadmium and nickel metal hydride industrial batteries, primary lithium batteries, and Li Ion batteries for defense and space applications. The mission of the joint venture is to develop and commercialize Li Ion batteries for a range of passenger car and heavy duty HEVs, BEVs and PHEVs.

The Li Ion technology base of the joint venture centers on established (NCA) positive and graphite negative electrode materials, electrolytes, separators, and the spiral winding manufacturing technique developed by SAFT over the last 15 years. Supported by world-class R&D, this development has yielded high-quality, mature cell and module technology in a range of cell sizes of both, high energy and high power designs that have been manufactured and tested in vehicles for 6-7 years by now. Many of the data in this report (see section 3.C) attesting to performance, long cycle and calendar life, and high safety levels of Li Ion technology were obtained by SAFT and provided to the Panel by JCS.

JCS is currently operating a pilot plant in Bordeaux (France) capable of producing 6 MWh/year of Li Ion cells in various capacities and power densities. Batteries made with cells and modules produced in this plant have been used in more than 60 experimental and demonstration BEVs that have accumulated an excellent safety record. Current applications include 23kWh batteries for 30 Renault Kangoo subcompact delivery vehicles converted to FPBEVs and PHEVs by Dassault, with a potential market of 60,000 such vehicles for the French Postal Service, and several prototype DaimlerChrysler vans converted to PHEVs with about 20 mile electric range. DaimlerChrysler just announced plans to fabricate about 20 Sprinter Li Ion battery powered PHEVs in the next phase of this program. Earlier in 2006, the joint venture was awarded a contract by USABC for improvement of high power Li Ion technology for HEV application.

JCS is in the process of negotiating a contract for production of high power Li Ion batteries for a major automobile manufacturer. This will require establishment of an automated battery manufacturing plant with a lead time of 1½ to 2 years from the go-ahead decision to validation of the process and product, indicating a possible 2008 start of volume production. Because of the high degree of automation of such a plant, it does not have to be sited in a low-wage country.

Through its affiliation with Varta, JCS also has NiMH technologies for application in ZEVs and near-ZEVs. Varta's 7Ah high power NiMH cell and module technology meets the performance and cycle life requirements for HEV applications, and its 25Ah and 45Ah technology has been used successfully in hybrid buses and, more recently, in prototypes of the DaimlerChrysler "Sprinter" PHEV-20 van. Both of theses technologies are in low volume production.

Kokam Co., Ltd. (Kokam) is a Korean company established in 1989 to develop and manufacture polyester film processing machinery. Drawing on its technology leadership and experience in film processing, Kokam developed a novel continuous process for production of Li Ion cells. This proprietary process involves lamination of positive and negative electrodes to a continuous polymer electrolyte-separator film, followed by a precision folding process and sealing of the resulting laminated cell stack into a metallized plastic enclosure. Due to this electrolyte and the very low resistance of the stacked-design cells, Kokam considers its technology to be safer than liquid-electrolyte cells. Performance of Kokam's cell technology equals or exceeds that of conventional spiral-wound cells; deep cycle life also is excellent, with more than 3000 cycles achieved at 80%DoD.

Kokam's cell production process is simpler and more flexible than conventional spiral winding of cell structures followed by electrolyte filling, and Kokam claims it can produce a new cell size in less than two months. With this flexibility, Kokam is able to rapidly utilize the excess capacity of existing Li Ion cell manufacturing plants for the production of a large variety of cells, from fractional Ah sizes to 240Ah, and in high energy as well as in high power designs. Kokam claims that its process is readily adaptable to different Li Ion chemistries, and a that new Li Ion chemistry promising exceptional levels of power, safety and cycle life is currently being adapted.

A wide range of consumer products applications is presently served by Kokam, and plans include establishment of technology and manufacturing capability for light vehicle, HEV and small BEV batteries. Prototype 30kWh FPBEV batteries comprising 100Ah cells and 5kWh PHEV batteries with 40Ah cells have been built as have 2.6kWh batteries for HEV applications. Because of the low resistance of Kokam's cells, even the high energy (FPBEV) design cell and battery has high power density.

Current cell production capacity is about 50 MWH per year, approximately the capacity of an economically viable, stand-alone cell manufacturing plant. A new plant of that size can be established in less than one year because of Kokam's vertical integration that includes fabrication of battery manufacturing equipment. Kokam America, a wholly owned subsidiary of Kokam, has taken steps to establish a cell manufacturing plant in the U.S., with the goal to have the plant on line in 2008 if justified by demand for the product.

Matsushita Battery Industrial Co. (Matsushita) headquartered in Osaka, Japan, is a major manufacturer of nickel cadmium, nickel metal hydride and lithium ion batteries marketed under the "Panasonic" name. Matsushita's strong corporate R&D was responsible for the development of the first generation of the NIMH battery technology for the Prius and Insight HEVs. Together with Toyota, the company owns Panasonic Electric Vehicle Energy (PEVE), the battery company manufacturing the very high power NiMH batteries for Toyota's HEVs.

Matsushita is a major manufacturer of type 18650 Li Ion cells for consumer products (400 million cells, or approximately 2000 MWh per year), and the company is now also manufacturing Li Ion cells for power tools. As part of NEDO's Japanese national program for development of Li Ion batteries for HEV applications, Matsushita met the program technical targets with cell technology based on NCA positives and an improved, partially graphitized negative electrode material. Matsushita's cells combine very high power density and good energy density. With some changes (including the positive material), this technology could become the basis for commercially produced Li Ion HEV batteries. These would be manufactured by an established HEV battery production company, presumably PEVE.

Litcel Co. (Litcel) is a small Japanese company, founded in 2000 and located in Fukuda-cho. Litcel is owned by Mitsubishi Motors Corporation (majority owner) and TDK Corporation. The mission of Litcel is to develop and manufacture Li Ion batteries for mobile and stationary applications. The Litcel technology uses a recently developed positive electrode composition (50% NCM/50% LMS) in combination with standard cell materials and spiral (oval) winding construction. Over the past five years, the technical team of Litcel has advanced this technology to the point (see Table 3-6) where it is believed to meet the performance, durability and safety requirements for BEV applications. Development work is continuing with the goal to increase cell and module energy densities (currently 115 Wh/kg) by 20% in the near term.

Construction of modules and batteries for BEV applications has been initiated, with focus on a

20kWh battery system for the recently announced “MIEV” minicar of Mitsubishi Motors. Litcel’s current production capacity is about 60 batteries (~ I MWh) per year, planned to increase to 1200 batteries (~20 MWh) per year within two years.

NEC Lamilion Energy (Lamilion) is a small Japanese company established in 2002 and located in Kanagawa near Tokyo. Lamilion, now owned entirely by NEC, has as its mission the development and manufacture of Li Ion batteries based on the laminated-electrode/polymer electrolyte Li Ion cell technology originally developed at NEC. Among the advantages of Litcel’s technology is simplified manufacturing and ease of thermal management of the flat cells. The technology uses lithium-manganese spinel (LMS) positive electrodes because of the high structural stability and potentially lower cost of LMS. The chemical stability against manganese dissolution has been improved through use of proprietary additives to the electrode and/or electrolyte.

The current focus of Litcel is the limited-scale manufacture of a Li Ion battery for evaluation and possible commercialization in the small R1e battery electric vehicle developed jointly by Fuji Heavy Industries (owners of Subaru) and Tokyo Electric Power Company (TEPCO). The R1e battery delivers about 9kWh, has a peak power of more than 60kW (90kW when fully developed), can be recharged to 80% in 15 minutes, and is expected to last 10 years or 200,000 km in deep cycling. Together with the projected battery costs and fuel cost savings, this is expected to make the battery and vehicle economically competitive in providing transportation services for TEPCO staff in the Tokyo metropolitan area.

Panasonic EV Energy (PEVE), jointly owned by Toyota (majority share holder) and Matsushita Electric Industrial Co., is the world leader in the manufacture of NiMH batteries for transportation applications. PEVE was formed in 1996 to manufacture and market NiMH batteries, originally for BEVs. The 95Ah NiMH cell technology, an early product of PEVE, established the technology’s excellent reliability and durability in nearly 3000 FPBEVs produced by several major automobile manufacturers, largely in response to the California ZEV regulations (see also Section 6 of this report). PEVE also produced 28Ah NiMH cells and modules for Toyota’s now abandoned eCom city electric vehicle. Production of the 95Ah and 28Ah NiMH technologies was discontinued by PEVE in 2003/04.

The PEVE plant in Kosai City, Japan, is the world’s largest, fully automated manufacturing facility for NiMH HEV batteries. The plant’s capacity has been increased several times and now enables module production for approximately 500,000 batteries per year, used in Toyota’s HEVs and most of Honda’s HEV products. In 2007, PEVE will add a new plant with an annual module capacity for 500,000 HEV batteries (approximately 750 MWh). According to PEVE, the costs of batteries produced in smaller volumes (e.g., 15-30k systems per year) are broadly consistent with the projections of the Panel’s cost model, but mass production costs were not disclosed.

In parallel with NiMH battery production, PEVE and its owners are carrying forward development and engineering activities to further improve the technology, with emphasis on achieving higher power densities to reduce the minimum capacities -- and thus the costs -- of batteries capable of meeting the performance requirements posed by established and emerging HEV types and models. PEVE is collaborating with Toyota and Matsushita in Li Ion high power battery development and expects to become involved in Li Ion battery manufacturing once the technology is considered ready for commercial application in HEVs.

Sanyo Electric Co. (Sanyo) is the world leader in the production of NiMH cells for consumer products, holding a 50% market share. On the basis of its commercial D-size NiMH cell technology, Sanyo developed several generations of spiral-wound cells for HEV applications. First generation batteries met peak power requirement for HEV applications but only at a 100% weight penalty over the generally accepted 50kg target for an HEV battery. Sanyo's 3rd generation NiMH technology has much higher power density that will enable a substantial cell and battery capacity reduction to meet the weight target. Further increases in cell and battery energy and power density, as well as improved life, are expected from introduction of Sanyo's "superlattice" nickel-based alloys as negative electrode materials.

Sanyo's HEV-type cell production capacity will soon reach 2 million cells per month, corresponding to an annual production rate of approximately 100,000 HEV batteries per year. Even at this rate, HEV cell production will make up not much more than 1% of Sanyo's total production of NiMH cells. Sanyo does not produce NiMH technology in the larger cell sizes that would be appropriate for PHEV or (FP) BEV batteries.

Sanyo also is the world leader in the production of small Li Ion cells for consumer products. From this technical basis, Sanyo has been developing Li Ion technology for HEV applications. The gravimetric power and energy densities of developmental high power Li Ion cells double NiMH cell performance while volumetric densities and shallow cycle life are comparable. Further gains are expected from continued development. Sanyo is prepared to make the large investments in mass production facilities once the technical and market prospects of Li Ion technology in the automotive market are sufficiently favorable.

F. Summary and Conclusions

The Panel's investigation of vehicle energy storage systems focused on batteries as the only viable energy storage option for zero and near-zero emission vehicles, at present and in the foreseeable future. The emphasis was on Li Ion technologies because of their rapid technical progress and excellent potential to meet the energy storage requirements for full (including fuel cell) hybrid, plug-in hybrid, and full performance battery electric vehicles. However, the Panel study also covered nickel metal hydride batteries because of their near term importance for HEVs (including fuel cell HEVs) and their potential for PHEV applications. Finally, it examined the status of ZEBRA (sodium-nickel chloride) and lithium-sulfur batteries because of their near and, respectively, longer term potential for FPBEV applications.

The investigations of the Panel established that battery technologies have advanced remarkably since the 1999-2000 review commissioned by the California Air Resources Board. These advances were, and still are, driven by several diverse but interrelated factors: the emergence of a substantial and growing market for hybrid electric vehicles, especially in the U.S.; the blossoming of lithium ion battery technology through discovery and exploitation of the extensive technical opportunities surrounding this "family" of batteries; and the resurgence of interest in battery electric vehicles under the double impact of escalating fuel prices and advancing battery technologies. The rapidly growing interest in plug-in HEVs is adding another incentive and challenge for the development of more capable batteries.

The main findings and conclusions of the Panel from assessing the technical and cost status and prospects of these battery types are summarized below, followed by some observations on the strategies and positions of battery and automobile manufacturers that bear on development and availability of batteries for ZEVs and near (including partial) ZEVs.

1. Panel Assessment

a) Nickel Metal Hydride Batteries

High power NiMH batteries designed for HEV applications are now mass-produced in Japan for a growing number and variety of HEVs. The performance (especially the gravimetric and volumetric power density) of the technology has been increased through several generations of cell and module design improvements, and batteries in the range of 1-3kWh now meet all performance requirements for full HEVs. The technology also appears to have sufficient shallow cycling capability and calendar life to last through manufacturers' warranty periods and for a nominal 10-year vehicle life. It is not yet clear whether the endurance of NiMH batteries can be extended to 15 years. To meet growing demand, the manufacturers' production capacities are being expanded by adding new plants with module capacities sufficient for up to 500,000 battery packs (complete systems) per year. These nearly fully automated plants reflect extensive manufacturing technology learning and represent large investments, likely to make it difficult for competitors to enter the market.

The biggest issue for the manufacturers and automobile industry users of high power NiMH batteries for full (including fuel cell) HEVs is their relatively high cost. While cost data were not made available by the manufacturers, we estimate on the basis of a simplified cost model developed by the Panel that such batteries cost approximately $1500/kWh to $1,000/kWh (100,000 to 1 million systems per year). This translates into a cost of about $2,000 to $1,300 for a compact HEV (1.3kWh) battery and $4000 to $2,500 for a midsize full HEV (e.g. 2.5kWh) battery. These costs make up much of the cost difference between presently marketed HEVs and their counterpart ICE vehicles, and they represent a strong motivation for manufacturers to seek battery cost reductions.

Higher battery power density permits the power and energy required by a full HEV to be delivered by a smaller and thus less expensive battery. However, because high power NiMH technology is getting close to the limits of power density, and since the costs of mass-produced NiMH batteries per kWh of capacity are unlikely to decline, the Panel concludes that reductions of HEV-design NiMH battery costs beyond incremental savings through the economies of mass production are unlikely. This is an important reason for the large current efforts to develop and introduce HEV-design Li Ion batteries that offer higher power densities and potentially lower costs (see below).

Medium energy/medium power NiMH battery technology is of possible interest for application in PHEVs with shorter (e.g., 10-20 mile) nominal electric range for which the technology can meet power and energy density requirements. PHEVs pose very demanding deep cycle life requirements that would have been considered beyond the capabilities of NiMH batteries five years ago. However, at least one manufacturer is claiming capability for 3000 deep cycles for his technology, and the results of ongoing PHEV-type battery cycling tests are confirming this claim. For all types of NiMH batteries, achieving the goal of a "vehicle lifetime" (10-15 year) battery is contingent on careful management of battery temperature (level and uniformity) and of battery charging. To reach a 15 year life may require materials advances to further reduce the already very low rates of negative electrode corrosion and hydrogen loss through cell walls.

The costs projected by the Panel's model for mass-produced medium energy NiMH batteries for PHEVs with 10 and 20 miles of nominal electric range are not much higher than the preliminary cost goals currently being considered for PHEV batteries. More importantly, for most of the foreseeable fuel and electricity price scenarios and vehicle efficiencies, the estimated fuel cost savings realized by shorter-range PHEVs in comparison with their counterpart ICE vehicle exceed projected battery costs. The Panel's battery cost model also projects lower life cycle costs for shorter-range PHEVs than full HEVs. This finding appears to mitigate the concerns about unacceptably high costs of PHEV batteries mentioned by automobile manufacturers.

The Panel concludes that medium energy/medium power NiMH batteries appear to have reasonable prospects for meeting the technical requirements and cost constraints for PHEVs with relatively short nominal electric range. However, only a few small manufacturers of NiMH batteries have built PHEV-design NiMH batteries and demonstrated them in experimental PHEVs and the major battery and automobile manufacturers do not seem interested in this NiMH application. One reason may be that medium energy Li Ion batteries appear to offer better technical and cost potential for PHEV applications (see below).

High energy NiMH battery technology is no longer a target of development and possible cost reduction efforts because of the realization that such batteries are unlikely to meet the performance and cost targets for full performance battery electric vehicles. The Panel's review did not identify significant advancements in FPBEV-design high energy NiMH battery technology. The costs of such batteries in mass production would likely be even higher than those projected in 1999/2000, primarily because of the nickel price escalation in recent years. These costs exceed not only FPBEV battery cost goals but the value of the fuel cost savings achieved by BEVs in all currently envisioned scenarios. The Panel concludes that large weight and high costs are likely to limit the technical and market prospects of the large-cell, high energy NiMH batteries that would be appropriate for FPBEV applications.

b) Lithium Ion Batteries

High power Li Ion battery technologies have been developed by a number of prospective manufacturers in Asia, Europe and the U.S., among them major producers of small Li Ion cells for consumer applications who are aiming to enter the expanding markets for power tool and HEV batteries. The high power Li Ion technologies and production techniques of these manufacturers appear to be close to commercialization. It seems likely that one or more of these manufacturers will be the first to commercialize Li Ion batteries for HEV applications, in close collaboration with automobile manufacturers, probably in Japan. The Panel was led to believe that commercial introduction of Li Ion batteries in HEVs will occur in 2008. In view of the number and capabilities of the companies engaged, it seems likely that substantial competition will develop over time to drive Li Ion technology forward and costs down.

Several entrepreneurial organizations, some associated with larger companies, are targeting the same markets for their Li Ion technologies, and a number of smaller organizations are concentrating on development and limited production of high power cells for premium applications in the space, military and industrial fields. These developments have resulted in a variety of advanced Li Ion cell materials including nanostructured (highly disperse), doped lithiated iron phosphate positives and titanium oxide negatives, and new manufacturing techniques such as lamination of cells using polymeric electrolyte-separator films. Most of these technologies have reached the limited cell production and prototype battery levels, and several U.S. companies in this group have, or are closely associated with, Asian Li Ion cell manufacturing facilities. Whether any of these developers has the focus and resources to enter the market for HEV high power batteries is not clear at this time. As little as one year, but typically 2-3 years, were mentioned as the time required from a go-forward decision to establishment of a first production plant, assuming availability of the required technical and financial resources.

The Panel's model projects that in mass production the costs of HEV-design, high power Li Ion technologies could be lower than those of high power NiMH batteries for the same storage capacity, substantially lower on the more important basis of equal power capability. The introduction of Li Ion batteries for HEV applications thus could reduce the cost difference between HEVs and conventional vehicles. It also can be expected to assist and accelerate the development and introduction of Li Ion batteries for PHEVs and for FPBEVs.

<u>Medium energy/medium power Li Ion battery technologies</u> meeting the performance and life requirements for application in small FPBEVs and in PHEVs have been developed to the prototype and low volume production level in Asia and Europe but apparently not in the U.S. The developing companies include several that are also active in high power Li Ion battery development and that use the same, well established Li Ion cell chemistries and manufacturing methods. A somewhat special role is played by JCI-SAFT Power Solutions, the joint venture between SAFT, a world leader in larger Li Ion cell and battery technology, and JCI, the world's largest battery company. The joint venture appears committed to the commercialization of Li Ion batteries not only for HEV but also for PHEV and small FPBEV applications, and its technology has established very long calendar life and the capability for more than 3000 deep-discharge cycles.

A few Li Ion battery developers are engaged exclusively with medium power/medium energy technologies. Driven by the need for the lowest possible costs per kWh of storage capacity to meet the cost constraints for PHEV and FPBEV batteries, these companies typically use lower cost positives such as NCM or LMS modified to increase stability, cell fabrication methods based on lamination and z-folding of electrodes, and lower-cost soft cell enclosures. While there are still questions whether the cycle and calendar life of these technologies can meet requirements for BEV and PHEV applications, at least one of the manufacturers (Kokam) claims a life of more than 3000 deep cycles and ten years, characteristics that would meet the requirements for BEV and even PHEV applications. Achievement of very long cycle and calendar life for all types of Li Ion batteries requires appropriate controls that keep average temperatures below approximately 45℃ and limit the time that batteries spend at high states of charge.

The costs projected by the Panel's model for PHEV-10 and PHEV-20 batteries are below the preliminary goal and below the NPV of fuel cost savings in all but the least favorable scenario. Further, the incremental cost of these batteries over HEV batteries is projected to be $1000 or less in mass production. Because of their projected propulsion energy cost savings, PHEVs using such batteries would have lower life cycle battery plus energy costs than HEVs. Even for the PHEV-40, projected Li Ion battery cost is comparable to, or less than, fuel cost savings except in the least favorable scenario.

The Panel concludes that medium energy/medium power Li Ion battery technologies have good prospects to meet the technical requirements and cost constraints for applications in PHEVs and small FPBEVs. Several fleet demonstrations of such vehicles, initiated or planned in Europe and Japan (see Section 6 A below), are expected to yield important information not only on performance, reliability and life expectancy of medium energy/medium power Li Ion batteries but also on life cycle ownership costs of PHEVs and small FPBEVs powered by such batteries. If these demonstrations establish technical and economic viability of Li Ion batteries for these applications, early commercial production of batteries could be established by several manufacturers beginning around 2009-2010.

The nature and variety of the candidate Li Ion technologies now being developed hold out considerable promise for availability of increasingly capable and lower cost batteries for future ZEV and near-ZEV applications.

High energy Li Ion battery technologies in cell sizes suitable for powering of medium- and larger size, full performance BEVs experienced a period of active development in the 1990s but have not received much attention since then, and their costs remain high. However, should a broad interest in FPBEVs arise again because of changing economic, energy-strategic and/or environmental conditions and concerns, the Panel concludes that many of the advances being achieved in medium energy and high power Li Ion technologies should be transferable to result in better-performing and lower-cost high energy Li Ion technologies.

Li Ion battery safety is an important concern of automobile manufacturers for all automotive applications of Li Ion batteries, and a key objective of battery developers. Under simulated abuse test conditions (excessive overcharge and/or heating; massive shorting), Li Ion cells can rupture due to evolution of internal gas pressure and vent flammable gases that can be ignited by sparks. However, cell and complete battery abuse tests by SAFT and other prospective manufacturers have demonstrated safe behavior, and some of the newer Li Ion chemistries are even more tolerant of overcharging and/or excessive heating.

The Panel observes that safety systems are part of candidate Li Ion battery technologies for ZEV and near-ZEV applications. These systems utilize several independent control variables and strategies on the cell, module and battery levels to prevent unsafe conditions such as those that caused overheating and fires of a number of laptop batteries. Li Ion batteries have proven safe under the operating conditions maintained in U.S. and worldwide field tests and demonstrations of several hundred BEVs and HEVs during the past ten years. The Panel concludes that recent and emerging advances in battery chemistry and control strategies can be expected to further reduce the already small safety risks with Li Ion batteries for HEV, PHEV and BEV applications.

Longer Term Outlook. Beyond the recent and prospective nearer-term advances discussed in subsection 3.C, it seems very likely that full exploitation of presently known and yet to be discovered advances in materials, chemistry and manufacturing techniques will result in Li Ion battery technologies that combine substantially higher performance with longer life and yet more robust safety at lower costs. In mass production, these costs should permit payback through fuel cost savings for PHEVs and HEVs but also for FPBEVs, especially if fuel costs continue at high levels and vehicle technologies keep advancing. However, realization of the ultimate performance and cost potential of the Li Ion "family" of battery chemistries for ZEV and near (including partial) ZEV applications is likely to take another decade

c) Other Candidate Batteries

The ZEBRA high temperature (~300℃) battery offers a number of attractive characteristics for vehicle applications but, compared to Li Ion and NiMH technologies, is handicapped by relatively low power density. This limitation appears to exclude the battery from HEV and PHEV applications. Automobile manufacturers are concerned also about the need to operate ZEBRA batteries at high temperature. However, ZEBRA batteries meet the performance requirements of smaller BEVs, and effective thermal insulation has permitted ZEBRA batteries to sustain operating temperature for periods up to 2 weeks without connection to a source of power. A number of successful applications are demonstrating the practicality and durability of ZEBRA batteries in small BEVs and heavy duty vehicles (including hybrid buses) driven regularly on public roads.

ZEBRA batteries are now produced in a fully integrated manufacturing plant at costs well below those of other candidate BEV batteries manufactured in similar limited volumes. Its material cost advantage will make ZEBRA batteries the lowest-cost high energy battery for FPBEVs also in early commercial and mass production. MES-DEA, the Swiss exclusive manufacturer of ZEBRA batteries, is currently taking steps toward these production capacities. The Panel believes, however, that large-scale introduction of the ZEBRA battery in ZEVs will be contingent not only on the battery's technical characteristics and cost but on acceptance of the technology by automobile manufacturers.

2. Industry Strategies and Perspectives

The Panel's interactions with battery and automobile manufacturers identified strategies, concerns and recommendations that, in the Panel's view, deserve consideration when contemplating measures to foster the development and availability of batteries for ZEV and near ZEV applications.

a) Battery Manufacturers

As expected, the strategies and positions of the manufacturers and/or developers of candidate ZEV/near-ZEV batteries depend on their current technology thrusts, capabilities and market positions. Mass-manufacturers of NiMH high power cells and modules for HEV batteries are focused on technology cost reduction and involved in capital-intensive production capacity expansions that assume increasingly competitive HEV mass-markets exceeding 1 million vehicles by 2010. FPBEVs are not a target of their NiMH battery technology development efforts and they consider PHEV battery requirements insufficiently defined to permit an assessment of NiMH technology and market prospects for this new application. Few development activities appear underway to explore whether NiMH has technical potential for PHEVs.

The mass-manufacturers of Li Ion cells for consumer products are now engaged in the development of established Li Ion chemistries for HEV applications, with commercialization possible as early as 2008 if Li Ion technology is perceived to meet all requirements including safety. Given the number of competent manufacturers (largely in Asia), a vigorous market competition of technologies and manufacturers can be expected to emerge. The same manufacturers do not appear to be pursuing development of Li Ion batteries for FPBEVs or PHEVs. Most of them stated that currently projected Li Ion battery costs would make FPBEVs too expensive, and government financial incentives are considered unlikely to induce a large number of customers to buy vehicles of limited range. There is also concern about high costs of Li Ion batteries for PHEV applications. However, the major impediment to engagement of these companies in developing Li Ion batteries for PHEVs appears to be that the battery requirements for this new application are insufficiently defined by automobile manufacturers, thus making it difficult for battery manufacturers to establish development targets and programs. Battery manufacturers are looking for a clear interest and active involvement of automobile manufacturers in PHEVs before becoming engaged in PHEV battery development.

Several smaller organizations in Europe and Japan have been developing medium and high energy Li Ion technologies for possible ZEV and near-ZEV applications. Their strategy appears to be the pursuit of limited-volume applications and markets that may be emerging, especially in small BEVs (including FPBEVs) and more recently also in PHEVs. The perception is that inner city operation of these vehicles as ZEVs could well become a market, and European automobile manufacturers are thought to favor PHEVs over HEVs for that reason. These organizations hold the view that Li Ion-powered PHEVs and small (FP) BEVs will be able to attain life cycle cost competitiveness with conventional vehicles in urban fleet applications, but it was left unclear which production volumes will be needed to achieve competitiveness. A few of them have established prototypical cell and module technologies as well as sufficient cell production capacities for hundreds to a few thousands of 10-25kWh batteries per year, sufficient for demonstration fleets. Although most of these organizations are owned by large companies, the resources being invested in development and demonstration of batteries for PHEVs and small (FP) BEVs are still very modest.

Investments by all types of Li Ion battery manufacturers in PHEV and small BEV batteries are likely to increase, possibly substantially, once automobile manufacturers commit resources and plans to the development and introduction of such vehicles. While the commercial prospects of (FP) BEV- and PHEV-design Li Ion technologies still seem unclear, several manufacturers noted that development of such technologies was likely to benefit from supported demonstration programs and/or financial incentives.

b) Automobile Manufacturers

Most major global automobile manufacturers have in-depth battery expertise and extensive capabilities in the evaluation, integration and testing of batteries in BEVs and HEVs. These capabilities are now engaged in the extensive efforts of automobile manufacturers to evaluate and advance the HEV design Li Ion battery system technologies that are likely to be commercialized within the next few years. Confidence in the readiness of Li Ion batteries for deployment in mass-produced vehicles is likely to grow with the experience from Toyota's "Vitz" minicar that uses a small Li Ion battery to perform the automatic start function of that ICE vehicle.

Based on their experience with the FPBEVs developed, constructed and sold or leased under the California ZEV initiative, most automobile manufacturers continue to hold the view that FPBEVs will remain niche vehicles, in large measure because of the current and foreseeable large weight and high costs of the required batteries. No efforts to advance battery technologies for FPBEV applications are being supported by them at present. It remains to be seen whether recent announcements by Mitsubishi and Nissan of plans for introduction of BEVs are going to stimulate efforts to develop Li Ion batteries that meet the requirements of these vehicles.

The prospects of PHEVs also were judged negatively by most major automobile manufactures until recently, largely because of concerns about battery costs and cycle life. However, several manufacturers are now active in modeling, designing and evaluating various PHEV architectures and technologies, with consequent attention to candidate battery technologies and their prospects. In the U.S., an effort sponsored by DOE and supported by USABC is now underway with automobile industry expert participation to establish PHEV battery performance, life and cost targets for a planned R&D program, and in Japan NEDO is launching an initiative to develop PHEV batteries with involvement of leading Li Ion battery developers. These initiatives and automobile manufacturers' initiatives such as GM's recently announced plans to offer a PHEV version of the Saturn VUE HEV and to launch the "Volt" PHEV if suitable Li Ion batteries become available are the signals needed by the major battery manufacturers to become engaged with their own resources in the development and manufacture of batteries for PHEVs.

4. Hydrogen Storage

A. Background and Introduction

Storing sufficient hydrogen on a vehicle to power it for adequate distance, safely, and at reasonable cost, without an excessive weight penalty has been and remains a serious challenge for the vehicle industry and its suppliers. All of the major potential manufacturers of fuel cell vehicles interviewed by the Panel highlighted hydrogen storage to be among the two or three areas of greatest concern, including all of the other cost and technology challenges associated with developing fuel cell systems for consumer vehicles; one major manufacturer identified it as the single greatest challenge.

Unlike other technologies being pursued in support of ZEVs, hydrogen storage technologies have advanced relatively little in recent years. The primary system advancements have been in the area of improving compressed gaseous hydrogen storage and, to some extent, improving liquid hydrogen storage. There are, in addition, many alternative storage concepts being pursued very recently (the last 3 or 4 years) at the research level, and a couple of concepts (e.g., metal hydrides and carbon nanotubes) which have been investigated at relatively low levels of effort for many years. However, as far as could be determined, none of the recent or earlier concepts has reached the point of representing realistic complete system alternatives.

It is also known that several major automobile manufacturers are researching alternative hydrogen storage technologies, although none seem to have progressed to the point of suggesting that they have developed viable complete systems. Further, as far as the Panel could determine, none of the manufacturers have plans for other than liquid or compressed gaseous storage for their hydrogen-fueled vehicles for the foreseeable future.

This apparent lack of major accomplishments and industry involvement is not too surprising since it has been only in the last 4 or 5 years that onboard hydrogen has begun moving towards industry acceptance as a workable transportation fuel. As a result, almost all visible work in progress for hydrogen storage concepts, other than liquid and compressed gas, is the result of efforts sponsored by the Department of Energy.

Range is a key vehicle performance attribute and virtually all vehicles sold in the United States for many years have had a normal operating range between fuel refills of 300 miles or more. Working closely with industry, the Department of Energy (DOE) has selected hydrogen storage parameters corresponding to a 300 mile range for its 2015 targets. Designing for any range significantly less than 300 miles, except for some niche applications, is not likely to result in a successful consumer vehicle.[1] Presumably, since the automobile industry was very much involved in setting all of the hydrogen storage targets for 2010 and 2015, none of the manufacturers seem to be pursuing significantly different targets.

The mass of hydrogen to be stored to meet any design range depends on the fuel efficiency of the vehicle in question as the range of a vehicle is equal to the vehicle efficiency in miles per kilogram multiplied by the usable kilograms on board the vehicle. This is illustrated in Figure 4-1.

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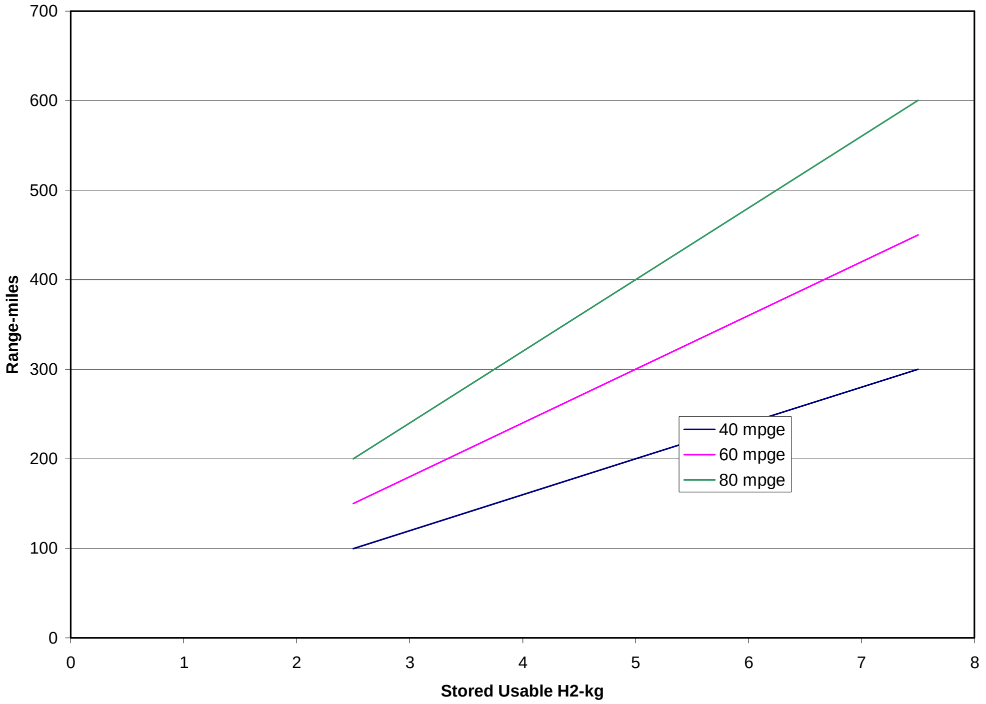
[1] Since the first generation of fuel cell vehicles is likely destined for controlled fleets and other niche applications, a range as low as 200 miles might be acceptable for an interim period but a range of 300 miles or more is necessary if fuel cell vehicles are to be competitive with conventional ICE vehicles.

Figure 4-1 Vehicle Range



mpge – fuel mileage converted to equivalent miles per gallon of gasoline

The National Renewable Energy Laboratory (NREL) has finished the first year of a five year DOE demonstration program currently involving over 60 hydrogen-fueled fuel cell vehicles. Most of these vehicles use 350 bar compressed hydrogen storage with only 4 using 700 bar and only 4 using liquid hydrogen storage. From this and other limited test results from existing experimental fuel cell vehicles currently being demonstrated, a reasonable efficiency estimate is about 40 to 60 miles per kg of hydrogen[2].] Thus, for a 300-mile range, fuel cell vehicles will probably need about 5 to 7.5 kg of onboard usable hydrogen. The focus of hydrogen storage efforts over the past several years has been finding sufficient space to carry a minimum of 5 kg of hydrogen onboard a vehicle while minimizing the weight increase and doing so at reasonable cost.

B. Physical Characteristics of Hydrogen and Resulting Storage Considerations

Table 4-1 shows a comparison of some selected properties of hydrogen as compared to other fuels.

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[2] Note: one kg of hydrogen has approximately the same fuel energy as one gallon of gasoline.

Table 4-1: A Comparison Of Selected Fuel Properties

Fuel		**Hydrogen**	**Natural Gas**	**Ethanol**	**Gasoline***	**Diesel***
Formula		H_2	CH_4	C_2H_5OH	C_4 to C_{12}	C_6 to C_{25}
For Liquid @ I Atm.						
• **Density**	Kg/L	0.071	0.72	0.79	0.74	0.85
• **Boiling Temp.**	℃	-253	-162	78	27-225	188-343
• **Heat of Vap.**	Kcal/kg	110	122	210	83	56
For Comp. Gas - 25℃						
• **Density**	Kg/L					
o **350 Bar**		0.023	0.23			
o **700 Bar**		0.04				
• **Energy Density**	Kcal/L					
o **350 Bar**		650	2700			
o **700 Bar**		1125				
Mass LHV	Kcal/kg	28,600	11,900	6,400	10,300	10,100
Vol LHV	Kcal/L	2,000	8,500	5,050	7,500	8,500
Autoign. Temp.	℃	~550	~540	~423	~257	~316
Stoich. A/F	By weight	34.3	17.2	9	14.7	14.7
Flam. Limits	% By Vol.					
• **Lower**		4	5	4.3	1.4	1
• **Upper**		75	15	19	7.6	6

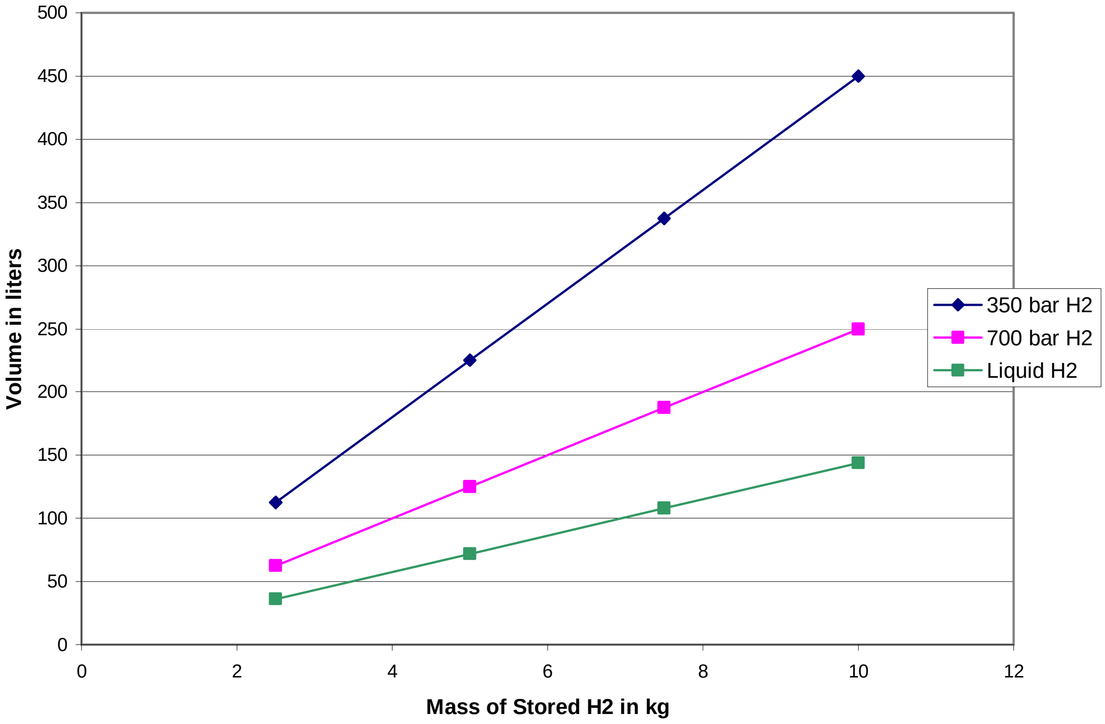
* Gasoline and Diesel are both blends with properties depending on the blends and additives. Approximate average properties are given.

Hydrogen has higher energy per unit of mass than any alternative fuel being considered for automobiles. In fact, it has approximately three times the specific energy (energy per unit of mass) of gasoline and five times that of ethanol. Unfortunately, it also has the lowest energy density (energy per unit volume) of any of the fuels considered. For example, in liquid form, it has less than one-third of the energy per gallon compared to gasoline. In other words, for equal fuel energy, the internal volume of a liquid hydrogen tank would have to be about three times the volume of the gasoline tank but the hydrogen contained in the tank would weigh only about one-third as much as the gasoline. Note that the actual hydrogen tank volume would be even greater relative to the gasoline tank since a very sophisticated method of insulation around the contained hydrogen would be necessary to prevent excessive boil-off from the hydrogen at -253℃ (-423℉).

The volume situation is even worse when the hydrogen is in compressed gas form instead of liquid form. At 350 bar (about 5000 psi), for example, the required volume for a given hydrogen storage mass increases by a factor of about 2.5 compared to liquid hydrogen. That means that, compared to gasoline, for the same fuel energy the required internal volume would be about seven times greater. Further, to contain the high pressure, the tank will have a required wall thickness which will add significant volume and weight to the tank system. Increasing the storage pressure to 700 bar increases the energy density (although not quite double due to non-ideal behavior of hydrogen gas at this pressure) compared to 350 bar. However, the additional tank wall thickness to contain the higher pressure results in a reduced internal volume for a given system (outside) volume, or an increased system volume for a given internal volume. Even at this pressure, the required internal volume would still be about 40% greater than liquid hydrogen and about 5 times that of gasoline for the same fuel energy. Figure 4-2 shows the internal volume required for these storage options.

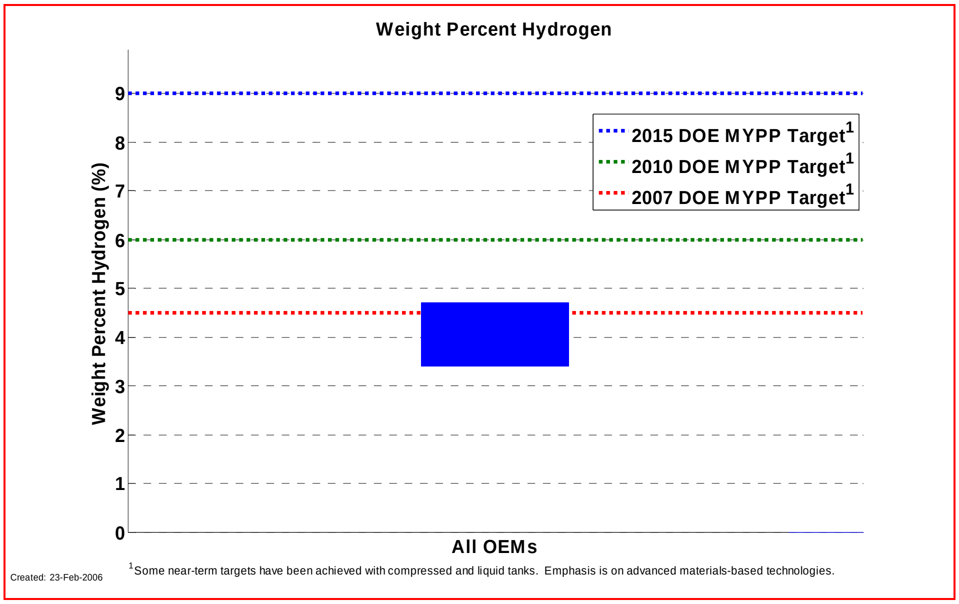
Corresponding to the increased volume required for either liquid or highly compressed hydrogen is increased weight. The weight penalty due to the larger size is further increased due to the need to highly insulate the cryogenic liquid hydrogen or safely contain the high pressure gas.

Figure 4-2 Required Internal Volume for Stored Hydrogen



Hydrogen storage systems employed on the current fleet of NREL/DOE fuel cell vehicles involved in the demonstration/infrastructure program have a hydrogen weight percentage (weight of hydrogen divided by weight of the storage system) of about 3.5% to 4.6%. Figure 4-3 shows the composite weight fraction of hydrogen data compared to DOE targets.

Figure 4-3 WEIGHT PERCENTAGE HYDROGEN



Source: NREL, Completed Learning Demonstration Composite Data Product as of 12/01/06

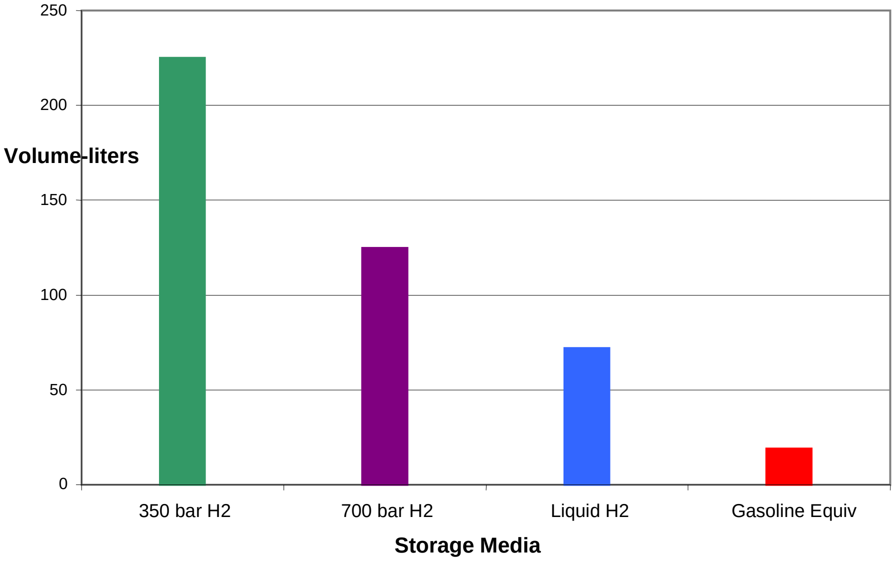
The systems included in the composite data actually store from somewhat less to somewhat more than 5 kg of hydrogen. If normalized to contain 5 kg of hydrogen, these systems would weigh between 110 and 140 kg.

C. Characteristics and Issues of Various Candidate Technologies

At present, only compressed gas and liquid storage are being used by the OEMs in their hydrogen-fueled vehicles. In fact, as far as is known, only BMW is using liquid hydrogen and that is for ICE vehicles. All of the other OEMs visited by the Panel use compressed gas storage, at either 350 bar or 700 bar storage pressure, for all of their fuel cell vehicles including buses and personal vehicles.

Volume requirements are clearly important issues for any type of hydrogen storage as compared to liquid fuels. For example, vehicle fuel efficiency and design range will determine the necessary amount of hydrogen to be stored onboard the vehicle. However, most OEMs seem to be targeting about 5 kg. This amount of onboard storage would require internal volumes of about 225 liters for 350 bar compressed hydrogen, about 125 liters for 700 bar compressed hydrogen, and about 72 liters for liquid hydrogen. These volumes are in sharp contrast to about 19 liters, for the same total fuel energy, for gasoline storage. This is illustrated on Figure 4-4. It should also be noted that for both liquid and compressed gas hydrogen, the external volume of the storage tank is considerably greater than the internal volume, especially for 700 bar.

Figure 4-4 Minimum Internal Volume for 5 kg of H2 Using Various Storage Media



Considerable research, funded both privately and by governmental agencies (mostly DOE) is continuing for alternative means of storing on-board hydrogen. These alternatives include novel concepts such as chemical storage, carbon-based materials, high surface-area sorbents, and metal hydrides as well as cryo-compressed gas. Some of the specific technologies being funded by DOE are listed below:

1. Reversible complex metal hydrides
2. Ionic liquid media
3. Binary clathrate hydrates
4. Metal-assisted nanostructured carbon
5. LiNH2 and related compounds
6. Boron nanoclusters

Many of these various hydrogen storage media being studied have the potential for absorbing and releasing relatively high weight fractions of hydrogen. However, essentially all are in research phase activities, too early for system projections. A few alternatives are briefly described below.

Metal hydrides.—The DOE hydrogen/system mass storage fraction targets of 6% (2010) and 9% (2015) are very ambitious. To reach these targets with metal hydrides, the bonding between hydrogen and the storage chemical specie must be stronger than between two hydrogen atoms. On the other hand, to achieve a rapid release of the hydrogen from the chemical specie suggests weak bonding. Using innovative approaches involving nanostructure to increase sorption rate while simultaneously decreasing desorption temperatures, researchers are achieving promising results.

Ionic liquid media.—Materials such as ammonia Borane, NH_3BH_3, contain relatively high weight fractions of hydrogen; in this case, 16.9%. Partial dehydrogenation can be thermally induced in solid state but more useful and controllable reactions can be obtained in a solution. The volatile organic solvents traditionally used are not suitable for storage. Research is being conducted to use ionic liquids to induce dehydrogenations at lower temperatures with better controllability.

Binary clathrate hydrides.—Clathrate hydrides are inclusion compounds where cages formed by a hydrogen-bonded water network accommodate “guest” molecules. It was demonstrated that hydrogen molecules can be stored in binary H_2/THF clathrate hydrides at much lower pressures than in pure hydrogen hydrates. Hydrogen storage is completely reversible in these materials, thus potentially offering advantages not found in other classes of materials.

Boron nanoclusters.—Boron is lighter than carbon and forms many compounds with high hydrogen weight fraction. A hypothesis being pursued is that at certain length scales, the structural units in certain boron-rich solids can be reversibly hydrogenated in the presence of appropriate catalysts to form boranes and/or carboranes.

There are also many funded studies focused, not on specific materials, but on better fundamental understanding of hydrogen absorption and release by various classes of materials. Based on these studies, several of the materials appear to have the potential for increasing hydrogen weight fraction capabilities well above those for compressed hydrogen. However, it is not clear that a complete storage system would offer a cost or weight advantage. It will require much additional work before potential system advantages can be ascertained.

Little was learned about any success that OEMs might be having with alternative means of hydrogen storage such as metal hydrides, carbon nanotubes, or liquid form hydrogen carriers. Most, if not all, of the OEMs are known to be looking at these alternative storage technologies but since all (except BMW) are currently using compressed gas storage, it is obvious that as yet there is no better alternative.

DOE prepared a table showing, mostly qualitatively, the expected pros and cons of some of those alternatives. Comments from that DOE table are reproduced in Table 4-2.

Table 4-2: Alternative Hydrogen On-Board Storage Systems

Storage Technology	System Status	Advantages/Disadvantages
Chemical hydride	1.6 kWh/kg, 1.4 kWh/L, $8/kWh	√ Low pressure x Low cost, energy-efficient regeneration processes have not been developed x By-product removal
Complex metal hydride	0.8 kWh/kg, 0.6 kWh/l, $16/kWh	√ Low pressure √ Reversible H_2 uptake and release x Insufficient storage capacity at practical temperature and pressure
Liquid hydrogen	2.0 kWh/kg, 1.6 kWh/L, $6/kWh	√ Lowest capital cost √ Highest gravimetric & volumetric capacities x Most energy intensive Boil-off requires venting, and presents an energy penalty and potential safety hazard
10,000 psi compressed Hydrogen tanks	1.9 kWh/kg, 1.3 kWh/L, $16/kWh	√ Near-term solution to hydrogen storage √ Most energy efficient method to densify H_2 x High pressure
5,000 psi compressed Hydrogen tanks	2.1 kWh/kg, $12/kWh	x Cost is high due to high pressure containment materials

Department of Energy 2010 and 2015 System Goals

Year 2010	Year 2015
• 2.0 KwH/kg (6 wt %)	• 3.0 kWh/kg (9 wt %)
• 1.5 kWh/L	• 2.7 kWh/L
• $4/kWh	• $2/kWh

Source: U.S. Department of energy, Hydrogen, Fuel cells and Infrastructure Technologies Program, 2003

It should be noted that "system status" does not refer to the actual commercial status of these technologies but refers to projections based on many assumptions.

D. Areas of Concern For On Vehicle Storage of Hydrogen

1. Volume

As noted earlier, compressed or liquid hydrogen will require substantially greater volumes than gasoline or diesel fuel to provide sufficient range between refills. Indeed, this will be true even if DOE targets for 2015 are achieved. Finding available space for the larger volumes will be less of an issue when new platforms are designed for fuel cell vehicles. However, for the first few generations of fuel cell vehicles, it is unlikely that most manufacturers will make the huge investment required to produce new platforms for relatively small numbers of vehicles. The high mass energy content of hydrogen and the expected high fuel efficiency of fuel cell vehicles somewhat alleviate the hydrogen storage problem, but it is still likely that a minimum of 5 kg will be required for a 300-mile design range. Even stored as 700 bar compressed hydrogen, about 33 gallons of internal storage volume would be needed with current technologies as compared to less than 10 gallons for a gasoline-fueled vehicle achieving around 30 miles per gallon or only about 5 gallons for a gasoline-fueled HEV achieving around 60 miles per gallon.

2. Weight

Current technology for compressed hydrogen yields a weight fraction (hydrogen/storage system) of around 4% as compared to DOE targets of 6% by 2010 and 9% by 2015. At 4%, the storage system to contain 5 kg of compressed hydrogen would weigh about 125 kg. This represents a very large weight penalty compared to the few kilograms required for a sheet metal or plastic gasoline tank. This problem is compounded by the lack of a universal and accepted procedure for certifying compressed hydrogen tanks for personal vehicle applications. The present procedures for certifying non-vehicle storage tanks to ASME standards apparently require testing to burst pressures of 4.5 times the maximum design operating pressures. By comparison, most hydrogen pressure tanks currently being used on fuel cell vehicles are burst tested to less than 2.5X. If higher burst pressures are ultimately required, tank weights will increase even more making it even more difficult for vehicles to accommodate.

3. Cost

At this time, both the materials and procedures for producing the high-pressure tanks are very expensive. For example, tens of kilograms of carbon fibers, at current costs of $25 to $30 per kilogram, are used in 5 kg capacity pressure tanks. Further, the procedures for winding the fibers, applying the epoxy bonding materials, and curing are slow and essentially one-of-a-kind procedures. Of course, this is to be expected at this point in time since they are indeed almost one-of-a-kind production runs. The point is that current costs for tanks, which is in the range of $50 to $100 per kWh, while certainly not representative of mass production costs, are thousands of dollars per tank. Even with mass production, to reach DOE cost targets of $4 per kWh of stored hydrogen by 2010 and $2 by 2015 will require significant “breakthroughs” if the technology of choice is compressed gas storage.

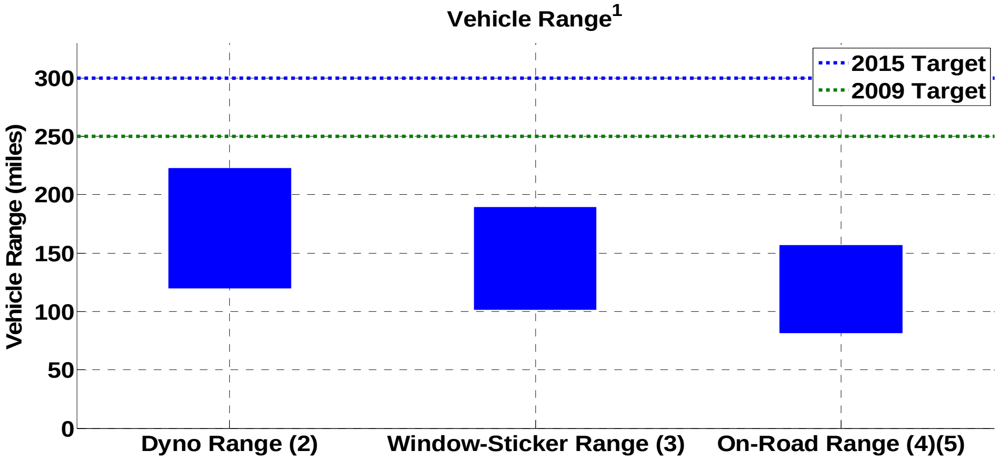
Even if the DOE targets are met, the storage system costs for 5 kg of hydrogen would be over $650 in 2010 and over $325 in 2015. These costs while far less than current hydrogen storage costs would still represent an incremental cost increase compared to most current gasoline or diesel storage systems. Clearly, if DOE targets are not met, onboard hydrogen storage could be a significant factor in the consumer price of hydrogen-fueled vehicles.

Since the boiling temperature of liquid hydrogen at atmospheric pressure is about –253℃ (–423℉), extensive insulation is required. The insulation not only adds significantly to costs, it also increases the volume required for a given mass of hydrogen storage. In addition, at such deep cryogenic temperatures, there are many materials limitations essentially excluding most materials currently used in automobile manufacturing. As a consequence, current liquid hydrogen storage technology is very expensive.

4. Vehicle Range

A range limitation of hydrogen-fueled vehicles is a major concern of essentially all of the major vehicle manufacturers. Consumers have become accustomed to vehicles which can be driven 300 miles, or more, between fueling stops. Vehicles which cannot at least approach the 300 miles are likely to be considered less desirable compared to conventional-fueled (gasoline or diesel) vehicles. Since the hydrogen-fueled vehicles are also likely to be more expensive, the reduced range would clearly add to the difficulty of getting beyond government and fleet sales. Figure 4-4 shows the composite range data for the DOE/NREL program previously discussed and illustrates that none of the 60+ vehicles being monitored has an actual on-road range approaching 200 miles.

Figure 4-4 VEHICLE RANGE



(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAEJ2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(5) Fuel economy calculated from on-road fuel cell stack current or mass flow readings.

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Source: NREL, Completed Learning Demonstration Composite Data Product as of 12/01/06

5. Safety

The ability of the storage system to safely contain the hydrogen is a major concern. In the case of high pressure gaseous storage systems, this means primarily insuring that the tank will not fail under normal operating conditions for the life of the vehicle. However, it also means that only negligible amounts of hydrogen will diffuse through the walls of the tank or leak from the valves and fittings bonded to the tank. It also means that the tank must not fail catastrophically in the event of severe collisions, fires, and even bullets from firearms penetrating the tanks. In addition, it must be possible to refuel the tanks with no danger to the person performing the refueling and no significant leakage of hydrogen. At present, some procedures for testing the tanks have been established through cooperative efforts of DOE, vehicle manufacturers, tank developers, and various other groups and agencies. In addition, apparently safe interfaces between refueling stations and vehicles have been developed along with protocols for conducting refueling operations. However, there are as yet no international or even national codes and standards for these devices and procedures.

Safety issues are different with other means of onboard hydrogen storage such as liquid storage or storage in solid or liquid materials that can absorb and release hydrogen. Of these, only liquid hydrogen storage is developed to the point where its use in early generation vehicle applications seems likely.

Safety issues with liquid storage are generally different, but just as challenging, when compared to compressed gas storage. Liquid hydrogen in the tank is stored at near-atmospheric pressure so, if the supporting system is operating properly, containing high pressures is not a factor. However, the liquid at –253°C can be extremely hazardous. Even air will liquefy if it comes into contact with surfaces at this temperature. Further, the liquid stored in the tanks is at, or very close to, saturation. This means that any heat absorbed by the liquid by transfer through the container walls or connecting wires and tubing, will cause evaporation of the liquid. Some of the evaporation can be reduced by temporarily “sealing” the tank and initially allowing the tank pressure to increase slightly. While this procedure can delay the need for venting the tank, it cannot eliminate it. Depending on the quality and quantity of the insulation, this process can delay venting for hours or possibly even days. Ultimately, though, venting must occur. When it does, it is obviously not desirable to simply vent hydrogen gas into the surrounding atmosphere which could be inside an enclosed space. Neither is it desirable to have an open flame where the escaping hydrogen is burned in air. An alternative, favored by BMW, is to pass the hydrogen through a catalytic burner such that no open flames or high temperatures are created.

There are many hydrogen absorbing (not referring to any specific process) materials which have promise and could become of wide interest, but they have not reached the maturity of compressed gas or liquid storage. Some of the resulting systems could offer potential safety advantages over cryogenic liquid or highly compressed gas storage. Only additional years of research and development can provide definitive answers.

There are some physical characteristics of hydrogen, and the burning of hydrogen, which are cause for concern for storing onboard a vehicle. For example, hydrogen has a far greater flammability (fuel/air ratio) range than any other known vehicle fuel. This range is from about 4% to 75% (fuel volume/air volume) where stoichiometric is about 40%. This means that the fuel/air mixture will burn from extremely lean (about 10% of stoichiometric fuel) to extremely rich (nearly double the stoichiometric fuel). By comparison, the range for gasoline is about 1.4% to 7.6% where stoichiometric is around 1.6%. Hydrogen gas also diffuses very quickly into the air, thus quickly making a near-homogenous mixture. This means that it would be much easier for a persistent fuel leak of gaseous hydrogen to produce a large volume of combustible mixture, in a confined space such as a garage, than it would for gasoline.

On the other hand, the density of gasoline vapor is much greater than air since the average molecular weight of gasoline is about 4X that of air. Thus, a small leak of liquid gasoline would produce a fuel-rich and highly combustible layer, just above and surrounding the “puddle”, which would persist for a long period of time. In this regard, a small gasoline leak might be a greater fire hazard where a hydrogen leak might present a greater potential for an explosion.

The likelihood of a hydrogen-air explosion is increased, relative to gasoline, not only by the very wide (especially lean) flammability range but also by the extremely fast flame propagation speed and low ignition energy. A hydrogen-air flame front moves at roughly an order of magnitude faster than a gasoline-air flame front. This greatly increases the possibility of a detonation wave explosion. The low ignition energy means that very weak sparks could initiate ignition.

Hydrogen has other properties which could pose additional risks associated with a storage tank leak, or leaks, during refueling processes. Namely, it is colorless and odorless. Those properties make it very difficult to detect a leak unless appropriate instruments are used. On the positive side, it is also non-toxic. This means that people or animals would not be harmed by breathing hydrogen vapor in air unless the concentration was sufficient to displace a significant portion of the oxygen in air or it was exposed to an ignition source.

The flames from burning hydrogen are also nearly invisible, especially in daylight or a well-lighted area. Therefore, a vehicle hydrogen leak could become ignited (especially since the ignition energy for hydrogen-air is extremely low) and be unknown to an observer. Clearly this could present a hazard to not only vehicle owners but those who service vehicles and especially to first-responders of vehicle accidents.

Another consideration associated with possible leaks of onboard hydrogen storage is parking in enclosed parking garages on driving through tunnels. In reality, the hazard associated with these is not very great due to the rapid rate of diffusion of hydrogen in air. This phenomena means that the leak would have to be of sufficient rate and time duration to create a combustible mixture, essentially throughout the interior of the structure. Thus, even if 5 kg of hydrogen escaped into an enclosure (with no ventilation), the volume of air with which it mixed would have to be less than 50,000 cubic feet to form a combustible mixture. For typical parking garages and tunnels which always have some ventilation and are generally much larger than 50,000 cubic feet, this would be a near impossibility. Nonetheless, there are many codes and regulations on such structures which currently could limit access for any vehicles with stored onboard hydrogen, or any other compressed gas which is flammable. Thus, whether hydrogen-fueled vehicles present a real hazard or not due to leakage, there are perceived hazards and restrictive codes and regulations that will have to be addressed.

6. Energy Requirements for Storage

Since uncombined hydrogen does not occur naturally in significant quantities on Earth, energy to produce it is clearly an issue. However, additional energy is required in conditioning the hydrogen (or hydrogen carrier) for storage or for removing it from storage. For example, depending on the initial pressure and temperature (as well as the extent of the compression system thermal integration), it could take from about 5% to over 20% of the hydrogen LHV to compress it to 700 bar. Liquefaction of hydrogen requires even more energy, up to 30% of the LHV. Further, all of the novel hydrogen storage concepts being considered require to either store the hydrogen or to liberate it after it has been stored. Some of the chemical hydrides require from 25% to over 50% of LHV to store the hydrogen and some of the metal hydride alanates require over 25% of LHV to liberate it. The key to a minimum efficiency effect due to storage requirements are the required temperatures. If the waste heat from the stack (~85C) can be utilized, then the efficiency effect will be minimal. On the other hand, if significantly higher temperatures are required (which is the case for most of the potential carriers) then additional fuel will have to be consumed. For compressed gas or liquid hydrogen, the additional energy will be reflected in the cost of the hydrogen. However, for storage systems which utilize fixed onboard storage media, the additional energy will likely be reflected in a reduced fuel efficiency of the vehicle.

7. Refueling Time

A major criticism of the EV was the length of time it typically took to recharge (refuel) the vehicles. This criticism was clearly based on hours for an EV recharge versus minutes for a conventional vehicle. It remains to be determined how many minutes beyond those required for gasoline vehicles will be deemed acceptable. Most likely, the acceptable refueling time will be related to the range; the more often a refill is required, the shorter will be the acceptable time increment for refills. For the composite compressed gas and liquid hydrogen tanks, the NREL data showed refill rates typically between about 0.3 and 0.9 kg per minute, with only a few events between 1.0 and 1.7, and a few between 0.05 and 0.3 kg per minute. The greatest number of refill events occurred at about 0.85 kg per minute which would correspond to a 5 kg refill time of slightly less than 6 minutes.

8. Accessibility of Refueling Stations

The vast majority of current vehicle owners in the United States refuel at one of approximately

200,000 gasoline stations with little or no deviation from their normal driving routes. It would be a negative factor in the acceptance of hydrogen-fueled vehicles if a detour of miles was necessary to refuel the vehicle. However, as is likely the case with regard to acceptance of refueling time, vehicle range will probably be a major factor in the acceptability of limited numbers of refueling stations; the more often one has to refuel, the less acceptable it will be to make a significant deviation in route to refuel.

9. Fuel Costs

Storage technology used on the vehicle will also likely have an effect, possibly significantly, on the delivered price of hydrogen. Currently, hydrogen is typically delivered by producers either in liquid or compressed gas form. Liquid is typically delivered in tankers with highly insulated, multi-walled containers. Compressed gas is typically delivered in trailers with a series of high-pressure cylinders. Liquid is generally more expensive to produce than compressed gas (additional energy of roughly 30% of the hydrogen heating value is expended in liquification) and, in both cases, the consumer price depends to a great extent on the location of the customer. Transportation of hydrogen is currently much more expensive than gasoline or diesel due to its very low energy density (see Table 4-1).

In addition to the difference in the price of liquid versus compressed gas, price will also be affected by the cost and complexity of interface facilities as well as any type of pre-treatment or post-treatment of the fuel. For example, to rapidly refill a vehicle tank to 700 bar might require pre-cooling the hydrogen fuel. In this case, in addition to the incremental energy cost of providing the higher pressure, there would be an energy cost of pre-cooling the gas as well as the capital cost of the facility to perform the cooling. Thus, the price of 700 bar hydrogen would likely be somewhat higher than 350 bar hydrogen and the price of pre-cooled 700 bar would probably be even somewhat higher.

While it is very early in the technology developments, many of the other storage concepts involve hydrogen-bearing solids or liquids. Most of these technologies will likely have some special interface requirement (e.g., control of temperature, pressure, rate of delivery, etc.) which could affect delivered hydrogen price. At least one, a liquid-bearing hydrogen concept, involves off-board treatment of the spent fuel to recharge it with hydrogen. The cost of such off-board treatment is unknown but the unit hydrogen price could be quite different from delivery to other means of hydrogen storage.

10. Public Perception of Hydrogen

For many years, there was a perception by a large segment of the population that hydrogen is extremely dangerous; even explosive. However, it appears that the perceived hazards of hydrogen are diminishing with time. This possibly is due to the ever-increasing awareness of the potential environmental benefits of replacing petroleum fuels with hydrogen. Indeed, there are many local demonstration programs, newspaper articles, television news or talk show segments, and even advertisements by OEMs touting these potential benefits. Obviously one or two serious accidents involving hydrogen could greatly diminish its acceptance by vehicle buyers.

11. Codes and Standards Affecting Hydrogen Storage

Codes and standards are vitally important to every aspect of hydrogen storage if mass-produced, hydrogen-fueled vehicles are ever to become reality. Without widely accepted and reasonable codes governing permanent storage facilities, transportation, and on-board storage, hydrogen might never achieve widespread distribution needed to be an acceptable vehicle fuel. In a similar light, standards are needed to insure compatibility between vehicles and various refueling stations, accurate determination of hydrogen flow rates and quantities transferred to the vehicles while avoiding many safety problems and many other issues.

One indication of the importance of hydrogen codes and standards emerged from a meeting convened on November 12 and 13, 2002, entitled, “Global Forum on Personal Transportation.” Attendance at the forum was by invitation from Secretary of Energy Spencer Abraham and involved “125 Senior automotive and energy experts from government, industry, and academia representing 12 countries, the European Commission, and The World Bank.” There were only four summary recommendations. The first two of these recommendations, were:

1. Commit to a global fuel cell and hydrogen infrastructure.
2. Reach agreement internationally on a common certification process, and harmonized codes and standards, for advanced technologies and move forward.

Clearly, this group of experts considered common certification processes and harmonized codes and standards to be of vital importance.

The U.S. Department of Energy has a separate budget line for safety, codes, and standards as part of the Hydrogen program. Recent funding in this category was:

2003 -- $4.53 million (including little or no earmark)
2004 -- $5.75 million (after earmarks removed)
2005 -- $5.80 million (after earmarks removed)
2006 -- $4.72 million (after earmarks removed)
2007 – Request $13.85 million

Table 4-5 (see section E-iii) shows DOE solicitations and awards for “Codes and Standards” as well as for “Storage” since 2003. The only major contract for codes and standards was for $6 M (over 5 years) and was awarded in Dec, 2006, to Regulatory Logic, LLC. This award, which included 15 sub-contracts, has only just begun and codes and standards activities are typically notoriously slow.

E. Current Research and Development Efforts

1. Introduction

Primarily because of the cost and weight problems noted above, considerable effort is being devoted to finding alternative technologies to liquid or compressed onboard hydrogen storage. Many of these efforts were initiated by, and are supported by, DOE. They are, however, generally research oriented (as opposed to development programs) and have goals of finding, and understanding, promising science which could then provide the basis for new system developments. Consequently, these various projects are typically not mature enough for reasonable predictions of cost or even, in most cases, overall storage system performance. They represent valuable efforts by researchers in industry, government, and academia and present an excellent possibility that one or more will lead to new system concepts with cost and/or performance advantages over current systems.

2. Department of Energy Hydrogen Storage Targets

As part of the PNGV program, various government/industry technical teams were formed in different areas of technology specialization. The combined efforts of these government and industry experts in the various teams provided a major input for the establishment of the DOE technology targets. Usually, the targets were based on compromises, using auto industry input for values which could result in competitive vehicles and technical specialists input for values that were based on reasonable expectations of being achievable.

At the time they were established, many of the fuel cell and hydrogen storage targets seemed, to many people familiar with the technologies, to be unachievable. Examples are some of the fuel cell performance parameters such as start time, freeze/thaw tolerance, power density, and others. Progress has been so rapid that most of these fuel cell targets have either been met or at least seem achievable. Hydrogen storage seems to be an exception in that none of the industry representatives contacted or surveyed seemed to expect either hydrogen storage weight fraction or cost targets to be met for 2010 or 2015.

Some of the hydrogen storage targets have already been shown and discussed earlier in this section. A further list of technical targets is shown below in Table 4-3.

Table 4-3: Selected DOE Hydrogen Storage Technical Targets

Storage Parameter	**Units**	**2010**	**2015**
System Gravimetric Capacity	kWh/kg	2	3
Usable, specific-energy from H_2 (net useful H_2/max system mass)[a]	Kg H_2/kg/system	(0.06)	(0.09)
System Volumetric Capacity			
Usable energy density from H_2	kWh/L	1.5	2.7
(net useful H_2/max system Volume)	(kgH_2/L system)	(0.045)	(0.081)
Storage System Cost[b]	$/kWh net	4	2
	($/kg H_2)	(133)	(67)
(Fuel cost)[c]	($/gge)	2-3	2-3
Durability/Operability			
• Operating ambient temperature[d]	°C	-30/50 (sun)	-40/60 (sun)
• Min/Max Delivery Temperature	°C	-40/85	-40/85
• Cycle Life (1/4 tank to full)[e]	Cycles	1000	1500
Charging/discharging Rates			
• System fill time (for 5 kg)	Min	3	2.5
• Minimum full flow rate	(g/s)/kW	0.02	0.02
Fuel Purity (H_2 from storage)	% H_2	99.99 (dry basis)	
Environmental Health and Safety			
• Permeation & Leakage	Scc/h	Meets or Exceeds Applicable Standards	
• Toxicity	-		
• Safety	-		
• Loss of Usable H_2	(g/h)/kg H_2 stored	0.1	0.05

Source: Dr. Sunita Satyapal, DOE Hydrogen Storage Team Leader, January 2007

Note: Above targets are based on the lower heating value of hydrogen and greater than 300-mile vehicle range; targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. Unless otherwise indicated, all targets are for both internal combustion engine and for fuel cell use, based on the low likelihood of power-plant-specific fuel being commercially viable. Also note that while efficiency is not a specified target, systems must be energy efficient. For reversible systems, greater than 90% energy efficiency for the energy delivered to the power plant from the on-board storage system is required. For systems generated off-board, the energy content of the hydrogen delivered to the automotive power plant should be greater than 60% of the total energy input to the process, including the input energy of hydrogen and any other fuel streams for generating process heat and electrical energy. All targets must be achieved at end of life.

[a] Generally the "full" mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.
[b] 2003 US$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.
[c] 2001 US$; includes off-board costs such as liquefaction, compression, regeneration, etc.; 2015 target based on H_2 production cost of \$2 to \$3/gasoline gallon equivalent untaxed, independent of production pathway.
[d] Stated ambient temperature plus full solar load. No allowable performance degradation from -20℃ to 40℃. Allowable degradation outside these limits is TBD.
[e] Equivalent to 200,000 and 300,000 miles respectively (current gasoline tank spec).

Meeting performance and cost targets is certainly not a guarantee of commercial success but the converse is probably true. Not meeting the targets will make commercial success very difficult. As an example, consider three important hydrogen storage targets for 2010 and 2015, volumetric energy density, gravimetric energy density, and cost for 5 kg of hydrogen storage:

3. Department of Energy Funding History for Hydrogen Storage

It should be noted that much more emphasis is put on DOE efforts regarding hydrogen storage than on other ZEV-related technologies. The reason is that, as was mentioned earlier, there is little evidence of significant industrial accomplishments for complete storage systems other than compressed gas or liquid hydrogen.

Funding for hydrogen storage was begun during the PNGV under the general heading of storage and fuel processors. After onboard fuel processors were no longer considered viable and it was decided to emphasize the FreedomCAR program, a separate budget item was created for hydrogen storage. Table 4-4 gives a summary of these funds for the last several years.

Table 4-4: Doe Hydrogen Budgets
(Thousands of Dollars)

	Fuel Processing and Storage[1]	Storage R&D[2]	Codes and Standards[2]
FY 2001	20,806		
FY 2002	21,300		
FY 2003	24,100	3,000	4,531*
FY 2004		13,628*	5,557*
FY 2005		22,418*	5,801*
FY 2006		26,600*	4,727*
FY 2007 (Req.)		34,620	13,848

- After earmarks removed

4. Major DOE Initiatives and Solicitations

For the last century, the only media used to store fuel onboard light vehicles were either liquid or compressed gas. However, since neither offer desirable characteristics for storing hydrogen, serious efforts are being made to develop other means of storage.

Many materials are known which contain larger weight fractions of hydrogen than the 6%, DOE 2010 target, or even 9% of the 2015 target. Unfortunately, there is much more to a storage system than a hydrogen-bearing material. Energy must be expended, usually by a controlled temperature, under controlled pressure, to absorb and release the hydrogen at appropriate rates. This requires a considerable amount of support equipment which adds cost, weight, and volume to the system.

Some R&D has been conducted for alternative hydrogen storage concepts for many years, but especially since early consideration of fuel cell vehicles over 20 years ago. However, major organized efforts involving government agencies, national laboratories, universities, and private industry expanded greatly as a result of the hydrogen-oriented FreedomCAR program. This led to increased budgets and efforts by DOE to resolve many hydrogen issues.

Especially significant among DOE efforts was the hydrogen storage “Grand Challenge” solicitation in July, 2005. Awards of $150 M (over 5 years) were announced in April 2004. This resulted in Centers of Excellence as well as independent projects. Table 4-5 gives a summary of DOE hydrogen storage solicitations and awards since 2003. Since these awards are multiyear and mostly involve basic research, there are generally insufficient results to date to make realistic projections for alternative storage systems.

Table 4-5 DOE Solicitations and Awards, Hydrogen Codes and Standards and Storage

TOPIC	SOLICITATION #	$ AMOUNT	SOLICITATION DATE	AWARD/Comments
Codes & Standards for the Hydrogen Economy	DE-PS36-06GO96011	$6M (over 5 yrs)	December 2005	December 2006; to Regulatory Logic, LLC (includes 15 sub-contracts)
Off-Board Hydrogen Bulk Storage	Small Business Innovation Research Phase I (hydrogen component)	up to $100,000 for Phase I grants	September 2006	NO AWARD YET - PROPOSALS UNDER EVALUATION
On-Board Vehicular Hydrogen Storage	DE-PS36-06GO96003F (Equivalent lab call: DE-PS36-06GO96012F)	$6M (over 2 - 5 yrs)	August 2006	NO AWARD YET - PROPOSALS UNDER EVALUATION
Novel Materials for Hydrogen Storage (Basic research for the Hydrogen Fuel Initiative)	DE-PS02-06ER06-17	~$12M annually (including storage, over 3 years)	April 2006	NO AWARD YET - PROPOSALS UNDER EVALUATION
Novel Materials for Hydrogen Storage (Basic research for the Hydrogen Fuel Initiative)	DE-FG01-04ER04-20	~$19.8M (over 3 years for storage out of $64M over 3 years for basic research for Hydrogen Fuel Initiative)	May 2005	Announced May 2005
The Hydrogen Storage "Grand Challenge"	DE-PS36-03GO93007	$150M (over 5 yrs)	July 2003	Announced April 2004 (includes Centers of Excellence and independent projects)

5. The Role of PNGV and FreedomCar

The Partnership for a New Generation of Vehicles (PNGV) was initiated by the Clinton administration in 1992. Among the power systems given consideration for the 80 mpg vehicle were fuel cells. Even though many individuals and organizations had previously done studies and simulations for fuel cell-powered vehicles, the PNGV was probably the first time that there were multiple groups working simultaneously on essentially common targets. In addition, the DOE was budgeting significant funds for fuel cells to help resolve some of the technical and economic barriers. Among the results were a rapidly expanding interest in fuel cells and some remarkable progress in advancing the technologies.

Initially, the PNGV fuel cell efforts focused almost entirely on liquid fuels, gasoline in particular, which would utilize onboard fuel processors. The fuel processors would produce a hydrogen-rich gas (reformate) from the liquid fuel to fuel the stack. Using gasoline it was believed would eliminate many of the problems associated with hydrogen, including lack of infrastructure, high fuel costs, and onboard hydrogen storage. Towards the end of the program it became apparent that the additional costs, efficiency losses, and resulting emissions associated with the fuel processor would negate many of the potential benefits and make meeting cost targets even more difficult. In addition, it was also obvious that operational demonstrations of fuel cell vehicles would not be feasible within the time frame set for the PNGV, the year 2000. Even so, the potential efficiency and emission benefits for fuel cells along with the impressive progress being made kept the focus on fuel cell vehicles active in the PNGV. Therefore, while the fuel cell-powered vehicle received considerable attention during the PNGV program, there was relatively little emphasis during most of the program on hydrogen-fueled vehicles and onboard hydrogen storage.

Independently of the PNGV program, however, DOE efforts continued on onboard hydrogen storage. The storage efforts included certification of pressurized tanks/cryotanks in 2000 and 2001, continuing R&D on hydrides/Alanetes hydrogen carriers with hardware demonstrations in 2000, and carbon nanofibers hardware milestones in 2000, 2001, and 2002. DOE hydrogen-related programs began to increase after President Bush announced his Hydrogen Fuel Initiative in January 2003. His entire proposed program emphasized hydrogen and fuel cells thus prompting increased efforts by DOE.

Based on the President's Hydrogen Initiative, the FreedomCAR program was created in the fall of 2003 and by early 2004 a substantial increase in hydrogen activities was underway, including focused efforts on hydrogen storage.

In summary, the PNGV was responsible for a considerable increase in the interest in fuel cells, including hydrogen-fueled fuel cells. Many productive programs were initiated in national laboratories, universities, and private industry but the major emphasis was not on hydrogen. The FreedomCAR program, on the other hand, put a great deal of emphasis on hydrogen fuel, fuel cell vehicles and many of the hydrogen-related barriers, including hydrogen storage. Thus, both of these programs had positive effects on the pursuit of hydrogen-fueled vehicles, especially fuel cell vehicles.

6. Active Participants in DOE Hydrogen Storage Technology Programs

DOE had an annual Merit Review, May 16-19, 2006, in Arlington Virginia, involving DOE contractors working in hydrogen technologies. There were 12 oral presentations and 12 poster presentations by DOE contractors. Virtually all of the contractors participating in the hydrogen storage sessions were from national laboratories or universities. The oral presentations were all fundamental research-oriented with most involving hydrogen interactions with solid materials and a few involving interactions with condensed phase materials. A summary of the presentation titles, lead author and affiliations, and a few words from their abstracts describing the projects are shown in Appendix G. Among the participants, were:

a) Government and National Laboratories

Ames Laboratory (AMES)
Argonne National Lab (ANL)
Berkeley National Lab (BNL)
DOE
JPL (JPL)
Lawrence Berkeley Natl. Lab (LBNL)
Los Alamos National Lab (LANL)
National Renewable Energy Lab (NREL)
Natl. Inst. of Science & Tech. (NIST)
Oak Ridge National Lab (ORNL)
Pacific Northwest National Lab (PNNL)
Sandia National Lab (SNL)
Savannah River National Lab (SRNL)

b) Universities

Caltech.
Clemson
Colo. School of Mines Tulane
Columbia
Drexel
Georgia Tech
Hamilton College
Iowa State
La. Tech
LSU
MIT
N.C. State
Penn State
Rice
Rolla
Rutgers
So. Illinois
UC Berkeley
UC Santa Cruz
UCLA
Univ. of Tenn.
Univ. of Illinois
Univ. of Michigan
Univ. of Missouri
Univ. of Pennsylvania
Univ. of Washington
UNLV
Va. Commonwealth
Washington State

c) Private Industry

Air Products
GE
HRL Industries
Intematix Corp.
Phillips Research
Rutherford-Appleton Laboratory
TIAX
United Technologies Research Center
UOP LLC
WUSTL

7. Industry Activities

With the exception of BMW, all of the major automobile OEMs in the USA, Japan, and Germany are devoting time, effort, and resources to hydrogen-fueled vehicles utilizing compressed hydrogen gas, either at 350 bar or 700 bar storage pressure. Honda alone indicated that they did not intend to go to 700 bar storage and would stay with the lower 350 bar.

All of the OEMs using compressed hydrogen storage chose either type 3 or type 4 tanks as further described below. Although several of the OEMs had developed, or were in process of developing, their own tanks (or other types of storage), apparently all had used either Dynetek type 3 or Quantum type 4 tanks in fuel cell test vehicles. Toyota had, for example, already fabricated tanks of their own design but these were similar to the Quantum type 4 tanks. Both types utilize small high-strength, carbon fibers wrapped tightly around a core body (actually the inner liner of the storage volume) and bonded with an epoxy-type material. Type 3 tanks utilize a metallic liner (e.g., aluminum) where the type 4 tanks utilize a high-strength, plastic-type material (e.g., HDPE). Both types have an outer covering of HDPE-type material to provide impact and environmental protection. Both types have also been successfully built and tested for both 350 bar and 700 bar applications, and each seems to have advantages and disadvantages relative to the other.

The windings and bonding agents are nearly identical for both types of tank, thus they both have similar upper limits on the temperature of these materials - about 85℃. Above this upper limit, the bonding agent could weaken sufficiently to potentially allow the winding to shift (creep), which could compromise the integrity of the tank.

The primary concern in exceeding the upper allowable temperature of the tank is during rapid refueling. The normal refueling procedure is to transfer hydrogen from a higher pressure supply tank into the vehicle tank. During this process, hydrogen in the vehicle tank is heated by compression. This causes a temperature gradient between the tank interior and the ambient air surrounding the tank. Thus, as the gas is heated by compression during the refueling process, heat is transferred from warmer hydrogen to the surroundings (e.g., the container walls then to the atmosphere) thereby reducing the interior temperature. The upper gas temperature reached in the tank during refueling is a function of many variables including the refueling rate, the temperature of the supply hydrogen, the initial temperature of the tank and residual gas in the tank, the ambient air temperature, and the amount of residual hydrogen in the tank prior to refueling.

For a given mass of hydrogen transferred into the tank during refueling, the temperature first increases and then due to heat transfer, it begins to decrease. However, as the gas temperature drops, so will the pressure. That means to achieve a desired tank pressure after the increased gas temperature has dropped back (which it will, after a period of time) to near-ambient, the tank must be filled to a pressure above, and possibly considerably above, the design service pressure. Essentially, the faster the fill and the higher the initial temperatures of residual and supply hydrogen, the higher would be the peak internal temperature reached and thus the higher the necessary fill pressure. However, this process must be carried out without exceeding either the maximum fill pressure or allowable maximum wall temperature. Thus, there is an upper limit on the fill rate which could be determined to be either the maximum allowable pressure or the maximum allowable temperature.

The allowable fill rate could be increased due to any, or all, of these factors:

1. A higher allowable material temperature.
2. An increase in the rate of heat transfer from the tank interior to ambient air.
3. A lower temperature of the supply hydrogen.

Number 1 above requires the “invention” of new bonding materials. Number 2 is affected somewhat by having a tank liner that is more conductive. In this regard, the type 3 tank with the highly conductive aluminum liner might have an advantage over the type 4 with the poor-conducting plastic liner. Alternative 3, a decrease in the temperature of the supply hydrogen, is achieved by “pre-cooling” the supply hydrogen prior to filling. Such pre-cooling might be optional for 350 bar tanks (to allow faster fill times) but might be necessary to achieve what might be considered minimum acceptable refill times when filling a near-empty tank to 700 bar.

In a paper entitled, “Fast Filling of Type 3 Hydrogen Storage Cylinders,” by M. Duncan of Dynetek Industries Ltd. and S. Macfarlane of General Hydrogen, presented at the Hydrogen and Fuel Cell Conference in Vancouver, B.C, 2003, test results on filling 205 liter, type 3 cylinders to 350 bar were reported. This tank, a Dynetek W205H350G8N, has a capacity of close to 5 kg of hydrogen at 350 bar and 15℃ and is therefore representative of single tank configuration that might be used in some early- generation, fuel cell vehicles. It should be noted, however, that some such vehicles will probably use multiple tanks and others will probably use much longer and smaller diameter tanks, which would cause refill parameters to be different.

For the referenced test tank (2110 mm long, 418 mm diameter, and 90 kg weight), tests were reported for two average fill rates. One fill rate was 10.6 g/s. In both cases, the peak nominal fill pressure was 400 bar. With the higher fill rate, the peak hydrogen temperature (measured at the non-fill end) was 94℃ and, for the lower fill rate, it was 85℃. The respective fill times were 400 and 496 seconds, respectively. In both cases, the average supply hydrogen temperature was 22℃. Of special interest is the result that the peak liner temperatures, measured at 63℃ and 61℃, respectively, were considerably lower than the peak hydrogen temperatures. Since it is the tank materials, not the gas, which should be kept below 85℃, this suggests that a more rapid filling (without pre-cooling) might be possible. The test results also suggest a temperature gradient in the hydrogen gas inside the tank, with the highest temperatures at the non-fill end. This would likely be due to the fact that the cooler, entering supply hydrogen is compressing the gas already in the tank. If so, this might have implications for the allowable fill rates of long, thin tanks.

Type 3 tanks have a potential disadvantage compared to Type 4 due to the differences in thermal expansion coefficient between the aluminum liner and the carbon fiber/epoxy structure surrounding it. In type 4 tanks, the thermal expansion coefficients are much more similar. Whether the dissimilarity could be a significant issue is not really known at this point in time. On the other hand, the various connectors, valves, etc., fastened to the tank (both internally and externally) are metal, which would appear to be more compatible with the Type 3 liner. As previously stated, both types have been successfully fabricated and tested for both 350 bar and 700 bar applications.

There are three major companies in North America which are known to design and fabricate high pressure, composite gas storage tanks. They are Lincoln Industries of Lincoln, Nebraska; Quantum Fuel System Technologies Worldwide, Inc., of Irvine, California; and Dynetek Industries of Calgary, Canada. All of the tanks noted at the various OEMs using pressurized hydrogen appeared to be fabricated by either Quantum or Dynetek, and all tanks have passed vigorous performance and safety tests.

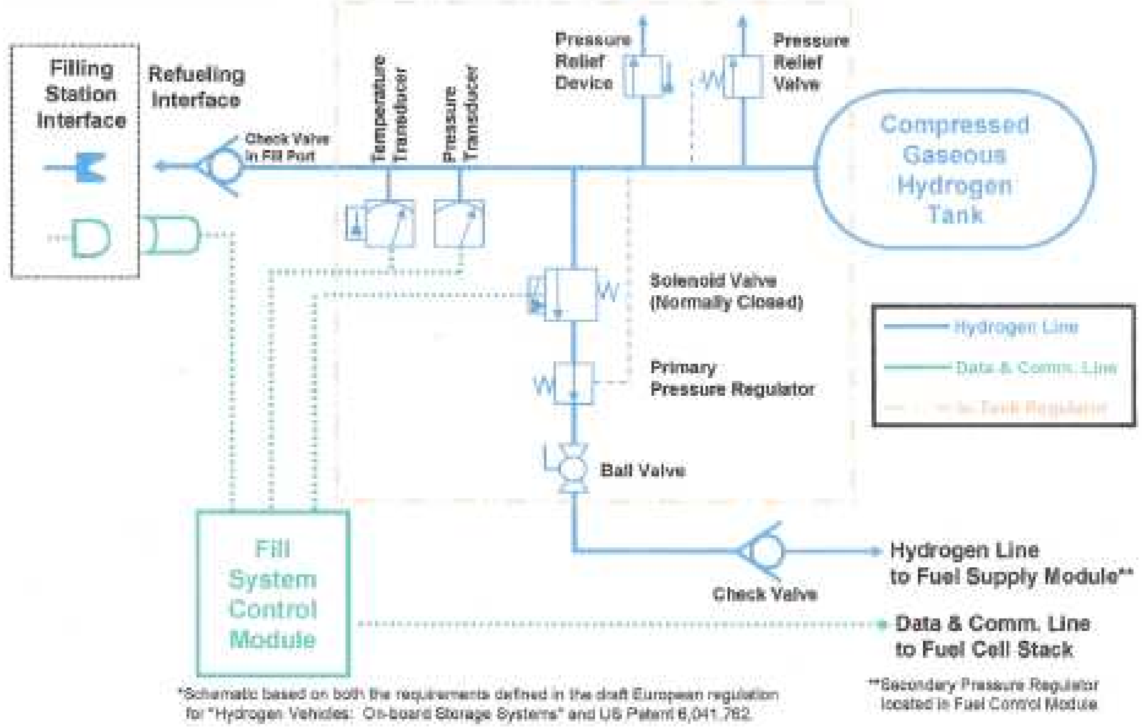
Visits were made to both Quantum and Dynetek and both demonstrated impressive capabilities to design and fabricate composite high pressure tanks. Of the two, Quantum is more R&D oriented, building relatively small numbers of special-purpose tanks. Dynetek seems to be primarily a manufacturing operation that has been producing and marketing high pressure tanks (mostly for compressed natural gas) for years. Dynetek also has a 100% owned subsidiary, Dynetek Europe Gmbh, in Europe also producing compressed gas storage tanks.

Quantum is pursuing primarily Type 4 tanks with high density polymer liners while Dynetek builds Type 3 with metallic (aluminum) liners. Each type has advantages and disadvantages with no obvious compelling reasons to choose, or not choose, either type.

F. The Status of Candidate Technologies Compared to DOE Targets

It is difficult to compare most of the alternative hydrogen storage technologies to DOE targets since all but compressed gas and liquid are still in research phases. Even comparisons of compressed gas and liquid hydrogen storage are difficult, especially from cost standpoints, since neither have benefited from mass-manufacturing cost reductions. However, a DOE-sponsored Cost Analysis Study[3] gave some projected costs. The study used a hydrogen storage system as shown in Figure 4-5 as a basis for the cost assessments. It was also based on typical Type 3 or Type 4 tanks.

Figure 4-5: Hydrogen Storage Schematic Used for Cost Studies



*Schematic based on both the requirements defined in the draft European regulation for "Hydrogen Vehicles: On-board Storage Systems" and US Patent 6,041,762

**Secondary Pressure Regulator located in Fuel Control Module

The TIAX cost study was based on tracking all required materials and components separately as well as costs for assembly and inspection. It was concluded that the majority of the weight (about 52% for 700 bar tanks and about 45% for 350 bar tanks) and cost (almost 60% for both 350 bar and 700 bar tanks) is due to the carbon fibers. It also concluded that "Aerospace-grade carbon fibers must be used to achieve reliability, safety, and life." Further, they concluded "Aerospace fibers are currently made in high volume and we do not anticipate much further cost reduction." Table 4-6 shows the model results from this study compared to DOE targets.

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[3] "Compressed Hydrogen and PEM Fuel Cell System," prepared by TIAX and presented October 20, 2004, for discussion by the FreedomCar Fuel Cell Technical Team. TIAX is an organization that specializes in cost studies, breaking costs down into basic materials and manufacturing costs including accounting for volume of production. They have done previous studies for DOE.

DOE, as well as the industry leaders in producing compressed gas tanks, recognize the importance of the cost of carbon fibers and are pursuing potential cost reduction alternatives. However, so far no path has been found to keep the high quality/strength (which minimizes weight) while reducing costs. The fibers are already being mass-manufactured so innovative changes in materials or processes are needed to accomplish this.

Table 4-6

TIAX STUDY RESULTS FOR COMPRESSED HYDROGEN STORAGE

System Metric	DOE Targets 2010	DOE Targets 2015	Model Results 350 bar	Model Results 700 bar
Cost ($/kWh)	4	2	9-13	12-16
Specific energy (kWh/kg)	2	3	2.2	2.1
Energy density (kWh/L)	1.5	2.7	0.6	0.9
Hydrogen weight (%)	6	9	6.7	6.3

It is noteworthy that even though the study was based on a production volume of 500,000 systems per year, projections for costs were far above (2x to 6x) the targets. Further, the cost per kWh increases if more than one tank is assumed. Using two or three tanks results in projected cost increases of about 50% for three tanks at 350 bar and about 25% for two tanks at 700 bar. Projections for performance metrics are closer to targets than cost, but none are projected to meet the 2015 targets.

No such detailed studies are known to have been performed for other storage technologies, even liquid storage. However, some less detailed projections such as shown in Table 4-7 from a January 2005 DOE presentation, have been made. Interestingly, the cost projections from the DOE presentation for liquid hydrogen storage seem to be somewhat lower than the estimates provided by BMW, who are actually developing liquid hydrogen storage systems. The DOE study shows liquid hydrogen storage (mass produced) at about $6 per kWh where BMW expects “mid-term” costs to be perhaps over $100 per kWh and “long-term” to be as much as $15 to $30 per kWh. Part of the difference is probably due to the volume production assumptions. DOE projections are based on the production of hundreds of thousands of units while BMW is projecting only for a relatively small number of large luxury class vehicles.

Table 4-7: HYDROGEN STORAGE TECHNOLOGIES

Approximate Status* as Compared to DOE Targets for Energy Density
And Cost Per kWh for Hydrogen Storage Systems

	Vol. Energy Density (kWh/l)	Grav. Energy Density (kWh/kg)	Cost Per kWh ($/kWh)
DOE 2015 Target	2.7	3.0	$ 2
DOE 2010 Target	1.5	2.0	$ 4
Chemical Hydride	1.4	1.6	$ 8
Complex Hydride	0.6	0.8	$16
Liquid Hydrogen	1.6	2.0	$ 6
Gaseous Hydrogen 10,000 psi	1.3	1.9	$16
Gaseous Hydrogen 5,000 psi	0.8	2.1	$12

*Taken from US DOE presentation by Mark Paster, “Hydrogen, Fuel Cells and Infrastructure Program,” January 2005.

G. *Future Outlook for Hydrogen Storage*

1. Near Term

In the near term, there is little doubt that, with the exception of BMW, the only hydrogen storage that will be widely used onboard light vehicles is compressed hydrogen gas storage. Every other OEM contacted indicated that this was the only real short term choice available and only Honda indicated that they intend to limit the storage pressure to 350 bar. The other OEMs seemed to prefer 700 bar, which will provide storage of over 50% more fuel in the same space envelope and correspondingly up to about 50% more range. Using 700 bar storage pressure is not, however, without problems. The volumetric density (kWh/L) will be higher but unit energy cost ($/kWh) is also expected to be higher and the gravimetric energy density (kWh/kg) about the same. It may also require either reduced fill rates or pre-cooling of the hydrogen prior to transferring into the vehicle tank to avoid overheating the tank structural materials.

Liquid hydrogen storage was also demonstrated to be workable, with limitations. It provides both higher gravimetric and volumetric density advantages over compressed gas storage but has issues with boil off and dealing with cryogenic liquids. It is not likely to be widely accepted by automobile OEMs in the judgment of the Panel.

Another issue with either the 350 or 700 bar compressed gas or liquid hydrogen storage is the need for widely accepted codes and standards for permanent storage, onboard storage, and all aspects of transferring and transporting hydrogen. This could be a major problem area, but probably it will be less of an issue in the short term since relatively small numbers of vehicles will be involved and they will likely be closely monitored and maintained.

Cost is also very much of an issue, especially for the short term since none of the storage systems are produced in volumes to allow significant production economies of scale. While none of the OEMs gave specific values for current or near-term costs for the essentially one-of-a-kind hydrogen storage systems, the Panel estimates them to have cost the industry $10,000 or more (in some cases, apparently much more) each for both liquid and compressed gas storage.

2. Longer Term

For the longer term, there is a possibility that some of the alternative storage technologies being researched can evolve into effective hydrogen storage systems. Both solid and liquid carriers are being researched with hydrogen "recharging" being carried out both onboard and off of the vehicle. There don't appear to be any clear winners at the present among these alternatives and, in fact, none of the researchers who responded to the hydrogen storage questionnaire made any projections for complete system performance or costs. It appears to be simply too soon to make reasonably accurate projections.

H. Summary and Conclusions

On-board hydrogen storage is a major problem enroute to a consumer hydrogen fuel cell vehicle. At present, the only technology being demonstrated by the OEMs, with the exception of BMW, is compressed hydrogen storage. Major issues for compressed hydrogen storage are volume, weight, and cost.

The volume issue can be partially resolved by using 700 bar storage (thus a smaller required volume) and by innovative vehicle design or modification. Such innovations might include utilization of a long, small-diameter tank running longitudinally where the center "tunnel" is located. An innovative modification could be replacing rear coil springs with leaf springs to increase space available for hydrogen tanks. Thus, depending on the type of vehicle and system efficiency, it seems likely that compressed hydrogen storage could provide a range in excess of 200 miles, perhaps reaching 300 miles or more.

Liquid hydrogen storage technology appears to have advanced sufficiently (primarily by BMW) that, within certain constraints, it could be utilized. The advantages of liquid hydrogen, higher storage density and low pressure, suggest that it also could provide an adequate range.

However, it seems unlikely that either compressed or liquid hydrogen storage systems can meet weight or cost targets, especially for 2015. Using the TIAX estimates for mass-manufactured tanks, the system cost would be about $10 to $12 per kWh for 350 bar systems and $13 to $15 per kWh for 700 bar systems. This is compared to DOE targets of $4 per kWh for 2010 and $2 per kWh for 2015. If it is assumed the compressed hydrogen storage system cost $12 per kWh, then for a 5 kg storage system (about 165 kWh), the cost would be about $2000. Similarly for liquid storage, the BMW projections would be about $2500 for the long term. There seems to be little expectation that the cost of either of these systems will go much lower even with the volumes projected for the respective vehicles.

The weight outlook is a little better than cost. The TIAX projections for weight fraction are slightly over 6% for both 350 bar and 700 bar systems, compared to the DOE targets of 6% for 2010 and 9% for 2015. The pressure tank manufacturers have also indicated that 6%, and perhaps a bit higher weight fraction is within reach. For a 6% weight fraction system to contain 5 kg of hydrogen, the system would weigh about 83 kg (about 183 lb). Neither the TIAX effort nor the tank manufacturers project that the 2015 target of 9% can be met with pressurized hydrogen tanks.

There are many alternative hydrogen storage systems under investigation. Some of the absorption materials being investigated are relatively inexpensive and have shown, at least in the research phases, the capacity to contain well over 6% hydrogen. However, the remainder of the support system could have a huge effect on both cost and weight fraction. It should be noted that most research efforts for novel hydrogen storage technologies have been underway for only a couple of years. There are many very capable researchers pursuing a number of novel approaches simultaneously, so there is reason for cautious optimism, although there are no apparent clear “winners” at present.

Therefore the main conclusion concerning onboard hydrogen storage systems is that there is currently no completely satisfactory solution and none in sight. It is fairly certain that the next generation (and possibly several generations) of fuel cell vehicles will utilize compressed hydrogen storage even though liquid hydrogen systems will apparently be used in some BMW vehicles. It appears likely that using innovative approaches, with compressed hydrogen, ranges of over 200 miles, and possibly over 300 miles, can be achieved. Such tanks, however, even if mass-manufactured, will be expensive (probably around $2000 for 5 kg storage) and heavy (probably between 75 and 100 kilograms) for 5 kg of storage). They will also require 5 or 6 times the volume (as much as 33 gallons for 5 kg of hydrogen storage) as would be necessary for equivalent gasoline energy (about 5 gallons).

As stated, it is certainly possible that some of the alternative hydrogen storage materials being studied will result in successful hydrogen storage systems. However, at this time, the technologies are simply too immature to make realistic cost and/or performance projections for complete functional systems.

5. Automotive Fuel Cell Systems

Since the review of automotive fuel cell technology by the 1998 ARB Fuel Cell Technical Advisory Panel (Kalhammer, et al, 1998), massive efforts by the major fuel cell developers and automobile manufacturers have resulted in impressive advances in every aspect of fuel cell technology. This section summarizes the most important of these advances and identifies remaining challenges in the production of technically and economically viable automotive fuel cell systems.

The 1998 Panel concluded that fuel cell technology had advanced to the point of meeting automotive requirements, that hydrogen was not a feasible fuel and, that the favored fuels were gasoline or methanol. To facilitate use in a fuel cell, the gasoline or methanol needed to be chemically processed on-board into a hydrogen rich fuel. The Panel recognized that the integration of the fuel processor, fuel cell stack and balance of plant was a significant technical challenge. However, the largest challenge was the achievement of cost goals to compete on a first cost basis with the internal combustion engine. Major resource commitments by large organizations were in place and the optimistic scenario was that the fuel processor, FCEV would be commercially available in 2004/2005.

Since the 1998 report, it is now clear that on-board hydrogen is the only fuel considered viable for FCEVs, and the change is attributed to:

- The failure to develop a cost effective fuel processor that would physically fit into and meet the operational dynamics of a FCEV,
- The fuel efficiency and emissions for the fuel processor FCEV were not clearly better than advanced diesels or hybrids that are now commercialized, and
- The FreedomCAR program with the emphasis on hydrogen was initiated. The issues of energy security, climate change and non petroleum based fuels such as hydrogen as a chemical energy carrier are now considered of national interest.

These changes lead to a major shift in focus and resources from fuel processors to hydrogen related issues and created a greater emphasis on fuel cell system efficiency to counter the limitations of hydrogen storage and related refueling infrastructure.

The following review of fuel cell systems is divided into five sub sections.

- The first, 5A, provides a general discussion of fuel cell technology,
- The second, 5B, summarizes technical requirements,
- The third, 5C, describes specific fuel cell components and development challenges,
- The fourth, 5D, presents the Panel findings including a description of the developers visited, the issues of cost and performance compared to goals, and
- The final, 5E, provides the assessment and conclusions of the Panel.

A. Fuel Cell Overview

A fuel cell is an electrochemical device that directly converts the chemical energy of fuel into electricity. The fundamental advantage of a fuel cell is the relatively high efficiency and zero tailpipe emissions when operating on hydrogen. The fuel cell concept was first recognized in 1839 and the first successful application of the fuel cell came in the 1960s for space flight. Although fuel cells have been in continuous development in stationary and mobile terrestrial applications for almost 50 years, only now are they being developed for use as a practical automotive power source.

1. Fuel Cell Operating Principles

All energy-producing oxidation reactions are fundamentally the same and involve the release of chemical energy through the transfer of electrons. During combustion of hydrogen and oxygen, there is an immediate and chaotic transfer of electrons in which heat is released and water is formed. A fuel cell accomplishes the same oxidation reaction in a controlled manner that allows the direct utilization of the electron transfer. A fuel cell produces direct current electricity and, in the case of a Polymer Electrolyte Membrane (PEM) fuel cell, low grade heat.

As illustrated in Figure 5-1, in a fuel cell, hydrogen and oxygen are fed separately to anode and cathode electrodes which are separated by an electrolyte that is impervious to the gases.

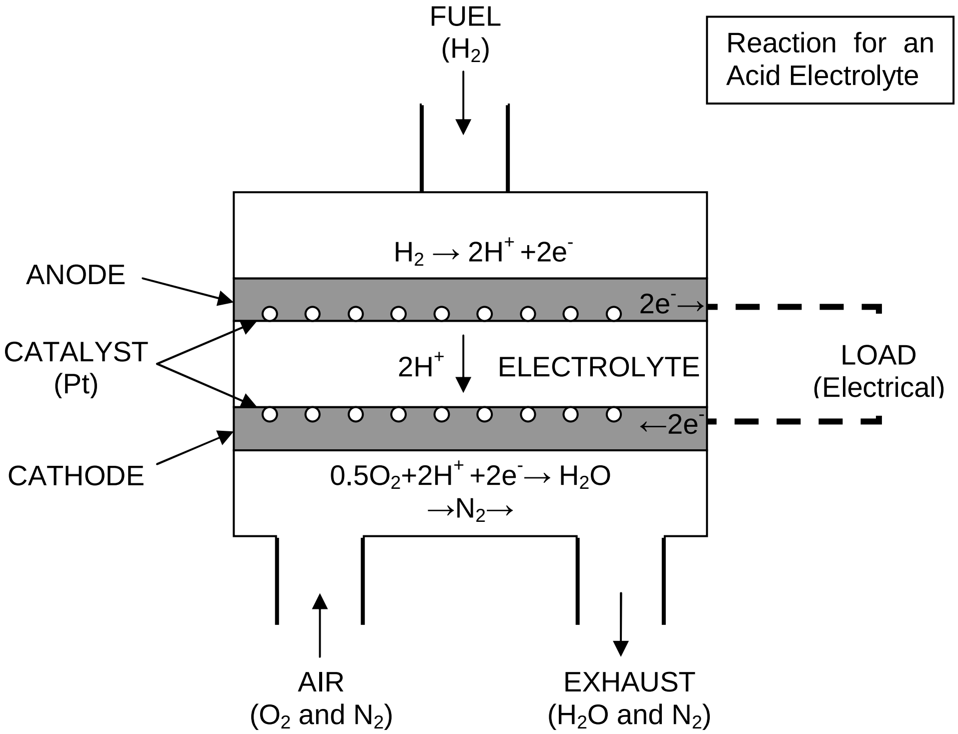


Figure 5- 1: Fuel Cell Operation Schematic

At the anode, the hydrogen molecules are split into hydrogen atoms (protons) that release electrons to the conducting anode which in turn becomes electrically negative. These processes are greatly accelerated by a catalyst, usually platinum, if the electrolyte is acidic and operates at relatively low temperatures. The electrons are separated from the hydrogen molecule by the catalyst (oxidation) creating a hydrogen ion (no electrons). The protons thus formed leave the anode surface and pass through the electrolyte to the oxygen (cathode) side. The electrons released from the hydrogen atoms at the anode cannot enter the electrolyte and are forced to take an external electrical circuit which leads to the oxygen side. At the cathode, oxygen is electrochemically reduced to hydroxyl ions in a series of steps that require a catalyst (again, platinum or a platinum group metal or alloy), leaving the cathode positively charged. Driven by the potential difference, electrons travel from the anode to the cathode if an external circuit is provided. The protons combine with hydroxyl ions to form water, which is the only chemical reaction product of a hydrogen-oxygen fuel cell. If air is used as the oxidant, only the oxygen is involved in the fuel cell process; nitrogen passes the cathode unchanged and is exhausted, together with the product water.

Chemical Reaction of PEM Fuel Cell

Anode side: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode side: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Table 5-1 provides the hydrogen/oxygen/water reaction enthalpy (heating value) and the resultant theoretical cell voltages. The Higher Heating Value (HHV) is the value that results when the product water condenses to a liquid. The Lower Heating Value (LHV) is the value that results when the product water does not condense but remains in gaseous form.

Table 5- 1: Hydrogen Thermodynamic Properties

Heating Value	ΔH Enthalpy of Formation J/Mole	kWh/kg	Voltage Based on Enthalpy
Higher (HHV)	-285900	39.4 kWh/kg	1.48
Lower (LHV)	-241800	33.3 kWh/kg	1.25

A theoretical fuel cell voltage can be calculated based on the energy of the reaction (enthalpy of formation) and the number of electrons that are transferred. This theoretical voltage of conversion $E_{\Delta H}$ is calculated by considering Faraday's constant (approximately 26.8 Amp hours = 1 mole of electrons) and the energy value of the fuel. The reaction provides 2 electrons per H_2 molecule. The voltage of the fuel cell is independent of its physical size.

$E_{\Delta H}$ = Energy (J) / (Amp/Sec)

$E_{\Delta H}$ (LHV) = -241800 J / (-26.8 x 2 x 3600) = 1.25 Volts
$E_{\Delta H}$ (HHV) = -285900 J / (-26.8 x 2 x 3600) = 1.48 Volts

The fuel cell cannot take advantage of the difference in the HHV and LLV to produce additional electricity. As a result, the actual fuel cell voltage (E_{cell}) is compared to the $E_{\Delta H}$ (LHV). Assuming a perfect condition in which all electrons from the reaction are forced to take the external circuit and there is no loss of hydrogen fuel, the energy conversion efficiency can be calculated by dividing the fuel cell voltage by the calculated $E_{\Delta H}$ (LHV),

Efficiency (LHV) = E_{cell} / $E_{\Delta H}$ (LHV)

In a typical fuel cell, the electrical power production usually occurs between 0.6 and 0.85 Volts per cell. Ideal conversion efficiency results in calculated efficiencies of 48 to 68% of the LHV of hydrogen. The large difference between the E_{cell} and $E_{\Delta H}$ (LHV) is the result of electrode kinetics (particularly on the air electrode). The voltage drop as a function of current is due to internal resistance (electronic and ionic) as well as reactant gas flow limitations and product water flooding of reaction sites.

Multiple cells are connected in series to ensure a practical voltage (100s of Volts) and are referred to as a fuel cell stack. To produce a large current (100s of amps), the cross-sectional area of the fuel cell must be large (100s of cm^2).

2. Fuel Cell Performance Characteristics

The performance characteristics of a fuel cell can be shown in graphical form in terms of voltage (E_{cell}), power (W) and efficiency (LHV) as a function of current. By convention, the power and current are defined in terms of W/cm^2 (specific power) and $Amps/cm^2$ (Specific Current).

The relationship between E_{cell} and specific current is typically characterized by three regions: 1) an initial region followed by 2) a linear region, and finally 3) a mass transfer limited region as illustrated in Figure 5-2.

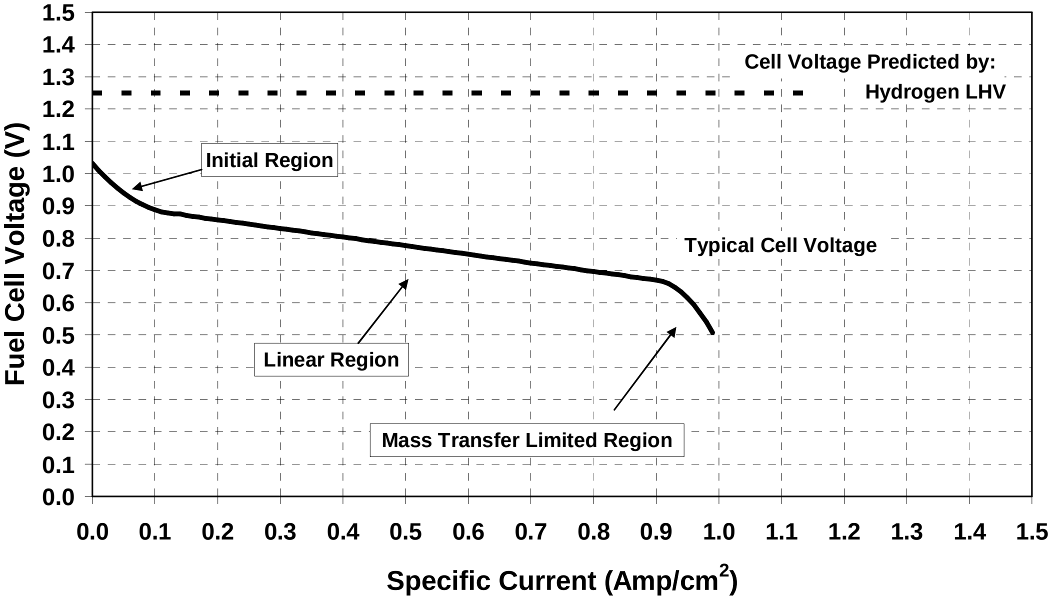


Figure 5- 2: Typical Fuel Cell Voltage, Specific Current Curve

1. The <u>initial region</u> shows an initial steep drop in the cell potential due to slow cathode kinetics. With sufficient voltage drop (0.1 to 0.15 volts over potential), the kinetics improves and is no longer limiting.
2. The <u>linear region</u> is characterized by a linear voltage drop primarily due to ionic resistance in the electrolyte.
3. As the current density further increases, the polarization curve enters the <u>mass transfer limited region</u> and cell potential drops off rapidly, primarily due to the inability of oxygen

to reach reaction sites fast enough. This inability may be caused by a combination of an oxygen gradient through the electrode, water blockage and/or nitrogen blanketing. Advanced engineering delays the onset of the mass transport region.

The calculated product of the cell voltage (V) and specific current (Amps/cm^2) is the specific power (W/cm^2) as shown in Figure 5-3.

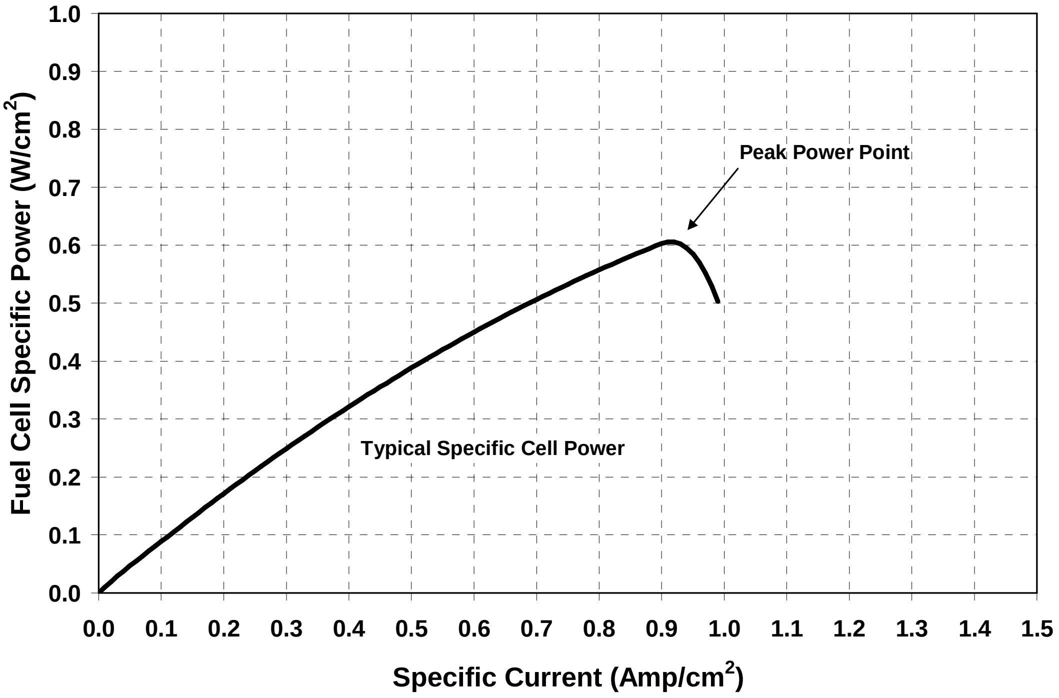


Figure 5- 3: Typical Fuel Cell Specific Power, Specific Current Curve

Up to the peak power point, the fuel cell produces more specific power as the specific current is increased. Operating the fuel cell at a higher current density than that which produces the peak specific power increases heat generation and fuel consumption and reduces specific power.

The peak specific power is a useful parameter for measuring progress in fuel cell performance. Higher specific power means that more power is available for a given size fuel cell and is likely to result in higher power per kg for the fuel cell system at a lower cost ($/kW).

The energy conversion efficiency of a fuel cell is primary related to the operating voltage as described in the previous section. Figures 5-4 and 5-5 present typical calculated and net energy conversion efficiencies as a function of specific current and as a function of specific power, respectively. The difference between calculated and net efficiency is due to the fuel cell requiring external support in its operation (i.e., a forced air supply must be provided).

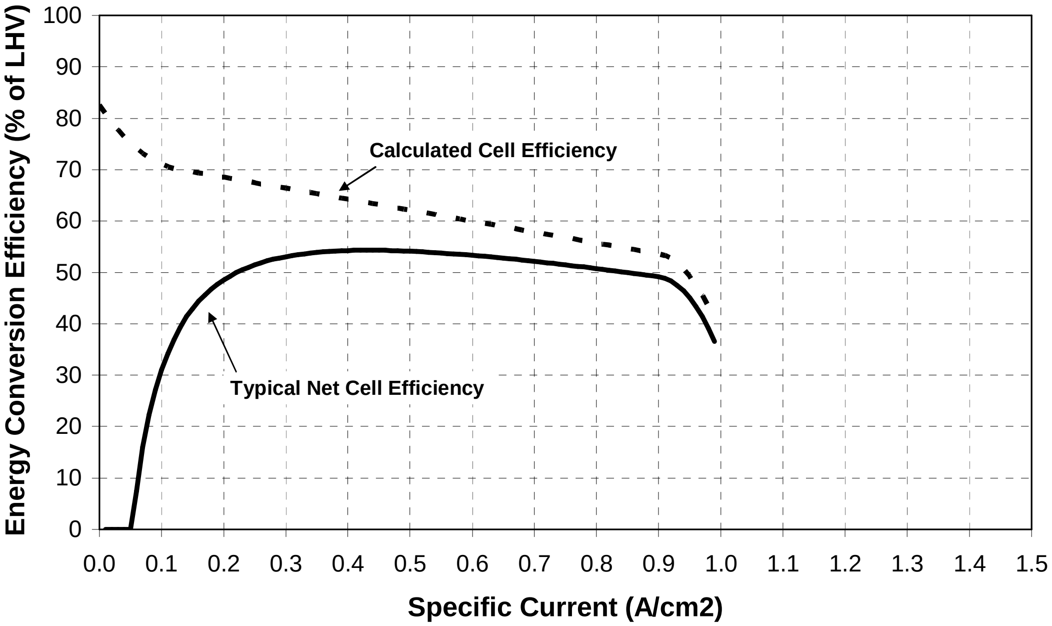


Figure 5- 4: Typical Fuel Cell Efficiency Specific Current Curve

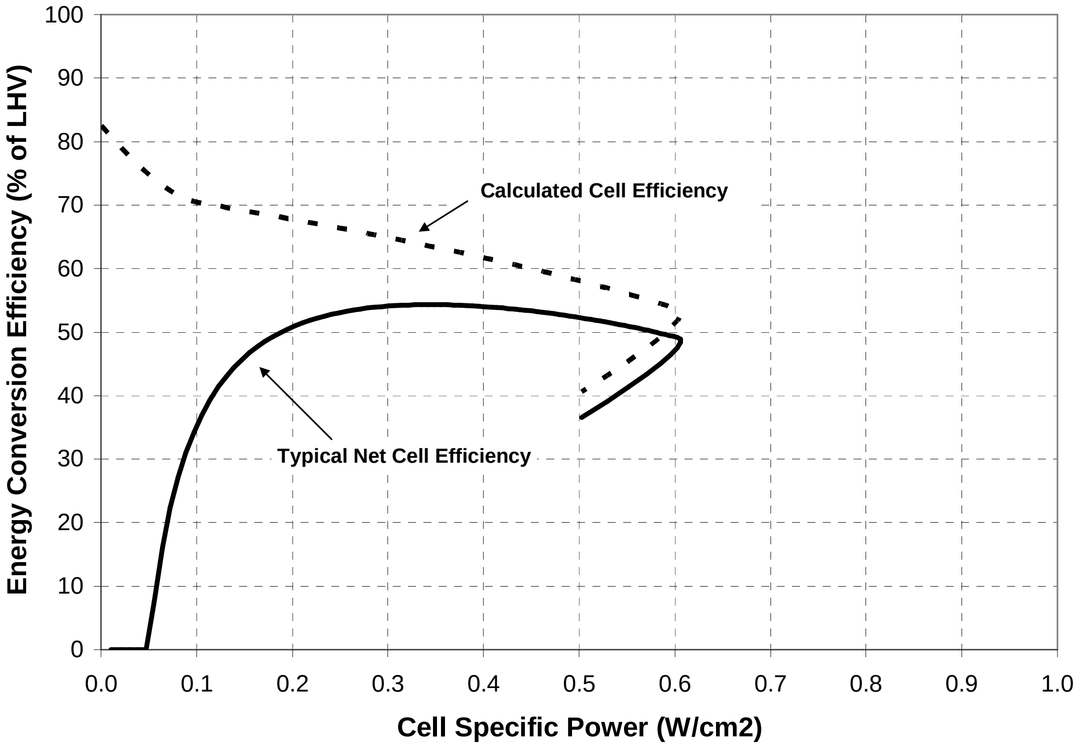


Figure 5- 5 Typical Fuel Cell Efficiency Specific Power Curve

The calculated cell efficiency curves shown in the two figures indicate that increasing current and power results in lower energy conversion efficiency. The net cell efficiency curves indicate that the cell is not energy sustaining at very low specific current conditions. As the specific current increases, the fuel cell then experiences a rapidly rising efficiency followed by decline in efficiency that approaches the calculated value. The characteristic of the net efficiency is the result of the overhead associated with support systems to operate the fuel cell (these support systems are described later). At very low current densities the idle power of the support system exceeds the cell power resulting in more energy being required than that which is being produced. In practice, the fuel cell would idle at the point where it just supports the system requirements.

3. Fuel Cell Electrolyte

Fuel cells are generally classified by the electrolyte used. The chosen electrolyte affects the specific chemical reaction, the cell operating temperature and the support system requirements. Suitable electrolytes for a fuel cell include alkaline, polymer electrolyte membrane, phosphoric acid, molten carbonic and solid oxide. Table 5-2 provides the normal operating temperature, and chemical reactions for each electrolyte. The specific application characteristics (automotive, utility power etc.) dictate which type of fuel cell is best.

Table 5- 2: Fuel Cell Types

Fuel Cell Type **Operating Temperature** **Electrolyte State**	**Anode Reaction**	**Cathode Reaction**
Alkaline (AFC) 80 to 120 ^{O}C Liquid Electrolyte	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ water production	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Phosphoric Acid (PAFC) 160 to 210 ^{O}C Liquid Electrolyte	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ Water production
Proton Exchange Membrane (PEM) 60 to 90 ^{O}C Solid Electrolyte	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ water production
Molten Carbonate (MCFC) ≈ 650 ^{O}C Liquid Electrolyte	$H_2 + CO_3^= \rightarrow H_2O + CO_2 + 2e^-$ water production	$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^=$
Solid Oxide (SCOFC) ≈ 1000 ^{O}C Solid Electrolyte	$H_2 + O^= \rightarrow H_2O + 2e^-$ $CO + O^= \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^= \rightarrow 2H_2O + CO_2 + 8e^-$ water production	$O_2 + 4e^- \rightarrow 2O^=$

Note: Temperature refers to nominal operating temperature, not necessarily start-up temperature.

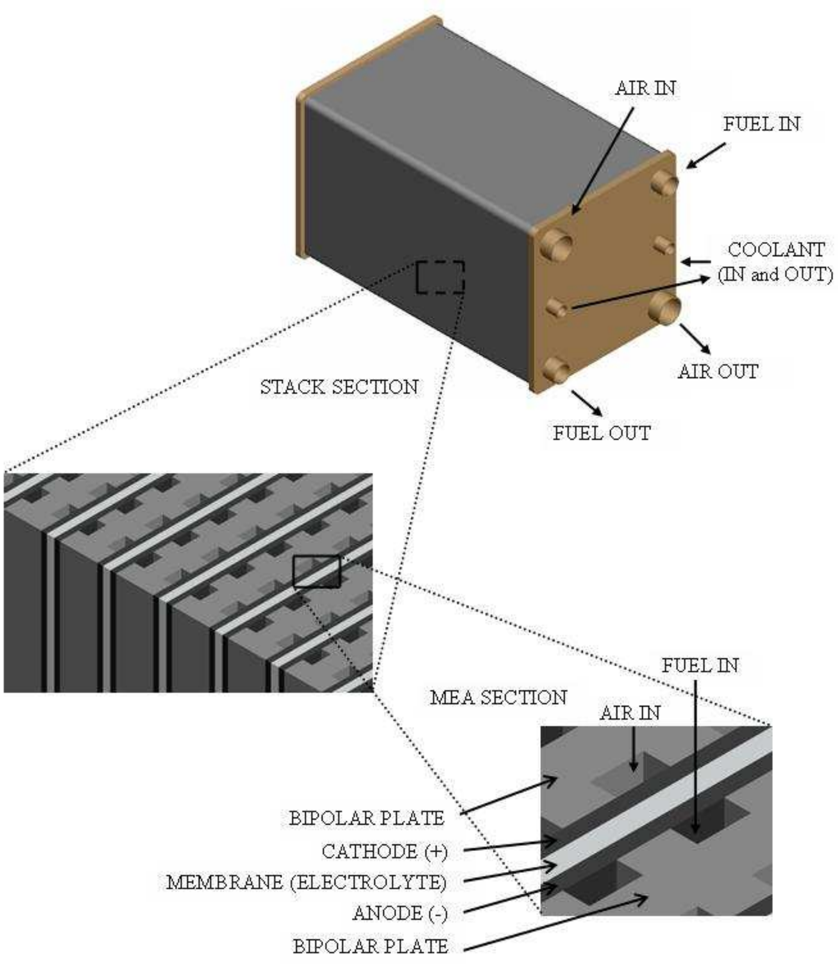
The Proton Exchange Membrane (PEM) technology has been selected by all automotive developers of fuel cells. The PEM has a relatively high specific power at an operating temperature near ambient. It can use air directly without concern for CO_2 and the solid electrolyte of the PEM can sustain a pressure differential from the fuel to air side which is important under dynamic electrical loading conditions. Recent PEM developments provide the ability for rapid startup under frozen conditions.

The solid electrolyte of the PEM is a polymer membrane. The membrane is impervious to the hydrogen and air gases and will only allow positively charged ions to pass through it. The membrane can be very thin and allows for a very compact design in comparison to a liquid electrolyte that must be physically constrained.

4. Fuel Cell Stack and Balance of Plant

To achieve a practical working voltage, individual fuel cells are arranged in a series configuration and are referred to as a fuel cell stack. Unlike typical storage batteries which will use a bus bar and strap approach, the typical fuel cell is constructed with bi-polar plates as shown in Figure 5-6. The reactants are typically introduced by a parallel manifold arrangement.

Figure 5- 6 Fuel Cell Stack Schematic



A typical cell pitch ranges from 3 to 5 cells per cm. A 100 cell stack would have a length of 20 to 33 cm. The stack voltage is the product of the individual cell voltage and the number of cells. The fuel cell stack design must allow for heat exchange and humidification of incoming reactant gases, thermal management, product water management, exhaust gases, and electrical management.

A PEM fuel cell uses a polymer electrolyte membrane. The membrane and associated electrodes are typically in a permanently laminated construction and are referred to as a Membrane Electrode Assembly (MEA). The MEA is the basic fuel cell component. The voltage of the fuel cell stack is determined by the number of laminations and the current is a function of the area of the MEA. To raise the power output, it is necessary to increase the number of laminations or enlarge the area of the MEA.

A fuel cell stack is not a naturally aspirating device like an ICE engine. When the fuel cell is in operation, the reactants, air and hydrogen must be supplied to the electrodes while heat, water and electricity must be removed. The systems that provide these functions are referred to as the

Balance of Plant (BOP). Figure 5-7 illustrates a typical automotive fuel cell power system consisting of the stack and the BOP components.

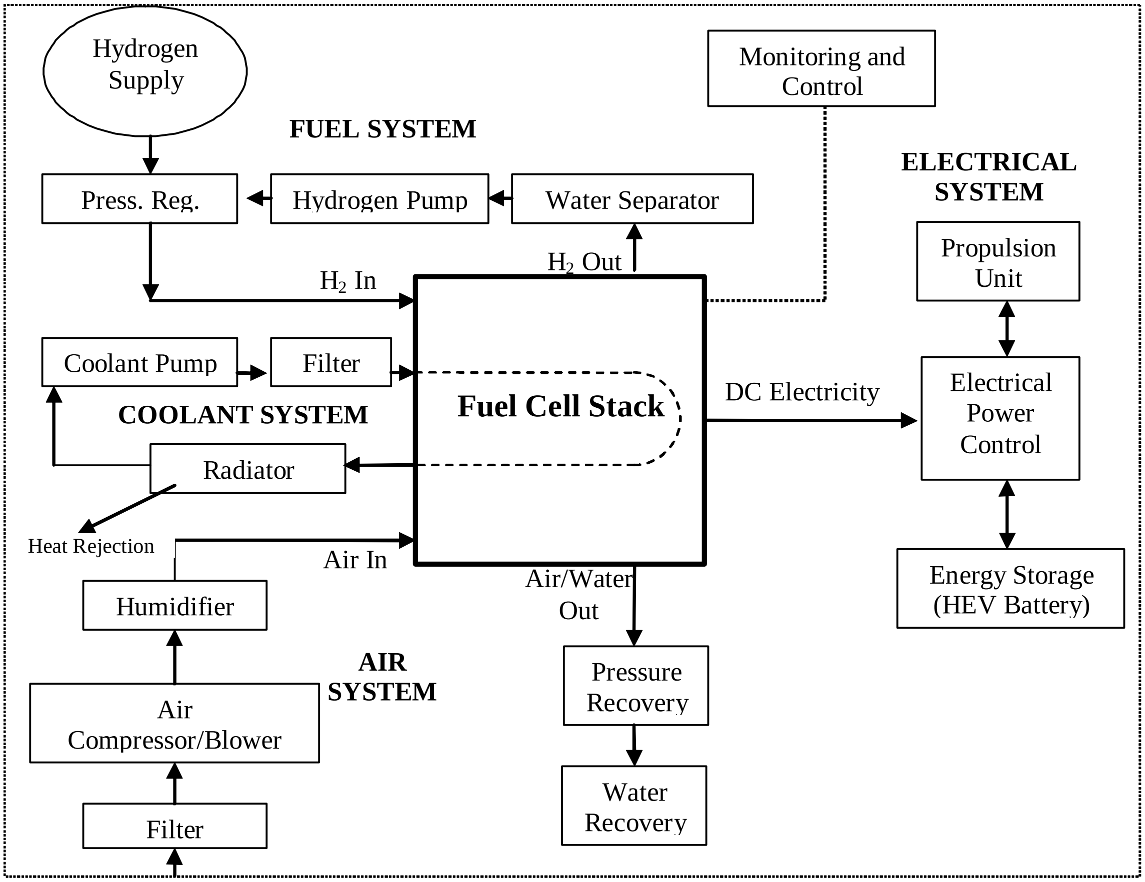


Figure 5- 7 Fuel Cell Subsystems "Balance of Plant"

To support the fuel cell operation, the balance of plant consists of the following subsystems:

- Hydrogen Supply System
- Air Supply /Water Management System
- Thermal Management
- Sensors and Control
- Energy Storage for Start-up Transient Response

The hydrogen and air supply systems provide the fuel and oxidant to the individual cells. These systems generally create a parasitic electrical load due to pumps and blowers. The water management provides gas humidification and product water removal as necessary. The thermal management system maintains the operating temperature of the fuel cell stack by removing heat as necessary. Sensors and controls monitor, manage and sequence the balance of plant to accommodate the electrical load demands on the fuel cell system. Energy storage provides the energy necessary for the fuel cell start up in order to meet automotive peak and regenerative power requirements.

B. Technical Goals and Standards

1. US DOE FreedomCAR Technical Goals

The US Department of Energy (DOE) FreedomCAR Partnership set technical goals for automotive fuel cell systems. The goals were created in cooperation with the automotive industry to identify and bench mark what was considered generally necessary for hydrogen fuel cell vehicles to be affordable and reliable.

Specifically, the FreedomCAR goals were chosen to be first cost comparable to conventional internal combustion engine/automatic transmission systems. The Partnership adopted specific cost goals for 2010 and 2015. The values are provided in the Table 5-3. For comparison, the table includes the FreedomCAR goals for internal combustion engine power trains fueled by hydrogen and clean hydrocarbons.

Table 5- 3: US DOE FreedomCAR Technical Goals

	Specific Power Power Density[1]	**Cost/Selling? Price**[1,2]	**Peak Energy Efficiency LHV**	**Life**
FC system H2 no traction electronics	325 W/kg 220 W/L Operating on Hydrogen Does not include hydrogen storage	$45/kW in 2010, $30/kW in 2015	60% fuel cell power system efficiency Including Hydrogen storage	15 Years
Hydrogen Fuel based ICE power train		$45/kW in 2010, $30/kW in 2015	45%. peak brake engine efficiency	
Clean hydrocarbon based ICE power train		$30/kW	45%. peak brake engine efficiency	

[1] Does not include Vehicle Traction electronics. [2] Cost references based on CY 2001 dollar values.

The table indicates that for a 100 kW fuel cell system to meet the technical goals it would have a mass of < 307 kg a volume < 454 liters and a cost of $3000 in 2015 based on 2001 dollar value. Assuming an inflationary rate of 2.5% this would mean that a 100 kW fuel cell system would cost approximately $4200 in 2015 ($42/kW).

The peak energy efficiency goal based on LHV means that every kg of hydrogen consumed at peak energy efficiency will provide at least 20 kWh of DC electricity. Based on the peak value, it is anticipated that a mid sized FCEV with a DC electrical consumption of 200 Wh/km would have a 100 km range per kg of hydrogen.

Implicit to the fuel cell system life goal of 15 calendar years, 5000+ hours of operation and 5000 to 10,000+ start/stop cycles are to be expected.

2. Automotive Fuel Cell System Standards

Standards benefit the commercialization of a new technology by helping to create an orderly market evolution and associated re-fueling infrastructure. Standards define the basic guidelines for design, manufacturing, safety and ease of use.

Standards in a new technology such as automotive fuel cells require industry cooperation to assure that the advantages are realized while not reducing the flexibility necessary to ensure technological developments. Typically, standards deal with general product safety, performance, compatibility and interchangeability. Standards may be necessary to facilitate the import and export of FCEVs and associated parts.

Automotive Standards for fuel cell systems in place or pending include:

- SAE 2572 (Draft) Recommended Practice for Measuring the Fuel Consumption and Range of FCEVs and HEVs Using Compressed Hydrogen. (Publication is anticipated in 2007) This draft standard is being used by NREL for FCEV dynamometer testing of efficiency values.
- SAE J2574 Fuel Cell Terminology
- SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety
- SAE J2616 Recommended Practice for Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System
- SAE J2615 Testing Performance of Fuel Cell Systems for Automotive Applications
- SAE J2617 Recommended Practice for Testing Performance of PEM Fuel Cell Sub-System for Automotive Applications
- SAE 2722 Durability
- SAE TIR J2719 Hydrogen Quality

Non-Automotive Standards for fuel cell systems include:

- IEC, Standards for Fuel Cell Modules, Stationary Power
- NFPA Standards for Fuel Cell Installations

Regulations are necessary to establish the legal requirements for certification and approval of a product and must be consistent with the industry standards.

C. Fuel Cell System Components and Subsystems

A PEM fuel cell system is made up of unique and specific components. To achieve cost and performance goals, each of these components must be optimized for the automotive application. This section reviews these components, their general function and technical status. The specific components reviewed are the PEM membrane electrode assembly, the fuel cell stack and the supporting subsystems which include hydrogen, air supply, thermal management, and system control.

1. Membrane Electrode Assembly (MEA)

The most fundamental component of the PEM fuel cell is the Membrane Electrode Assembly (MEA). It is the prime contributor to the PEM fuel cell system performance, cost and life. The MEA is made up of three basic components that including the solid electrolyte and the anode and cathode electrodes. The anode and cathode electrodes utilize a platinum or platinum alloy catalyst to facilitate the electrochemical reaction. The catalyst generally consists of finely dispersed electrochemical grade platinum particles. This is typically achieved by supporting small platinum clusters on high surface area carbon. A gas diffusion layer may be part of the

MEA and provides a method of gas distribution across the electrode and current conductivity to the stack bi-polar plates.

The challenges associated with the MEA are to reduce cost while simultaneously increasing specific power, life, and durability. Other challenges include operating at higher temperature and recovery from freeze and abuse conditions.

To increase the MEA specific power (W/cm^2) requires a reduction in the ionic resistance of the membrane material and improved electrode-layer structures that more readily allow hydrogen and air to reach the catalyst while allowing the water by-product to be removed.

To give adequate ionic conductivity, conventional membranes absorb water from inlet gases and produce water. Thus, water management (membrane hydration) of the MEA is one of the primary factors in determining performance. Proton conductivity of the membrane is dependent on the water content. Alternatively, excess humidification leads to liquid water (flooding) in the cell which blocks the reactant gases and results in increased concentration polarization. As water is absorbed, the membrane volume increases resulting in mechanical stress. The water content in the membrane also changes during load and start-stop cycles. This mechanical cycling can lead to edge tears and pinholes.

Hydrogen starvation of the anode can lead to MEA failure. This condition can exist in the fuel cell during start-stop cycles. Before startup of the power plant, air is present on both the anode and cathode due to leakage from outside air and/or cross-over through the membrane. During startup, when the hydrogen is introduced to the anode, a condition is created where hydrogen occupies only part of the anode. This creates a high interfacial potential difference in the region where hydrogen is absent causing carbon corrosion and oxygen evolution at the cathode. A similar transition can occur during the shutdown procedure, when the air introduced to the anode from the outside or through the membrane, replaces the hydrogen. This mechanism is also possible during operation when localized hydrogen starvation occurs, even for a short time. The carbon corrosion weakens the physical platinum catalyst support. The platinum moves in location since it is no longer supported for electronic conductivity and becomes effectively inert.

MEA catalyst cost is a major contributor to overall fuel cell system cost. The reduction of the catalyst loading on the air electrode is the easiest means to reduce MEA cost. However, it must be balanced by higher utilization to maintain performance while achieving long life. The platinum catalyst activity can increase when alloyed with other lower cost noble metals such as ruthenium and iridium. Reducing the platinum loading by alloying with other transition metals is being actively researched. The alloying may modify the electronic structure to change the electrochemical potential at which platinum oxidizes which could increase the voltage for the adsorption of oxygen and potentially benefit the catalytic efficiency. State of the art catalysts for the oxygen side reduction are clusters of platinum alloyed with cobalt which are supported on very high surface area globular carbon (Pt-Co/C).

The use of a fluorine electrolyte membrane is limited by high temperature. Structural integrity is lost near 100^{o}C which limits the typical working temperature to 80^{o}C. At low temperatures (<5C^o), there is high ionic resistance. New membrane technologies using an aromatic electrolyte are being developed. Compared to the conventional membrane, the aromatic electrolyte membrane maintains a structural integrity at or above 100^{o}C and has a lower ionic resistance at low temperatures.

An increase in MEA operating temperature provides large system advantages including a smaller and simpler vehicle thermal system as well as the reduction or elimination of humidification and water recovery. Operating at a higher MEA temperature, the fuel cell thermal system could be integrated with the electronic cooling loops and provide more effective cabin heating. Higher temperatures however, typically accelerate degradation mechanisms. Further, chemical degradation processes can be expected to increase exponentially with temperature since the rate of chemical processes typically doubles for every 10℃ increase in temperature. This characteristic adds further complexity to the trade-off of the MEA performance and life.

MEA progress in recent years includes:

- Improvements in applying and immobilizing the platinum catalyst
- Improvements in platinum support
- Improvements in composite membrane structures which increase the mechanical strength and improve dimensional stability
- Improved gas diffusion which allows > 1 amp/cm^2
- Reduced gas cross-over

Future work on high temperature membrane and low humidity requirements will allow higher stack operating temperatures

2. Fuel Cell Stack

The function of fuel cell stack is to provide all the conditions necessary for the MEA to operate. This includes mechanical support of the MEA, supply of reactants, removal of heat, and electricity. All PEM fuel cell stacks use a bi-polar plate configuration. The bi-polar plate is an electronic conductive plate that is sandwiched between successive MEAs. The bi-polar plates incorporate a complex series of manifolds to supply the respective reactants to the MEA and provide thermal management. The bi-polar plates are designed to be as thin as possible to reduce volume and mass while providing the lowest possible electronic resistance between successive MEAs.

The fuel cell stack must manifold six stream flows: air in and out, hydrogen in and out (due to the need for recirculation) and thermal coolant in and out. These flow streams must be kept separated and may include two phase flow. The design of the manifolds presents a complicated 3 dimensional engineering challenge.

Critical to the success of the fuel cell stack are the seals that are utilized between the bi-polar plates to prevent intermixing or external leaks of the flow streams. Further, the sealing must be done in such a way as to prevent electronic shorting between successive bi-polar plates. Significant advances have been made in stack sealing which have nearly eliminated external stack leaks and transfer leaks between internal manifolds. The issue of sealing during thermal cycling has been generally overcome. The bi-polar plates and associated seals represent a significant cost and are the main contributor to mass and volume of the fuel cell stack.

Historically, PEM fuel cells could not start from a frozen state (≤ 0C^o) and had to be carefully monitored to operate in freezing conditions. The maximum power available at low temperature was insufficient to power the start-up functions and provide the heat required to warm the stack to the operating temperature. There were three basic reasons for this:

- the conductivity of hydrogen ion exchange membranes declines as the temperature decreases below 0^{o}C.

- the contact resistance of carbon separators increases significantly as the temperature decreases below 0^{o}C.
- carbon separators have a low thermal conductivity and take a long time to warm up.

This freezing problem has been overcome by:

- metal bi-polar plates, lower intracellular electronic contact resistance and flow field design,
- reduced stack heat capacity,
- improved water management at shutdown and startup, and
- improved and more robust MEA and gas diffusion materials.

The remaining stack challenges include the need for continued reduction of mass, volume and cost, and the development of volume production for the unique manufacturing requirements of fuel cell stacks.

3. Hydrogen Supply

The function of the hydrogen supply system is to provide hydrogen to the fuel cell stack and associated MEAs. The hydrogen flow is pressure regulated and recirculated. The recirculation rate is maintained at a flow rate greater than fuel consumption to prevent fuel starvation during rapid load changes, and to remove liquid water from the anode. Within the hydrogen supply system, inert gases (nitrogen and other gases) can accumulate due to cathode gas cross-over of the membrane and fuel quality. Occasional purging of the recirculation loop is used to control inert gases.

Re-circulation of the hydrogen flow stream requires a pump. This has been accomplished in the past by a venturi method but today a variable flow pump is generally used. This adds parasitic electrical load but is able to better manage the recirculation functions of liquid water control and fuel starvation. The hydrogen recirculation pump presents difficult design requirements that include the management of two phase flow.

4. Air Supply and Humidification

The primary function of the air supply and humidification system is to provide oxygen to the cathode side of the MEA in proportion to the fuel cell stack electrical load while maintaining membrane hydration. The system typically consists of an air filter, blower/compressor, humidification section and, in some cases, a pressure recovery device. The air supply system is the largest parasitic load on the fuel cell system.

The fuel cell stack requires a supply of excess air greater than the calculated stoichiometric value, typically 1.5 to 2.5 times that of the ideal mixture. As the air passes over the MEA, oxygen is consumed. The MEA material closest to the air inlet then experiences a higher oxygen partial pressure than does the MEA material closest to the air outlet.

The dynamic electrical loads on the fuel cell necessitate a rapid change in air flow in order to correctly supply a flow rate proportional to the electrical load. Inadequate electrical load following of the air supply can result in oxygen starvation, poor humidity control and MEA flooding.

Increasing the cathode air pressure by means of the blower or compressor improves the reaction kinetics and water management. Typical operating pressures are 1 to 3 bar over atmospheric pressure. However, the parasitic power to provide the air compression is significant and results in a net loss in fuel efficiency. Exhaust pressure recovery to offset the blower or compressor's parasitic power is possible but adds cost and complexity to the system. The general development trend is to operate at lower air pressures, reducing parasitic power requirements and helps mitigate associated vibration/noise issues.

Water management challenges include gas humidification and anode/cathode flood control, as well as product water removal. Product water can create droplets in the bi-polar plate gas channels that must in turn, be forced out the air exit. This liquid water creates a flooding condition which blocks the gas passage and results in oxygen starvation. Indirect monitoring and management of the product water is critical to the fuel cell operation. Successful development of a high temperature MEA could significantly reduce or eliminate the need for water management.

5. Thermal Management

The function of the fuel cell thermal management system is to provide an optimum operating temperature for the stack and thus the MEA. Heat removal from a fuel cell stack is difficult due to the relatively low operating temperature of the MEA and the quantity of heat that must be removed. Unlike an internal combustion engine, the fuel cell exhaust carries little heat from the stack. The majority of waste heat from the fuel cell reaction (approximately 80%) must be removed by the thermal system. If the thermal system is inadequate, it will restrict the length of time the fuel cell can operate at full power.

A circulating liquid loop is typically used and is designed to minimize stack volume and to provide consistent thermal management for all the MEAs. A variable speed electric pump is used to circulate the coolant. The coolant must maintain dielectric characteristics or be stack voltage isolated. The coolant pump rate must be adjusted for warm-up (recirculation) and to reduce parasitic losses during normal operation.

FCEVs typically use two separate thermal systems, a low temperature loop for the fuel cell and a higher temperature loop for power electronics. The development of a high temperature MEA may allow for a common thermal system with significant cost savings.

6. Sensing and Controls

An automotive fuel cell system must meet a wide variety of operational requirements from freezing start-up conditions to high temperature desert hill climbing. The challenges associated with maintaining fuel efficiency, performance, durability and safety can be substantially mitigated by accurate sensing and control of the fuel cell operation. Following materials and system design solutions, control strategies are generally considered the tool used last by the designer to solve issues and improve performance.

Historically, fuel cell stack voltage and temperature monitoring was done at the single cell or small group of cells to avoid failures by voltage reversal. Other parameters monitored include gas pressure, flow rates, humidification etc. To be effective, the control and sensing system reliability must be higher than that of the fuel cell system. The design is challenging in that the fuel cell controls and associated wiring and sensors become overly complicated, use unique parts, and are costly to build and install.

State of the art fuel cell sensing and controls minimize the number of sensors required and utilize production hybrid vehicle components and engine controllers.

D. Automotive Fuel Cell System - Findings

1. Automotive Fuel Cell Developers

The Panel visited 10 companies that are actively pursuing the development and commercialization of automotive fuel cells. The following are the ZEV Panel findings regarding individual automotive developers, in alphabetical order. Summaries of the individual companies are provided only for those companies who gave prior approval of their specific summary, so as not to inadvertently release confidential information.

a) Ballard Power Systems

Ballard has been actively developing the PEM fuel cell for 20 years and is broadly recognized as a world leader in PEM fuel cell technology. They have protected a large number of key inventions through worldwide patents and have experience in a variety of fuel cell applications. Ballard has clearly defined their focus on the fuel cell stack. Located in Burnaby, Ballard has a purpose built research and development facility with state of the art test and reliability equipment and an aligned manufacturing facility. Hundreds of professionals, many of whom are long-term are employed at Ballard.

The Panel visited and toured Ballard's R&D, Product Engineering, Test & Reliability and Manufacturing facilities. The Panel observed activities ranging from customized research cell testing for water management, individual cell testing, environment testing (stack freeze start) as well as durability testing of commercial-size stacks for automotive fuel cell vehicles and buses. The Panel observed a well organized manufacturing facility using automated equipment that has been designed or modified to fit the needs of low volume fuel cell manufacturing.

Ballard is the exclusive supplier of automotive fuel cell stacks for two major automotive manufacturers, DaimlerChrysler and Ford. These automotive manufacturers hold ownership in Ballard at 19% and 11.4%, respectively. The relationship provides a joint funding arrangement that leads to shared research and field experience. Ballard develops, manufactures and sells the fuel cell stack and in turn, the automotive manufacturers provide the necessary subsystems, vehicle packaging and integration. The combined experience of Ballard and associated partners has resulted in a total of 130+ FCEVs, including buses and light duty vehicles that have operated a total of 3.3 million km. They have the largest number of vehicles and total driven km of any fuel cell Alliance or developer.

Ballard described that its automotive fuel cell development and commercialization activities have led to early success in non-automotive markets such as materials handling and residential cogeneration. Ballard pointed out that fuel cells and batteries are complimentary technologies. The combination of a fuel cell and batteries used in automotive and other applications results in improved fuel economy, fuel cell durability and reduced cost.

Ballard has made significant technical progress. Fuel cell stack power density exceeds 1500 W/kg. Freeze start has improved with start times of less than 90 seconds demonstrated at –25^{o}C in R&D stacks, and –15^{o}C in full 100 kW stack modules. Ballard has developed analytical tools that are fuel cell specific to assist in the technical aspects of cell/stack design and to provide the analysis of the trade-offs between variables that affect cost, performance, weight, volume, heat rejection, fuel efficiency and durability.

Ballard described to the Panel a four phase automotive technology development plan to demonstrate commercial viability of fuel cell technology by 2010.

The technology demonstration phase (Mk902 stack) is now in DaimlerChrysler, Ford and Honda vehicles that in most cases, are part of the NREL monitored fuel cell fleet (data presented at the ARB September 2006 ZEV Symposium[4]). The customer acceptance phase (Mk1100 stack) is focused on improvements in manufacturability, power density, freeze start capability, robustness and durability. The cost reduction phase will continue the technical advances of the Mk1100, through significant reductions in the use of platinum metal, while substantially increasing volumetric power density and durability. The market introduction phase will pursue further cost reduction and increased reliability.

According to Ballard, cost and durability are the largest barriers remaining to the commercialization of automotive fuel cell stacks. The major cost component of the fuel cell stack is the MEA. The MEA cost issue is being addressed with a focus on the composite membrane material and engineered electrocatalyst layers. Durability is being improved through increased understanding of the key failure mechanisms and accelerated design iterations with improved modeling, tools and test methods. To reduce manufacturing cost, Ballard is developing a multi-step process with the ultimate goal of implementing continuous manufacturing methods.

b) BMW

The BMW Group is a manufacturer of premium vehicles. The BMW objective is to produce vehicles with power trains that exemplify “Efficient Dynamics” which equates to more power, less mass, less fuel consumption and lower emissions. In BMW’s view, the combustion engine will remain the main source of automotive propulsion power as it benefits from maturity and optimum cost-efficiency for their target market, at least for the next decades.

BMW is developing small fuel cells for use as Auxiliary Power Units (APU). Both PEM and SOFC fuel cell types are being considered. In the long term BMW sees potential for fuel cells in the electrification and control of ancillary units such as air conditioning and power steering. Rather than being parasitic to the combustion engine, these electrified components will be powered by an APU fuel cell, independent from the ICE. The fuel cell reduces load from the hydrogen ICE for increased driving performance and leads to a greater overall fuel efficiency. New customer benefits are possible like electric air conditioning when the ICE is switched off and driving in pure electric mode within cities at low speed.

In addition to further improvements of the hydrogen ICE in terms of efficiency and NOx-emissions (< 10% of SULEV limit), the integration of the ICE and a small fuel cell in a hybrid power train offers a high power-to-weight ratio and dynamics at low cost (ICE) in combination with high efficient low-load-conditions at acceptable cost (small fuel cell).

The BMW PEM based APU development is in cooperation with UTC Power. BMW provides vehicle integration and, together with UTC Power, the system development. The SOFC based APU development is an in-house activity at BMW.

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[4] “Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Project Overview and fall 2006 Results” National Renewable Energy Laboratory. Wipke, K. & et. al.

The Panel visited the BMW Engineering facility in Munich and was shown a PEM APU fuel cell, and a research hydrogen ICE engine, both operating on the test bench. The Panel was given the opportunity to drive the hydrogen powered ICE 7 Series sedan (no fuel cell APU) and observe refueling of liquid hydrogen.

BMW described the key developments needed to facilitate a PEM fuel cell as:

- A membrane with low humidification demand for easy water management, lower amount of platinum for the catalyst, and longer life time.
- A higher power density to reduce weight / volume and an increased efficiency to reduce the cooling system size.
- Reducing cost by using cheaper materials for the catalyst and the bipolar plates and reducing system complexity.

The answers BMW provided to the ZEV Panel questionnaire describe that performance; durability and cost are conflicting issues in the development of the fuel cell APU. They also described that FCEV performance and cost parity with ICE vehicles was not possible. However, BMW pointed out the efficiency of an FCEV could be greater than an ICE vehicle. They believe that the FCEV cost will be significantly higher than that of a hydrogen ICE with a small fuel cell. Further, BMW is of the opinion that the small fuel cell APU approach is seen as an add-on solution and will help introduce fuel cells to automotive applications.

c) Daimler Chrysler

DaimlerChrysler (DCX) is part of a cooperative alliance with Ford and Ballard Power Systems. DCX holds an approximate 19% ownership in Ballard while Ford has 11.4%. There is also a joint venture between DaimlerChrysler and Ford called NuCellSys in Nabern, Germany. The NuCellSys venture is a 50%/50% relationship between DCX and Ford.

DCX started the development of FCEVs in the early 1990s and has demonstrated fuel cell powered cars, mini-vans and buses. The panel visited the fuel cell development center in Nabern, Germany. During this visit, the panel saw an impressive history display of the DCX fuel cell developments and vehicles,

DCX has over 100 FCEVs in world wide operation with over 2 million km of experience. Achievements that occurred from 1994 to 2004 include increased efficiency, reduced operational noise, improved performance and packaging. The technology road map for light duty vehicles being undertaken by DCX is as follows:

1. Technology Demonstration	2004 (Gen 1, Ballard Mk 902)
2. Customer Acceptance	2009 (Gen 2)
3. Cost Reduction	2012 (Gen 3)
4. Cost Reduction and Market Introduction	2015 (Gen 4)
5. Mass Production	2020 (Gen 5)

The DCX Gen 1 vehicles are currently part of the NREL monitored FCEV fleet. The challenges that DCX sees in the immediate future for Gen 2 include fuel cell system mass reduction, increased reliability and durability, the ability to withstand freeze starts, and thermal management. The Gen 2 stack is currently being developed by Ballard in collaboration with DaimlerChrysler and Ford. The Gen 3 and 4 fuel cell stacks are now at the research phase.

To achieve the technological advances necessary for market introduction (Gen 4), the fuel cell system requires further mass and size reduction with increased power. The system complexity needs to be reduced by component optimization and elimination with a significant reduction in cost. It is expected there will be a high level of power electronic integration. DCX sees that conventional hybrid developments had supported some of the electronic component developments. Mass production (Gen 5) will require further optimization and significant cost reduction, and technical achievements such as extreme cold start capability and hybridization.

DCX described that fuel cell system performance and cost targets can be achieved by eliminating and simplifying the components. The architecture can be met only if new fuel cell stack design developments can be accomplished. Hence, the level of development of the fuel cell stack ultimately determines the performance characteristics and cost of the fuel cell system.

DCX described that simultaneously reducing cost and improving performance and durability is the major challenge for stacks in Gen 3 and beyond. Gen 4 fuel cell stack innovations and inventions require flow field design, water management, corrosion resistant bipolar plates, improved catalysts (low loading, higher durability), and low cost gas diffusion material.

DCX described that the ultimate fuel cell drive train costs have the potential to be reduced considerably by a combination of technological improvements and economies of scale. Cost reduction approaching the level of conventional vehicles is possible. Sales in the range of 100,000 FCEVs per year can only be reached if the fuel cell component suppliers can expand accordingly. Onboard fuel storage and hydrogen infrastructure are also barriers to widespread introduction of fuel cell vehicles.

d) Ford

Ford is part of a cooperative alliance with DCX and Ballard Power Systems. Ford holds 11.4% ownership in Ballard while DCX has 19%. There is a joint venture between Ford and DCX called NuCellSys in Nabern, Germany. The NuCellSys venture is a 50/50 relationship between DCX and Ford. The technology sharing through these partnerships is essential to accelerate the development of these pre-commercial fuel cell technologies. Ford started the development of FCEVs in 1995 and has demonstrated fuel cell powered cars, and SUVs. Ford is increasing research and development activities of fuel cell systems and vehicle research despite corporate financial difficulties.

The panel visited the Ford FCEV development center in Dearborn, MI. During this visit, the panel was presented technical and cost data. The panel saw vehicle and research laboratories, and was given the opportunity to drive a demonstration vehicle based on the Ford Explorer. This technology demonstrator was purpose built within the constraints of the Explorer chassis. The Explorer FCEV utilized an under the hood position of the fuel cell system with centralized hydrogen storage in “drive shaft position”. The vehicle was impressively smooth, responsive and quiet in operation. This is however, a purpose-built vehicle, not a production model.

The Ford Focus FCEV is part of the NREL monitored Department of Energy (DOE) Learning Demonstration fleet. It was purpose built within the constraints of the Focus chassis. The Focus FCEV utilizes a Ballard Mk902 fuel cell stack (440 cells) hybridized with a Sanyo battery pack. The fuel cell system provides a net peak power of 68 kW. The fuel cell balance of plant uses a screw type air compressor with a contact humidifier and a multi-stage jet pump for hydrogen recirculation within the fuel cell stack. The Focus FCEV has a city/highway fuel consumption that is 55%/66% that of its non hybrid gasoline counterpart.

The Ford philosophy for commercialization of FCEVs is that it must have no customer compromise compared to other alternatives. Ford believes that until the technical and commercial challenges are overcome, the FCEVs will not be commercially viable. The no compromise characteristics include:

- Cost (initial and lifetime operational cost)
- Performance
- Reliability & Durability
- Vehicle Utility

The technical challenges that Ford is addressing for a fuel cell propulsion system include the stack and system useful life, durability, and robustness, and on-board fuel packaging and weight. Ford believes that preparing for high volume production detracts from advancing core fuel cell technology because it employs resources that could otherwise be used for research and development. Fuel cell system costs are a major concern for commercial viability because more than an order of magnitude reduction is required. Customer acceptance of new, unfamiliar, and expensive technology with limited fueling infrastructure also makes commercialization of this technology very difficult.

Ford emphasized that commercialization will require time and resources to overcome technical and commercial issues to attain the no customer compromise compared to other alternatives. Ford anticipated that between the years of 2015 to 2020, low volume government and/or commercial demonstration/development fleets are possible. Ford expressed concern about inadequate resources for research and development timelines if an early commitment to high volume FCEV production were to be made.

Ford described that fuel cell technology holds great promise to be a sustainable mobility option; however there are no clear winners. Ford also described their commitment to a portfolio of advanced environmental technologies, including E85 flexible fuel vehicles, clean diesel, hybrid electric vehicles, hydrogen internal combustion engines, and fuel cell vehicles.

e) General Motors

General Motors has a variety of fuel cell activites underway working toward the goal of developing an automotive competitive fuel cell propulsion system (FCPS). GM's fuel cell program started in the mid 1990s. The panel visited the GM fuel cell development centers in New York, Detroit, Torrance and Mainz, Germany. During these visits, the panel observed activities ranging from basic material development to the engineering of complete systems. These next generation designs have begun to incorporate manufacturing considerations and are now in validation. Additional generations with simpler designs, improved materials, and volume manufacturing processes will be required before fuel cell electric vehicles (FCEVs) can be produced on a large scale.

Where possible, GM is leveraging its conventional and hybrid development programs to support fuel cell development. An example is the engineering integration of high volume electronic control modules to GM fuel cell systems. GM noted however, that many of the fuel cell critical path components (stack, unique subsystems, and hydrogen storage) are not supported by conventional or hybrid development programs. These critical path components require development programs that involve substantial resources and time.

GM described the path to developing an automotive competitive FCPS and the subsequent introduction of vehicles into the marketplace as follows:

1) Advances in technology through material solutions, design and systems solutions.
2) Comprehensive strategies to mitigate the constraints associated with the introduction of a new technology at low initial volumes.
3) Extensive market development to avoid introducing the technology too quickly (immature) or too slowly (delayed benefit and higher cost due to inadequate volume).

GM has made significant technical progress from membrane electrode assembly development to vehicle packaging. GM is working on system power density, freeze durability, high ambient temperature operation, subsystem simplification and efficiency gains and believes these issues will be addressed. Issues of durability and cost remain as the most significant hurdles to the development of an automotive competitive FCPS.

GM's next generation of demonstration fuel cell vehicles (2007 to 2010) will incorporate some of these technical advances. The "Equinox" is based on a 4-passenger version of a Chevrolet crossover vehicle and is expected to meet all FMVSS and ZEV requirements. It is designed for freeze durability and a 50,000 mile operating life. The EPA city and highway combined range is 200 miles with hydrogen storage of 4.2 kg at 700 bar.

The GM goal for 2010 is to design and validate a fuel cell propulsion system that is automotive competitive. This means that assuming high volume manufacturing, the fuel cell propulsion system would have performance, durability and cost equivalent to today's internal combustion engine propulsion system (on a common functionality basis). In addition, substantial production and manufacturing process development will be required to execute the design solutions into marketable fuel cell vehicles.

GM has the most aggressive cost goals of any fuel cell automotive developer. It believes cost targets can be met with the current family of stack materials. Achieving the $50/kW fuel cell propulsion system cost target will require a progression of generational design simplification, materials thrifting and substitution, supplier engagement and manufacturing process development..

GM described that FCEV production will also require the development of a strategic supplier network for unique fuel cell system materials and components. The majority of current suppliers are not traditional suppliers to the automotive industry. Long term commitments and substantial resources will be required.

GM believes initial market entry of production FCEVs could occur sometime before 2015. Depending on external factors such as the availability of safe, convenient, and affordable hydrogen fueling and supportive government policies, larger volume production could occur sometime after 2015. Based upon current information it appears that the volume necessary for per unit breakeven (not cumulative cash breakeven) would be in excess of 500,000 FCEVs per year.

Substantial government assistance (at the federal, state, and local levels) will be required to overcome the near-term and longer-term business risks / costs associated with hydrogen refueling and FCEV market introduction and acceptance. This assistance needs to include at least the following elements:

- Implementation of a comprehensive and clear national energy strategy that focuses on

every sector, not just the vehicle.
- Sustained long-term financial incentives for automakers, suppliers, infrastructure providers and customers.
- Government as an early and ongoing fuel cell vehicle customer at meaningful volume levels.
- Support for uniform vehicle and infrastructure codes and standards.
- Actual implementation and deployment of a comprehensive fueling infrastructure and affordable hydrogen fuel to assure customer acceptance of FCEVs.

f) Honda

Honda has a large fuel cell development and commercialization program that was initiated in 1989 and significantly expanded in the mid 1990's. Honda first demonstrated their FCEV in 1999 using a Ballard Power System fuel cell stack. The use of Ballard stacks continued through 2004. In parallel, Honda developed its own fuel cell stacks and introduced them for early applications in the MY 05/06 FCX with cold start capability to -20C. Honda has delivered over 40 FCEVs (model years 03 to 06) to the US and Japan for customer evaluation.

At their fuel cell development center in Japan, Honda presented to the Panel, information about their automotive fuel cell technology development and gave the Panel a tour of the fuel cell development laboratory facilities.

Honda's plan for FCEV commercialization includes four major steps:

1.	R&D Demonstration	2005 (Gen 1)
2.	R&D Demonstration	2010 (Gen 2)
3.	Pre-Commercialization	2015
4.	Early Commercialization	2020

The R&D demonstration phases 1 and 2 include production of a limited number of FCEVs that are highly instrumented to permit rapid analysis and information feedback into development cycles. The pre-commercialization step will focus on increased durability, operation in temperature extremes, increased driving range and cost reduction. The early commercialization step is intended to further improve durability and reliability to match that of a conventional vehicle and reduce cost.

In Honda's view, the three major areas of fuel cell durability, driving range, and cost reduction require substantial improvement before commercialization can occur. Honda pointed out that there is a significant difference between laboratory durability results and real world experience. Honda is mitigating these degradation mechanisms through further development. The cost issues involve the fuel cell stack, the fuel cell system components, energy storage and electric drive. Fuel cell cost reduction will require additional material R&D and production process development. Specifically, reductions in the costs of the MEA and bi-polar plates are necessary. Honda noted that in order to reach cost targets for early commercialization, a catalyst breakthrough or alternate catalyst was necessary in addition to Honda's use of an aromatic hydrocarbon electrolyte membrane that permits higher temperature fuel cell operation for increased stack performance.

g) Nissan

Nissan has an advanced fuel cell development and FCEV commercialization program that started in 1996. During its visit of the Nissan fuel cell development center in Japan, the Panel observed activities ranging from basic material development to the engineering of complete systems. Also, the Panel had an opportunity to drive a demonstration FCEV vehicle based on an SUV chassis. The vehicle operation was smooth and responsive.

Nissan has 10 FCEVs in leased or customer vehicles in Japan and expects to have 8 customer vehicles testing by the end of 2007 in the USA. These vehicles will have a 90kW fuel cell stack and system developed internally at Nissan. The fuel cell system is hybridized with a Li Ion battery and has a 7.2 second startup time.

The Nissan research and development effort is focusing on resolving issues in two key areas:

- Durability and reliability
- Assurance of low temperature starting ability

The durability of the PEM fuel cells must be improved to meet the operating life of more than 5,000 hours under normal automotive driving conditions. Operating at a near constant load, the fuel cell can exceed 5,000 hours. This is however, significantly reduced to 1000-2000 hours under the dynamic electrical loads of an automobile. Nissan is addressing degradation mechanisms associated with system start/stop, electrical load cycling, and thermal cycling. They are also developing new materials for the catalyst layers and the solid polymer membrane and technologies for suppressing their degradation. To address the low temperature start-ability, Nissan is developing methods to prevent product water from freezing or quickly liquefying on cold start.

The durability of the PEM fuel cells must be improved to provide an operating life of more than 5,000 hours under normal automotive driving conditions. Operating at a near constant load, the fuel cell can exceed 5,000 hours but life is reduced to 1000-2000 hours under the dynamic load cycles imposed by automobile operation. Nissan is addressing degradation mechanisms associated with system start/stop, electrical load cycling, and thermal cycling. They are also developing new materials for the catalyst layers and the solid polymer membrane as well as techniques to suppress their degradation. To address the low temperature starting ability, Nissan is developing methods to prevent product water from freezing or quickly liquefying on cold start.

Nissan emphasized the need for drastic cost reduction for the FCEV commercialization, including:

- Cost reduction of the MEA
  - Reduction of the amount of Pt in catalyst
  - Reduction of membrane cost
- Simplification of the fuel cell system
  - Innovation of stack materials
  - Elimination of BOP (examples: external humidifier; hydrogen pump)

Nissan estimates that based on materials cost alone, the cost of a fuel cell system is still several times higher than that of an ICE. In order to lower the cost, it is necessary to simplify the balance of plant and to reduce the quantity of platinum used in the MEA. No time estimates for commercialization were provided.

h) Toyota

Toyota has had an automotive fuel cell development program since 1992. Visiting the Toyota fuel cell development center in Japan, the Panel toured engineering laboratories and was given an opportunity to drive a demonstration FCEV vehicle based on an SUV chassis. The vehicle operation was smooth, quiet and responsive. Toyota has demonstrated fuel cell technology in mini-cars, cars, buses, fork lifts and stationary applications. Demonstrations of Toyota FCEVs started in 2001 in the USA and there are now a total of 25 Toyota FCEVs in California.

Toyota is independently developing a 90kW fuel cell stack and balance of plant. The specific technical issues that they indicated need to be addressed include:

- Fuel cell durability,
- Start and operation in low and high ambient temperatures,
- Need for higher efficiency
- Hydrogen embrittlement of components
- Hydrogen storage technology

Toyota has reduced the fuel cell durability problems by developing improvements in the physical and chemical stability of electrolyte membranes. They have demonstrated a hybridized FCEV start-up period of one minute from a starting temperature of -30^{o}C and consider hybrid technology important to the fuel cell system. Toyota indicated that a further reduction of the start-up time and improvements to the drive performance will be necessary for commercialization. Regarding efficiency, Toyota indicated that vehicle fuel cell efficiency (km/kg) during on-road driving was dramatically reduced when compared to dynamometer testing (10:15 mode). Further, air conditioning and average speed significantly influence fuel consumption and vehicle range.

In order to achieve commercialization, Toyota estimates fuel cell system cost will need to be reduced to 1/100 of the cost of current prototypes. Cost reduction by a factor of 10 is projected for innovations in design and materials. Another 10-fold reduction will have to be achieved through the efficiencies and economies of mass production. Specific targets for cost reductions include reduction of platinum catalyst loadings to 10% of the current values; membrane cost reduction, as well as changes in the design of manufacture technology and of the manufacturing processes themselves.

Toyota noted that the FCEV is still in the R&D phase with additional development and more time needed before commercialization is possible. Technical development targets, cost and vehicle range as well as adding appeal to the product are considered key challenges. Toyota did not provide dates for commercialization but indicated the general progression from small demonstration fleets through small scale production (e.g., 1000 per month) to larger volume production.

i) UTC Power LLC

UTC Power is a division of United Technologies Corporation, a $47.8 billion company that provides high-technology products and services to the building and aerospace industries. A full-service provider of environmentally advanced power solutions, UTC Power has nearly 50 years of experience. The company is a world leader in developing and producing fuel cells for on-site power, transportation, space and defense applications, and a developer of other innovative combined cooling, heating and power applications in the distributed energy market. It has been a supplier to BMW, Hyundai, Nissan and numerous fuel cell bus programs. Since 1997, UTC Power has been actively developing automotive PEM fuel cells and the company has developed unique intellectual property in the area of bi-polar plates that use a porous, hydrophilic material to facilitate water management. Specifically, the process humidifies inlet gas streams to maintain saturation of the membrane.

The panel visited and toured the UTC Power manufacturing and development facilities and observed activities ranging from engineering development to cell and stack durability testing.

UTC Power believes that the key to fuel cell performance and durability is water management. By proper humidification of the membrane, a high conductivity and long life is possible. By efficiently removing product water, gas transport is maintained and local fuel starvation is avoided. UTC Power presented to the panel the durability data of a 20-cell stack load cycle which performed 100,000 cycles in 3000 hours without failure. The success was attributed to the unique method of water management.

UTC Power is focusing on increased system power density by reducing the volume of the fuel cell stack and system balance of plant simplification. The projected fuel cell system power density for 2007 is greater than 0.5 kW/liter and is predicted to be 0.65 kW/liter. Advanced fuel cell stack power densities, projected to be greater than 1.4 kW/liter in the near future, are consistent with the system power densities projected above. UTC Power has done laboratory demonstrations of 20-cell stacks doing freeze starts from -20^{o}C with no performance degradation, as well as -40^{o}C parts survivability. In-vehicle verification of the advances made in durability, power density and freeze capability are ongoing.

UTC Power described the obstacles to widespread adoption and commercialization of automotive fuel cell systems to be: 1) continued support for development, scale-up, and vehicle integration, 2) cost 3) on-vehicle hydrogen storage and 4) hydrogen fuel infrastructure.

2. Fuel Cell System Performance Estimates

The performance of fuel cells has dramatically improved in recent years. Stack power densities in excess of 1 kW per kg are now common. Figure 5-8 provides an estimate of automotive fuel cell stack and system peak power density as a function of time. The figure presents the cumulative data from developer’s estimates in comparison to the FreedomCAR fuel cell system goal. The peak power density of the fuel cell stack is expected to be substantially higher than the system goal to accommodate the mass of the balance of plant.

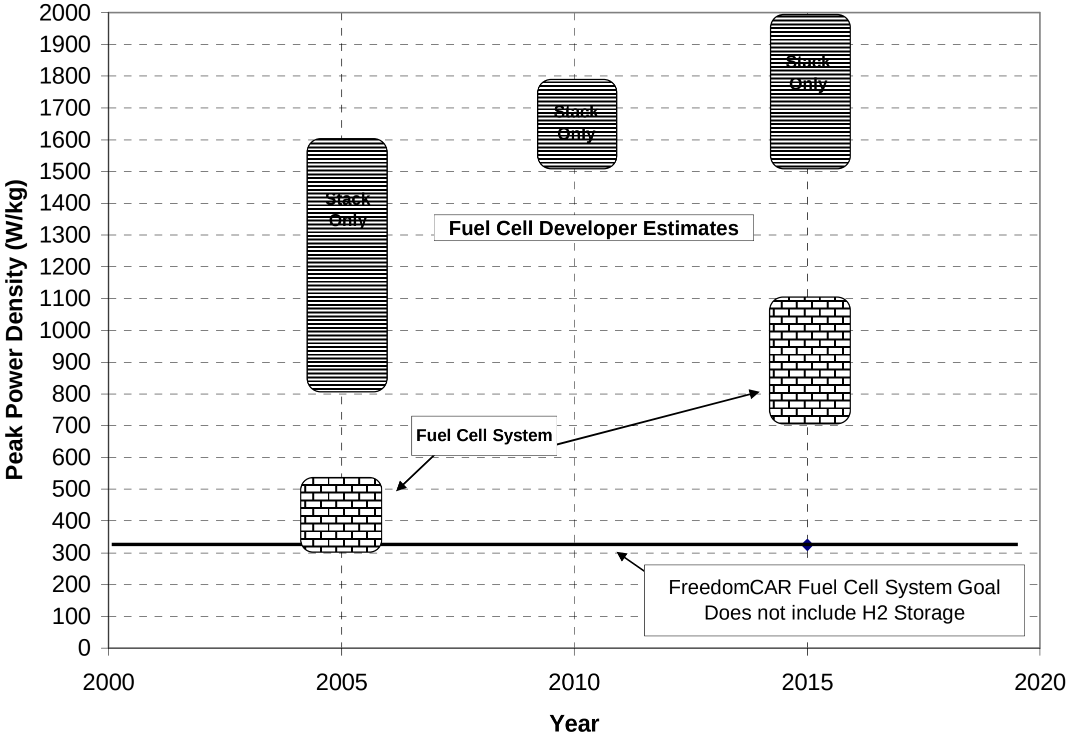

Figure 5- 8: Fuel Cell Stack and System Power Density Development

As shown in Figure 5- 8, the 2005 fuel cell stack peak power density ranges from a low of 800 W/kg to a high of 1600 W/kg. This broad range is likely the result of the timing of different development programs and represents technology over a number of different years. Further increasing the stack peak power density will be achieved by a combination of higher specific power MEA and lighter bi-polar plate materials. Comparing estimates of 2010 and 2015 shows only a relatively small change in stack power density.

The system power density in 2005 is approximately equal to the FreedomCAR goals and by 2015 fuel cell systems are estimated to exceed the goals. The panel did not receive any estimates of system power density for 2010.

The fuel cell system life is vital to its commercial success and can be based on hours of use, years of typical service, kWh of energy produced and so on. The FreedomCAR goals are generally considered to be greater than 5000 hours of use in a 15 year period. The following Figure 5-9 provides developer’s life estimates in comparison to the FreedomCAR fuel cell system goal of 15 years.

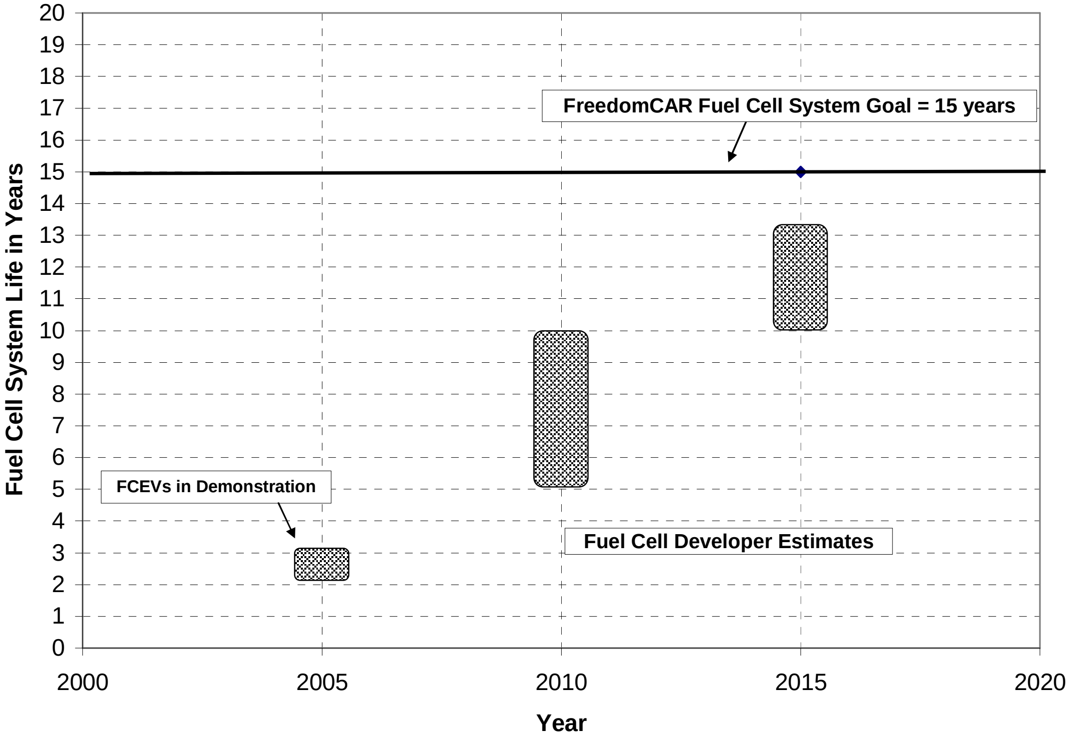

Figure 5- 9 Fuel Cell System Life in Years

Figure 5-9 indicates that in 2005, the fuel cell system life is significantly less than the goal. The issue of durability is considered a major challenge by the developers as there are many possible failure mechanisms. Understanding of failure mechanisms is paramount and the use of improved materials, controls and statistical control of manufacturing are expected to improve the fuel cell system life.

Developers are optimistic that the life issue can be improved but indicate it will be difficult to reach the 2015 FreedomCAR goal. Accurate accelerated testing procedures are still being developed to realistically age the fuel cell system over a shorter period of time. Demonstration fleets are currently the only available means of characterizing real world performance and durability for the fuel cell system.

Some fuel cell developers view hybridization and associated fuel cell load management as a significant method to improve fuel cell durability and to lower the overall system cost. In battery dominated hybrid applications such as fork lifts and buses, fuel cell life has been significantly greater than in light duty vehicle applications. Hybridization will improve vehicle efficiency by brake energy recovery but will not reduce the overall vehicle cost for the same continuous power (trailer towing application). If full power is not needed to be continuous, then energy storage can reduce the overall system cost. In this case, the goal of the power train designer would be to install the smallest fuel cell possible to meet vehicle performance requirements.

Platinum used in a fuel cell MEA has been and remains a fundamental impediment to automotive commercialization. The need for a high specific MEA power combined with low cost makes the automotive application particularly difficult to meet. The MEA platinum loading (total mg/cm^2) has been on a steady decline as methods of preparation, application and support have improved. However, the rising cost of platinum necessitates significant further reduction. The following Figure 5-10 presents a composite of developer estimates of platinum loading as a function of time, as well as those estimated by US DOE contractors TIAX and Directed Technologies Inc.

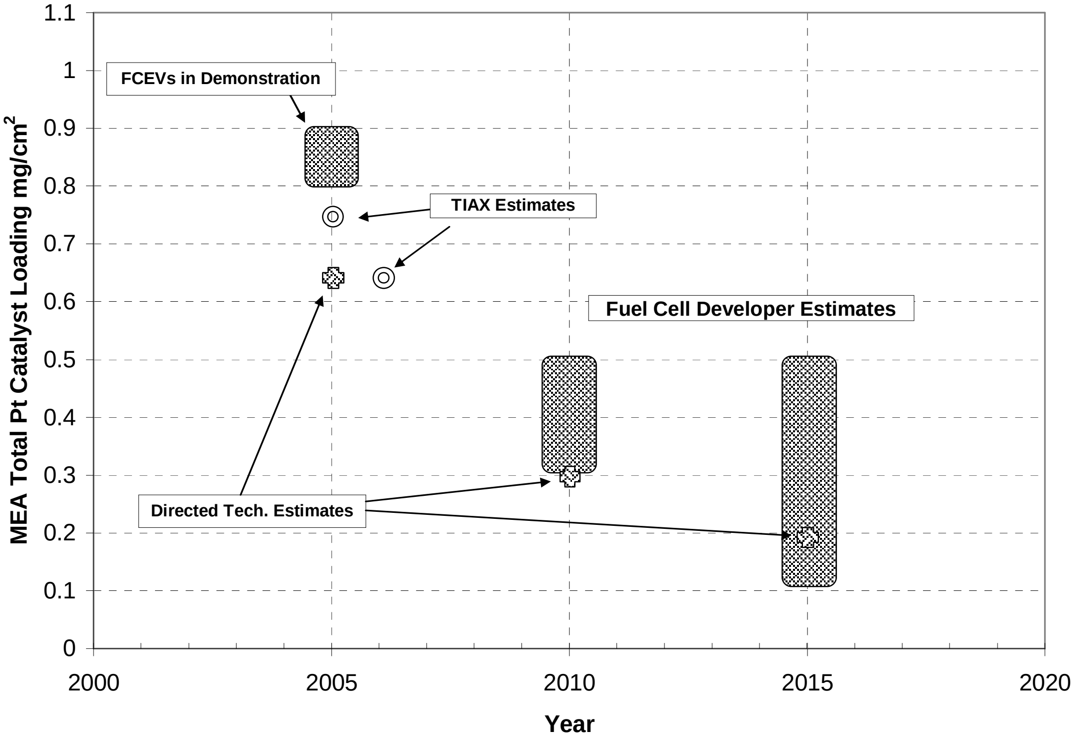

Figure 5- 10 MEA Platinum Loading Estimates

Figure 5- 10 indicates that fuel cell developers are predicting a sharp decline in MEA platinum loading between 2005 and 2010. Between 2010 and 2015 some developers predict a further significant decline while others feel that due to life and durability considerations, the Platinum loading will not significantly change. The lowest value in 2015 (and beyond) was estimated to be 0.1 mg/cm^2.

Platinum is a world wide commodity and is valued for jewelry and its catalytic properties. It is the rarest and the most expensive of the three "precious metals" (Ag, AU, Pt) Platinum is physically harder than gold and silver and has a higher melting point. These attributes make it more difficult to alloy and prepare as a fuel cell catalyst. In the past 6 years there has been a significant increase in the commodity cost of platinum as shown in Figure 5- 11 (Johnson Matthey price data). The actual cost of fuel cell grade platinum is higher than commodity cost due to preparation.

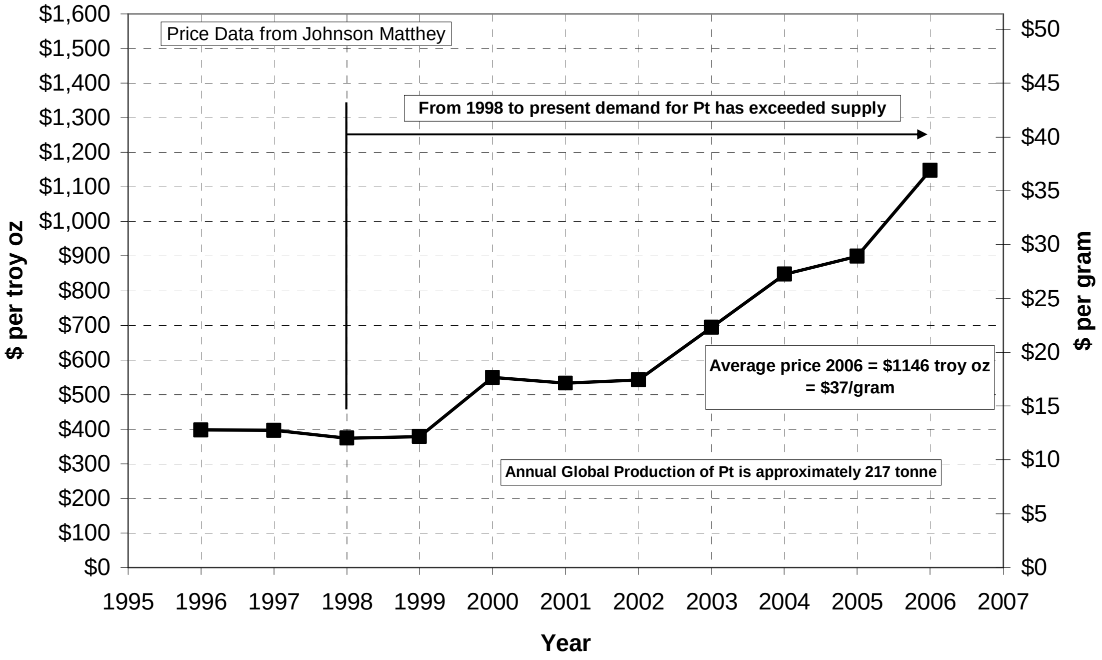

Figure 5-11 Average Annual Platinum Cost 1996 to 2006

Developers are working to mitigate the increasing costs of the platinum catalyst by a combination of:

- Reduced platinum loading (See Figure 5- 10)
- Platinum replacement by alloying
- Higher platinum utilization by increased MEA specific performance (See Figure 5- 12)
- Reduced catalyst preparation cost

The specific power of the fuel cell MEA is increasing. A higher MEA specific power allows a given fuel stack to produce more power and thus achieve a lower $/kW. Nearly every stack cost factor, for a given voltage, decreases in inverse proportion to MEA specific power. A higher MEA specific power is accomplished by lower resistance and improved electrode-layer structures to ensure voltage at a higher operating current density.

The following Figure 5-12 presents developer's MEA specific power estimates as a function of time, as well as those estimated by US DOE contractors TIAX and Directed Technologies Inc.

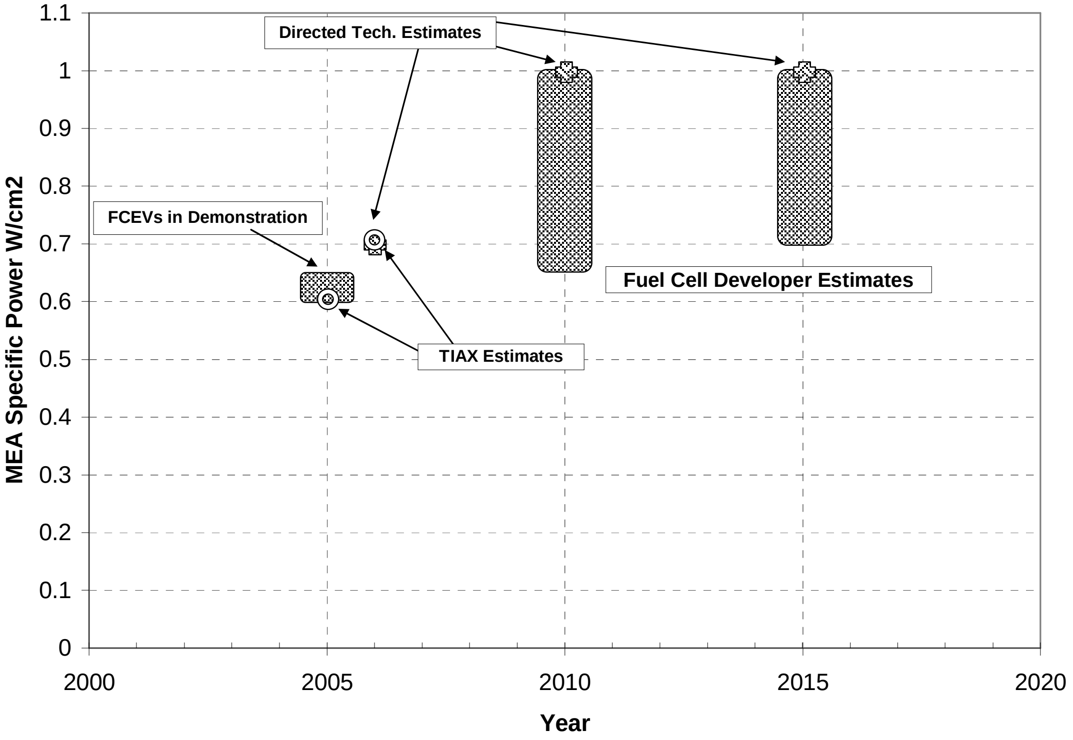

Figure 5- 12 MEA Specific Power Estimates

The figure indicates that developers anticipate an increase in MEA specific power by 2010. By 2015, the estimated maximum specific power will not have further increased but the lower value within the estimated range has increased. The highest foreseeable specific power is 1 W/cm^2. This will require operating the MEA at approximately 1.5 Amps/cm^2 and a cell voltage of 0.66.

3. Fuel Cell System Cost Estimates

Fuel cell system cost remains high with developers estimating that several generations of technology development will need to occur prior to volume production. System cost estimates are confidential to the individual developers and the panel received limited cost data on a relative and absolute basis. Figure 5-13 presents the US DOE relative percentage cost estimates for the major components of a fuel cell system in 2006. The fuel cell stack is the major component of this cost almost 60%.

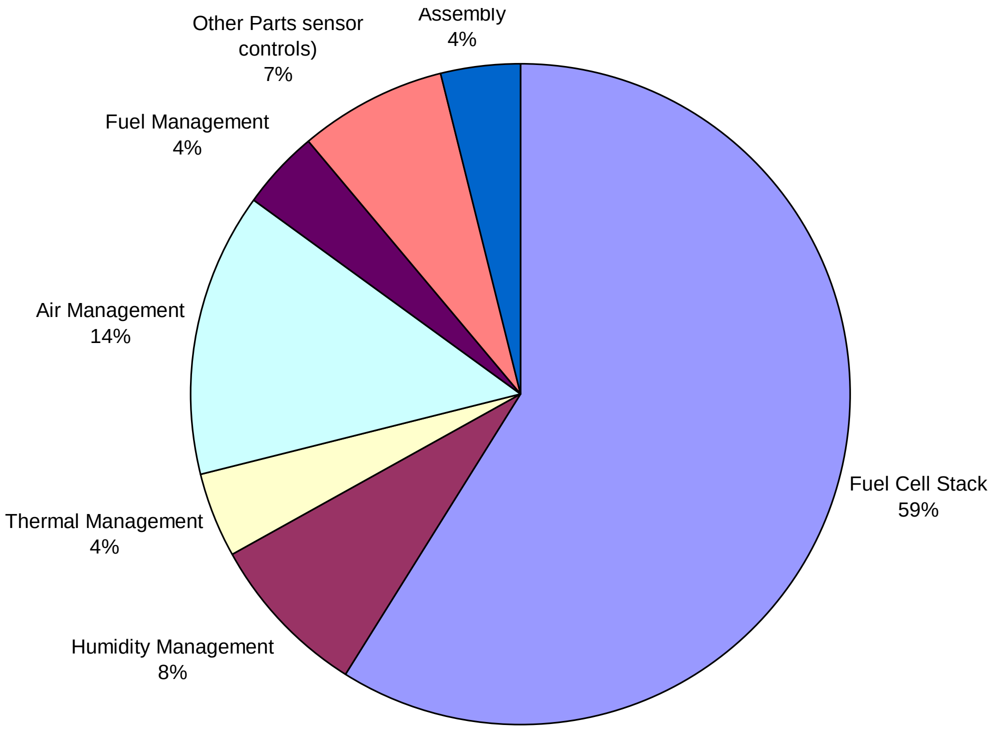

Figure 5- 13 Fuel Cell System Cost Estimate -TAIX

The relative cost values presented in Figure 5- 13 were compiled based on the limited data provided to the Panel by the developers.

The $/kW cost of a fuel cell system in volume production is dependent on the level of design maturity, material cost assumptions, and manufacturing method. The limited data provided to the Panel was not consistent in assumption of design, material cost and level of volume production. The following Figure 5-14 presents a composite of developer estimates of fuel cell system cost as a function of time, as well as those estimated by US DOE contractors TIAX and Directed Technologies Inc.

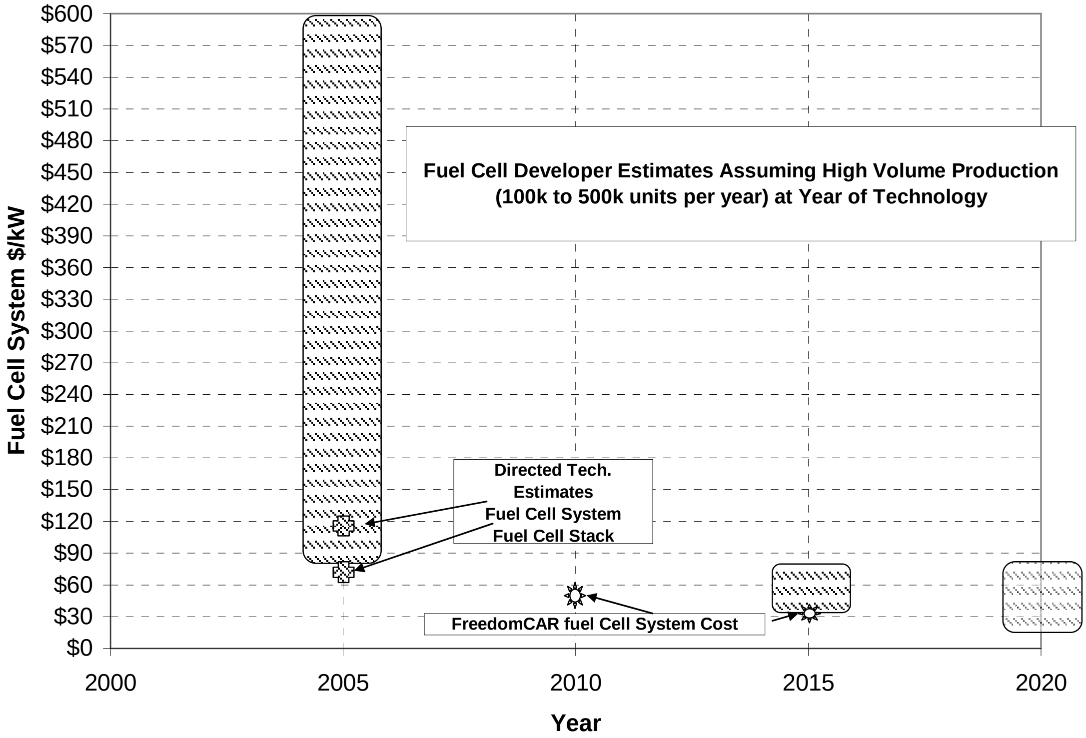

Figure 5- 14: Volume production Fuel Cell System $/kW

As shown in Figure 5-14, the developer cost estimates vary widely for volume production of 2005 technology. The reason for this wide variation in the composite data is the relative confidence in the maturity of the technology and assumptions on materials and volume production (10 to 500 k units per year). The estimated values for 2015 converge to values that range from the FreedomCAR goal to 2.5 times that goal. The Panel was also given some long term projections of cost (indicated at the year 2020) that indicate the $/kW ranging from less than the FreedomCAR goal to 2.5 times that goal.

Continuing development will likely increase the performance and decrease the cost of the stack. Some developers estimate that cost reduction by technical innovation could reduce the prototype fuel cell system cost by a factor of ten while manufacturing could possibly further reduce cost by another factor of ten.

a) *Fuel Cell Stack Cost Estimates*

The fuel cell stack dominates the cost of the fuel cell system, see Figure 5- 13. Individual developers consider stack cost estimates confidential and therefore the panel received limited cost data on a relative and absolute basis. Figure 5-15 presents the US DOE percentage cost estimates for the major components of a fuel cell stack in 2006. The MEA and gas diffusion layer material account for approximately 88% of the total stack cost.

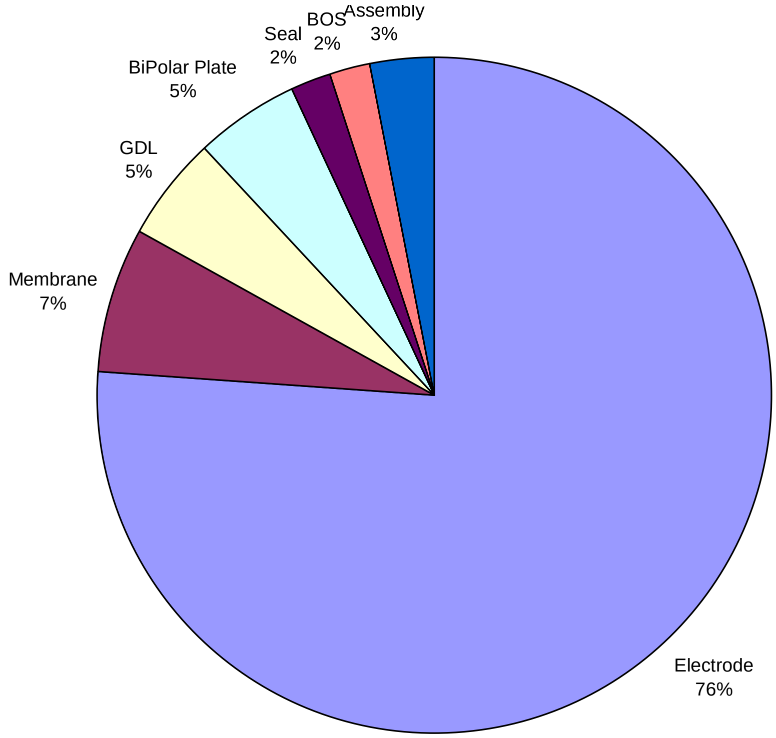

Figure 5- 15 Fuel Cell Stack Cost Estimate - TIAX

As noted earlier, in the past 5 years there has been a significant increase in the cost of platinum. As a result, the fuel cell stack cost is dominated by electrode costs as illustrated in Figure 5-15.

b) Recycling of Fuel Cell Stack materials

The recycling of the fuel cell MEA may be necessary to create a sustainable supply of platinum. The membrane materials are also sufficiently expensive that some form of reuse could have economic benefits for fuel cells. US DOE sponsored research has shown it is possible to recycle platinum and the membrane materials. The platinum will need to be removed from the MEA in a way that does not emit hydrofluoric acid as occurs with conventional combustion processes. Although platinum recovery from fuel cells appears feasible, the recovery costs for large scale recycling is unknown. Early data indicates that MEAs made from recycled materials can deliver performance essentially equivalent to that of an MEA made from virgin materials. Stack and balance of plant materials may be recycled but hold a lower strategic value than MEA platinum and membrane materials.

4. Fuel Cell Efficiency

The lifetime operating efficiency of a fuel cell system is fundamental to its successful application as an automotive power plant. Efficiency is important to the achievement of acceptable range within the constraints of the on-board hydrogen storage and, it directly impacts the vehicle operating cost, while indirectly impacting the re-fuelling infrastructure (more efficient FCEVs require less hydrogen generation).

A DOE project awarded in April 2004 has created four integrated auto and energy company teams to validate hydrogen fuel cell vehicle and infrastructure technologies in different geographic and climatic conditions. The data collected through these projects will help identify new research needs and evaluate technology readiness for the commercial marketplace. The teams are:

- GM/Shell,
- Chevron/Hyundai/Kia,
- Ford/BP
- DaimlerChrysler/BP.

As of the 4th quarter in 2006, there are 63 vehicles in the project, approximately ½ of the total expected number of vehicles. The vehicles are at somewhat different development stages, but generally represent the state of the art FCEVs for model year 2005. The vehicles are being operated in Southern and Northern California, Michigan, Florida, Washington, D.C. and New York until 2009. Operational data is being submitted by all teams to the Hydrogen Data Center at The National Renewable Energy Laboratory (NREL). The data is being analyzed and periodically published in an agreed composite format. For example, each make/model will only generate one data point for on-road fleet average hydrogen consumption.

Recent NREL data presented at the ARB September 2006 ZEV Symposium[5] provided fuel cell system efficiency and in-vehicle fuel consumption for participating vehicles. The limited data indicates net in-vehicle fuel cell system efficiency ranges of 52.5% to 58.1% at 25% of system net power ranges. These values can be considered idealized and actual in-use efficiency values will be less.

The NREL data also provided dynamometer measurements (SAE 2572) of on-road fuel economy as follows:

Dyno City/Hwy	50 to 67 miles/kg	(0.93 to 1.24 kg of H_2 per 100 km)
On-Road*	31 to 45 miles/kg	(1.38 to 2.00 kg H_2 per 100 km)

*Note: on-road data excludes trips of less than 1 mile.

The dramatic difference between the dynamometer City/Hwy values and the on-road values (62% and 67%) may be explained by a combination of aggressive driving, use of air conditioning and dynamic operation of the fuel cell system.

The Efficiency of a fuel cell system is influenced by:

- Cold start/ freeze start
- Average power – High speed driving inherently raises the operating power and lowers efficiency. Alternatively, if the power requirements are very low the efficiency declines.
- Parasitic losses of the Balance of Plant
- Load Dynamics – during rapid electrical load changes, hydrogen purging occurs more frequently and there are limitations of the air supply to maintain an optimized condition in the stack
- Outside load factors such as air conditioning

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[5] "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Project Overview and fall 2006 Results" National Renewable Energy Laboratory. Wipke, K. & et.al.

The fuel cell developers provided some net fuel cell efficiency estimates to the Panel. The provided estimates are not directly comparable due to differences in assumptions e.g. constant 25% net power and type of driving cycle. Figure 5-17 presents a composite of the developer net fuel cell efficiency data and the NREL data.

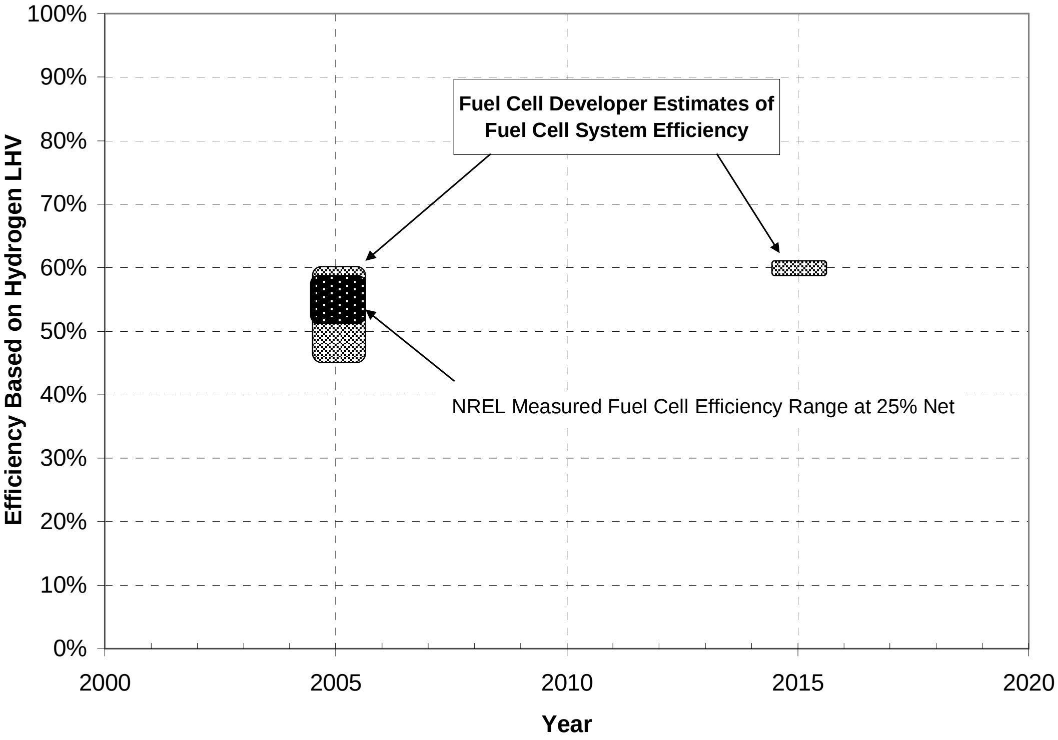

Figure 5- 17 Fuel Cell System Efficiency

Figure 5- 17 shows that the 2005 estimate of net fuel cell efficiency and the NREL measured values coincide. It would be expected that the NREL values would be high in the composite data as they represent net efficiency under near idealized conditions. The developers expect the fuel cell system to marginally increase in peak efficiency. The 2015 values provided to the Panel were virtually all the same. It is not clear that this is a realistic expectation.

Toyota presented on-road fuel consumption data at the EVS 22 conference, October 2006 in Yokohama Japan, se Figure 5-18. The data compares the fuel economy of a Toyota FCEV on the Japanese 10-15 mode driving cycle, simulated results, and actual values on public roads.

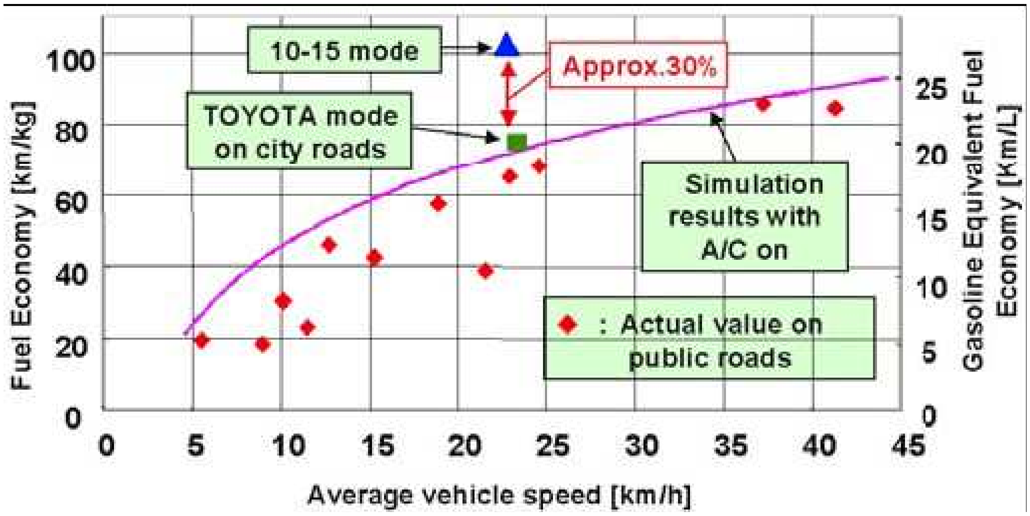

Figure 5- 18 FCEV On-Road measured fuel consumption vs. average vehicle speed

Note: The 10-15 Mode Urban driving cycle is currently used in Japan for emission certification of light-duty vehicles.

The measured Toyota data indicates significantly lower fuel economy when compared to the 10-15 mode and even the simulated results with the air conditioner on. The date suggest that the fuel economy at low speed on public roads is surprising low and that the system is not yet optimized for this driving condition.

In general, the developers indicate a high fuel cell system efficiency of 50% to 60% is possible with some qualification for start-ups and dynamic operation. The effect of dynamic load on efficiency was calculated as being small. The developers did not have an explanation for the difference in NREL data.

To reduce hydrogen consumption, developers felt it was less expensive to optimize the hybridized power train, use light weight components and improve aerodynamics to decrease the fundamental vehicle energy needed than to further increase the fuel cell system efficiency. A plug-in FCEV was also described as a method of reducing operational cost.

Fuel Cell system developers are working to improve the fuel cell system efficiency in the vehicle by optimizing:

- Sizing and hybridization of the application
- Idle condition fuel consumption
- Fuel use during normal start up and shut down (hot start)
- Fuel use during normal start up and shut down (cold start, freeze condition)
- Inert purging and flood control
- Transient load response
- Reduced balance of plant power requirements
- Hydrogen Purging requirements

E. Panel Assessment and Conclusions

The Panel concludes that automotive fuel cell technology continues to make substantial progress but is not yet proven to be commercially viable. Technological and engineering advancements have improved, simplified and even eliminated components of the fuel cell system. Prototype FCEVs now have functionally viable fuel cell systems that are freeze capable, relatively quick to start, quiet, and satisfying to drive.

Progress made since the 1998 ARB fuel cell report include large improvements in the MEA and fuel cell stack. The Balance of Plant has a reduced number of components and now uses some parts that are of automotive quality and cost. The fuel cell system has a reduced start time and, in-vehicle start-up from a frozen condition has been demonstrated. Great strides have been made in the science of materials and operational characteristics of fuel cells. This increase in fundamental understanding shows promise for solving life, abuse and durability issues of fuel cells.

Fuel cell technology has advanced, but not in the manner or at the rate expected in the 1998 ARB report. Switching to on-board hydrogen as the designated fuel reduced the complexity of the fuel cell system but effectively increased the need to maintain a high net conversion efficiency to achieve range goals.

The largest challenge for the developers is to continue increasing performance of the MEA while reducing overall system cost and increasing system life. The consensus among the majority of fuel cell developers is that in order to achieve commercialization there are simultaneous requirements for:

6) Higher MEA specific power (goal of 0.8 to 1.0 W/cm^2)
7) Reduced MEA catalyst cost (goal of total MEA loading <0.1 to 0.5 mg Pt/cm^2)
8) Longer fuel cell system operating life and increased durability (goal of >5000 hours of customer use)
9) PEM materials that are stable and can operate at a higher temperature (above 100^{o}C)
10) Engineering advances

The increase in MEA specific power allows a given fuel cell stack to produce more power and thus achieve a lower $/kW. Nearly every stack cost factor, at a given voltage, decreases in inverse proportion to MEA specific power. The higher MEA specific power can be accomplished by lower resistance and improved electrode-layer structures to ensure voltage at a higher operating current density. Increased MEA specific power has been accomplished at the cell level with some stack experience.

The MEA catalyst cost is related to the price of platinum. The price of this noble metal is rising due to world wide demand exceeding supply and it represents a significant barrier to automotive fuel cell commercialization. A reduction in the MEA catalyst cost can be achieved by reducing the amount used (higher utilization) and alloying. Low platinum catalyst loading has been demonstrated at the cell and stack level but further reductions of approximately 2X will be required to achieve cost goals. Platinum alloying has been tested at the cell level with improved cycle life at high current densities. Platinum recovery from fuel cells appears to be feasible although the recovery costs for large scale recycling is unknown. In order to be directly ICE cost competitive, a new non-platinum catalyst invention may be needed.

The life and durability of fuel cells in automotive applications is not yet proven. A life of 5000 + hours in a light duty vehicle type load cycle has not been demonstrated at the cell or stack level. A factor of at least 2X increase in life is required. The correlation between laboratory life testing and customer use life is not fully understood and the 5000+ hour life requirement may need to be increased to simulate actual customer use.

High temperature membranes (100^o+C) have only been demonstrated at the cell level. This development can potentially reduce the size and complexity of the FCEV thermal system and may possibly eliminate the need for stack humidification. This significant change can reduce the cost and improve the life of the fuel cell system. The Panel is optimistic about these developments but cautious because the rates of chemical degradation can be expected to increase exponentially with temperature.

Engineering advances and innovation are focused on materials, stack design, and balance of plant to reduce cost and increase life. This includes the simplification and where possible, the elimination of subsystem components. Manufacturability, vehicle packaging, serviceability, net fuel efficiency, noise and vibration are all being optimized.

Overall, the Panel concludes that at this time no fuel cell developer has achieved the necessary requirements for automotive fuel cell commercialization. The developers are relying on future technological improvements to meet both cost and life goals. Achieving these goals creates some contradictory requirements for the fuel cell system. The Panel believes that these requirements are difficult to achieve separately and because they are interrelated, even more difficult to solve simultaneously. These technological improvements include the development of MEAs that use significantly less catalyst material, operating at high specific power and temperature over a longer system life. To simultaneously increase performance and life at a lower cost will likely take ingenuity and invention.

Each of the developers believes that the simultaneous requirements can be met but on different time schedules. For example, one major developer's objective is to compete with the "upper" segment of ICE vehicles in the year 2020 at volumes of 100,000 units per year. Another major developer's assessment is that a commercially viable fuel cell system would be available in 2010, given a production rate of 500,000 units per year. Many developers believe that the FreedomCAR cost goals are not possible and the time schedule too ambitious.

At this time, large conventional automotive suppliers are not active in fuel cell development and are taking a wait and see attitude. If the market develops, it is conceivable that they will rapidly acquire the technology. A small number of non-automotive fuel cell applications are now being commercialized (higher $/kW and shorter life applications). This commercial activity may start to establish a supplier base that could grow to meet automotive demands.

The Panel remains cautiously optimistic for fuel cell system commercialization. There are large technical barriers that can be solved but there are other issues that are beyond the control of any single auto manufacturer. Wide spread deployment of FCEVs will require continuous strong support from government agencies. This support must include a clear message of long term commitment to fuel cell FCEVs. These include adequate and affordable hydrogen refueling, as well as a host of sustainable financial incentives to help minimize the capitalization risks of all key stakeholders during the initial transition years. Ultimately, consumer knowledge and willingness to buy these vehicles in high volume is required.

6. Vehicle Integration – Automotive Manufacturers

This section considers the status and prospects of vehicle integration of zero emission vehicles (ZEVs) by ten major original equipment automotive manufacturers (OEMs), and a few examples of smaller, automotive manufacturers, as well as their advanced technology vehicles (ATVs) that could have synergistic benefits supportive to the introduction of ZEVs. It uses the outcomes of the detailed analysis in the sections above that address the goals, status, major issues and potential of three key ZEV enabling system technologies, the vehicle energy storage system (VESS), vehicle hydrogen storage system (VHSS) and vehicle fuel cell system (VFCS). In addition to vehicle technical considerations, vehicle business considerations (e.g., manufacturing cost, capital investment, marketability, etc.) also are addressed, as the ARB requested the Panel to forecast the future prospects, introduction timing, and volume milestones of the ZEV and ATV technologies.

The ZEVs considered include full performance battery electric vehicles (FPBEVs) and fuel cell electric vehicles (FCEVs). ATVs considered are those that share technologies with ZEVs and include neighborhood electric vehicles (NEVs), utility electric vehicles (UEVs), city electric vehicles (CEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), hydrogen internal combustion vehicles (H2ICVs), and fuel cell auxiliary power unit vehicles (FCAPUVs).

Both ZEVs and ATVs, in combination with the off board infrastructure required to produce the various fuels used by these vehicles, have the capability to provide important societal benefits - improved air quality, reduce greenhouse gas emissions and increase energy independence. However in this report, emissions, fuel consumption and greenhouse gas are considered only from the vehicle perspective (“tank to wheels”). At the request of ARB, infrastructure (“well to tank”) and overall (“well to wheels”) energy perspectives were not part of the scope of the Panel’s study and report. Apparently, ARB will be handling infrastructure separately. For the purposes of this study, energy infrastructure is addressed only from the customer’s vehicle experience and satisfaction level, a necessary and important consideration in attempting to predict volume milestones.

A. Zero Emission Vehicles (ZEVs)

Zero emission vehicles (ZEVs) have zero exhaust emissions of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter (PM), which are the main contributors to air pollution. Moreover, emissions of ZEVs do not change with age or improper maintenance and an increase in total fleet mileage does not increase vehicle emissions. Conversely, exhaust emissions of conventional vehicles are not zero, so increased fleet mileage increases vehicle emissions, and the emissions increase with time, due to normal mechanical wear and aging of materials. Deterioration of conventional vehicle exhaust emissions can be especially severe if the owner fails to properly maintain his/her vehicle.

Only two types of motor vehicles have been successfully demonstrated as true ZEVs – battery electric vehicles (BEVs) without fuel fired heaters, and fuel cell electric vehicles (FCEVs) that consume hydrogen fuel.

1. Full Performance Battery Electric Vehicle (FPBEV)

A battery electric vehicle (BEV) receives electric energy from the electric grid, usually overnight, stores the energy in electrochemical batteries, and uses the stored electric energy the next day to power the vehicle with an electric motor propulsion system. BEVs without fuel fired heaters have zero exhaust emissions, and on a vehicle basis do not directly consume any hydrocarbon based fuel (gasoline, diesel, compressed natural gas (CNG), propane, ethanol, etc.) and create carbon dioxide (CO2), which is the main greenhouse gas.

For this report, BEVs have been divided into two main categories – (1) full performance battery electric vehicles (FPBEVs) of all sizes and driving ranges, and (2) all other, less than full performance, battery electric vehicles, including neighborhood electric vehicles (NEVs), utility electric vehicles (UEVs), and city electric vehicles (CEVs). This distinction is relevant when considering the practicality and likelihood of high volume BEV substitution for conventional vehicles and the associated societal benefits. FPBEVs are not performance limited (i.e., acceleration and top speed) compared to conventional internal combustion engine (ICE) powered vehicles and are fully capable of U.S. urban freeway driving. This is an important consideration given that driving conditions and practices in most U.S. urban areas include a significant amount of freeway driving.

As discussed below (see 6. B. 1.), the California ZEV regulation uses “common description” terms of “Full Function EV” for BEVs with 100+ miles of driving range and “City EV” for those with 50 to 99 miles of driving range, but this range criteria has not been used here for the definition of a FPBEV.

a) Manufacturers/Vehicles/Specifications/Performance

In the past, several major attempts to commercialize FPBEVs have been conducted.

In the United States, eight FPBEVs were produced by six major OEMs. These were the General Motors EV-1, first introduced as the GM Impact concept vehicle at the January 1990 Los Angeles Auto Show, and the others that were developed primarily in response to the September 1990 California ZEV mandate; Chevrolet S-10 EV, Chrysler EPIC, Ford Ranger EV, Ford Postal Van EV, Honda EV Plus, Nissan Altra, and Toyota RAV4 EV.

The specifications and performance of these vehicles are shown in Appendix J. Although they are almost 10 years old, and this is not new information, it is useful to consider them, as they provide the only large body of comparable data from the major OEMs from which to draw some conclusions about FPBEVs. It represents a significant case study of a major effort to try to commercialize advanced technology vehicles – without the enabling system technologies being ready (primarily battery cost) and without fully considering mass-market customer expectations and preferences. This was a comprehensive attempt to commercialize FPBEVs, consisting of, (1) six of the world’s largest automotive competitors with independent technical teams, (2) a wide variety of types and sizes of vehicles, and (3) three different battery types from eight different battery suppliers. The results were disappointing; (1) limited driving range, (2) very low volumes, and (3) lack of commercial success. On the other hand, most of the technology developed for these vehicles, and the general realization of the benefits of electric propulsion systems, has led to commercialization of NEVs and HEVs, a major industry effort now underway to try to commercialize FCEVs, and a growing level of interest in PHEVs.

Range of the previous generation of FPBEVs varied from 30 miles to 122 miles per overnight charge. This variability is primarily due to different battery technology, battery system size and vehicle size, weight and design, but, climatic conditions, terrain, load, and driver diversity (driving style) also significantly affect real world driving range of individual vehicles.

Energy consumption results were obtained in both sets of testing and varied about 300% from best to worst in both cases. Again, these vehicles had significantly different payloads, performance, size and weight, different types of batteries, and the ambient temperatures during charging varied significantly. The Panel expects that technology available today would reduce this variability and achieve better energy consumption results.

In Europe, several BEVs were produced in the mid 1990's, including the Peugeot 106 and Partner, Citroen AX, Saxo and Berlingo, Renault Clio Electrique, and Fiat 600 Ellettra. These vehicles could achieve driving ranges of about 80 to 100 km (50 to 60 mi) and maximum speeds of about 100 kph (60 mph). They were intended for use in European city centers, and not for freeway driving, so in the sense that they could meet the customer's performance requirements, they can be considered "full performance" BEVs for that specific application.

Recently a few small companies have developed FPBEVs and are offering them to retail customers. Two examples are the Tesla Motors' Roadster and AC Propulsion's conversion of the Toyota Scion xB to the AC Propulsion eBox. The specifications and performance of these vehicles are shown below:

Table 6-1: FPBEV Specifications[1]:

Vehicle	**Platform**	**Motor**[2] (kW)	**Battery** (kWh – Type)	**Curb Weight** (pounds)
Tesla Roadster	Tesla	50/185	50 Li Ion[3]	~2,500
AC Propulsion eBox	Scion xB	50/120[4]	35 Li Ion[3]	3,050

1. Source: manufacturer, ZEV Symposium, and press releases
2. Continuous power rating/peak power rating
3. See Appendix J for discussion
4. Governed to limit battery current, 120 seconds

Table 6-2: FPBEV Performance[1]:

Vehicle	**Payload** (pounds)	**0-60 mph** (seconds)	**Driving Range** (miles)	**Consumption** (AC kWh/mile)
Tesla Roadster	>300[2]	~ 4	250[3]	0.204[3]
AC Propulsion eBox	>750[4]	~ 7	150[5]	0.250[5]

1. Source: manufacturer, ZEV Symposium, and press releases
2. Payload not available, based on 2 passengers and FMVSS minimum payload of 150 pounds per seating position
3. HFET
4. Payload not available, based on 5 passengers and FMVSS minimum payload of 150 pounds per seating position
5. "Road test result using driving routes and speeds typical of the Los Angeles area including freeway speeds up to 75 mph, congested freeway driving, and urban and suburban driving at local speed limit, all with heater and A/C off."

As can be seen from this data, Li Ion batteries can provide a significant improvement in energy storage capability, performance and driving range. It also appears that advancements in charging system efficiency and vehicle electric drive efficiency have been made.

Compared to the average U.S. price of about $26,500 for a light duty vehicle, these FPBEVs are expensive, the Tesla Roadster price is about $100,000 and the eBox is quoted at $55,000, plus about $15,000 for a customer supplied Scion xB conversion vehicle. As discussed in Appendix H, the batteries for these vehicles alone are likely to cost between $18,000 and $36,000, and their life is uncertain. Tesla has a 5 year, 100,000 mile warranty and eBox has a 1 year warranty on the conversion components.

Automotive News reported that at the recent National Automobile Dealers Association convention in Las Vegas, Miles Automotive showed their Javlon XS500 electric car. The article stated that the four dour sedan designed by Pininfarina will have a 150 mile driving range, a top speed of 80 mph, and a price of about $32,000.

In France, The Société de Véhicules Electriques (SVE) – Groupe Dassault is converting 30 Renault Kangoos to FPBEVs, using both SAFT Li Ion and ZEBRA NaNiCl2 batteries for testing in the Cleanova II program. The Société de Véhicules Electriques (

b) Units in Operation

Plug In America estimates 5600 FPBEVs were leased or sold nationwide and Electrifying Times estimates that 2,300 were placed in California between 1997 and 2002. Plug In America estimates about 1280 remain on the road nationwide.

Solar Energy International estimates there are 4,000 Electric Vehicles operating in the United States.

In France, about 10,000 FPBEVs with NiCd batteries were produced as part of the mid 1990's program and many are believed to be still in operation, primarily in the vehicle fleets of Electricitè de France (EDF).

EDF estimates the total number of BEVs in the world is about 30,000, or about 0.004 % of the total number of light vehicles (~800 million).

c) Technical Issues

Architecture ("Conversion" vs. "Ground Up")

As demonstrated by the vehicles listed in Appendix J, FPBEVs can be either conversions of existing vehicles or new dedicated vehicle platforms (a.k.a. "ground up"). Conversions have the advantage of starting with the platform of a volume based conventional vehicle but usually have payload restrictions due to the added battery weight, or packaging compromises due to the volume necessary to package the battery system. Achieving the increased range the customer wants makes this conversion issue even more challenging. Dedicated vehicles minimize these technical compromises but require much greater capital investment.

Battery Performance and Life

A detailed discussion of the status, major issues and future potential of the vehicle energy storage system (VESS) technologies is presented in Section 3, with emphasis on NiMH and Li Ion batteries. One conclusion of that discussion is that the performance of high energy NiMH battery technology of the type used in past FPBEVs has not progressed significantly in the past five years. NiMH gravimetric energy density, in particular, remains marginal or inadequate for FPBEV applications and is likely to remain so. On the other hand, Section 3 makes clear that Li Ion battery technology has advanced very substantially, driven not only by the rapidly growing market for consumer products but by the emergence of power tools and HEVs as potential applications. Of particular relevance to FPBEVs is that cycle and calendar life, considered inadequate 5-6 years ago, are improved to the point that automotive applications are considered feasible. However, no Li Ion battery technology designed for full size FPBEVs has become available or seems to be under development. One likely reason is that the prospective costs of Li Ion (and NiMH) batteries in the capacities required for full size FPBEV applications remain high, even if these batteries were mass-produced (see Tables 3-13 and 3-14 and the discussion below).

Battery Temperature

FPBEVs must be able to be parked unplugged during the day in a cold environment, such as is experienced in the northeastern U.S., yet their batteries must still provide enough energy and power for safe vehicle performance. Li Ion (and NiMH) batteries cannot meet this requirement at temperatures below approximately -20 to -30 ℃ (-4 to -22 ^{o}F), depending on the specific Li Ion technology. In addition, battery powered electric resistance heaters can significantly reduce driving range in cold weather. Although the use of fuel fired heaters for ZEVs is allowed below 40℃ under the present regulations, they result in a FPBEV that is not a true ZEV and they require the customer to refuel them separately. Batteries also need to be able to be charged and operated when FPBEVs are parked and operated in high ambient temperatures, such as is experienced in the southwestern U.S. Under these conditions, battery cooling may be required, again with expenditure of battery energy and loss of vehicle range. Control of battery temperature within limited ranges is required also to maximize battery cycle and calendar life, as discussed in the VESS section above.

Battery Safety

The original design verification process and experience of the past decade with several thousand FPBEVs propelled by NiMH batteries has shown that NiMH batteries do not present significant safety issues. However, concerns about safety and the need to develop robust systems that prohibit or safely contain failure modes are among the major factors that have delayed the introduction of Li Ion batteries in automotive applications. Recent well publicized incidences with laptop computer battery fires, and widespread Li Ion battery recalls, has made the general public aware of the potential issue of Li Ion battery safety. Fortunately, as reviewed in the VESS section, more than 200 prototype FPBEVs and HEVs have been operated on public roads worldwide without significant safety incidents. Technological advances in battery chemistry, design and management have enhanced every aspect of automotive Li Ion battery safety, and continuing advances can be expected to further reduce the already small safety risks. The current use of a small Li Ion battery for the start-stop function of the Toyota Vitz mini-car, use of Li Ion batteries in several small FPBEVs planned for Japan (described below), and the plans to introduce Li Ion batteries in HEV applications within the next few years, indicate that technical progress has improved Li Ion battery safety to the point where it is now considered acceptable by several OEMs.

d) Commercial Issues

Vehicle Cost

Historically, FPBEVs have cost substantially more to manufacture than their counterpart ICE vehicles because of the high costs of the electric propulsion systems, including the electric drive system, electric accessories, and, in particular, the battery system. With the rapid proliferation of models and market growth of hybrid electric vehicles (HEVs), as well as major efforts underway to develop fuel cell electric vehicles (FCEVs), discussed later, substantial progress is being made in lowering costs for the high voltage electrical systems – drive motors, power electronics and accessories (e.g., electric power steering and electric air conditioning). Although not yet at levels necessary to be fully competitive with conventional ICE technologies, the costs of these systems in mass production are not considered to be a major issue. Thus, the major commercial issue for FPBEVs continues to be the battery system's initial and life cycle cost.

A battery system with a rated capacity of 40kWh would provide a medium sized family sedan FPBEV with a maximum driving range of about 125 miles, assuming 0.250 kWh/mile DC energy consumption and 80% DOD. Based on the cost projections developed in the VESS section, a comparison of the cost goals and status for a 40kWh battery system with a 10 year life is shown below:

Table 6-3: 40 kWh Battery System Goals / Present Status / Projected Status

Battery System[1] (40kWh)	**Long-term goals** (2005-2008)[2]	**Present Status** – Best Case[3]	**Projected Status** – Best Case[4]
Type	n/a	NiMH	Li Ion
System Price ($)	6,000 – 3,000	15,360 – 11,430	13,680 – 8,395
System Price ($/year)	600 – 300	1,536 – 1,143	1,368 – 839

1. The battery system includes the battery modules, module support structure, battery management system and software algorithms (full or partial), wiring, thermal management sub system, and enclosure. For interfacing with the vehicle, the battery system also includes a high voltage DC connector, CAN bus connector, thermal management connection (liquid or air) and mounting brackets.
2. Source: Table II-5 (page 14), U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries, 2005 Annual Progress Report, Energy Storage Research and Development, FreedomCAR and Vehicle Technologies Program, U.S. Department of Energy, January 2006. Price of 150 $/kWh (desired to 75 $/kWh) is supplier selling price at volumes of 10,000 40 kWh units/year., http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2005_energy_storage.pdf
3. Source: VESS, Table 3-14, price range reflects 12,500 – 100,000 40 kWh units/year
4. Source: VESS, Table 3-13, price range reflects 12,500 – 100,000 40 kWh units/year

As can been seen above, the battery pack's life cycle price is much higher than the USABC goals, even considering up to 10 times higher volume over which to spread fixed costs and take advantage of automated manufacturing processes.

When customers consider the purchase of an alternative fuel vehicle (e.g., a diesel passenger car), they often want to know whether or not their potential fuel cost savings will offset the incremental price of the vehicle. Some may do their own calculations, but many potential customers rely on calculations or estimates done for them by others, such as the automotive press and other media. It may be reasonable to assume a FPBEV *without a battery* could be offered on a commercially viable basis, if mass produced by a manufacturer, at the same price as a comparable conventional vehicle, and that the incremental cost of the battery would be the incremental cost of the vehicle. Using the battery system prices from above, the chart below shows the price of gasoline that would be necessary for a customer to recover his/her cost for the battery system over a 10 year period on a simple payback basis, assuming he/she would be willing to pay the manufacturer's incremental cost of the battery:

Table 6-4: Gasoline Price ($/gallon) Required for Customer Breakeven[1]

Electricity Rate ($/kWh)	**Long-term goals**[3] ($600 – 300 /year)	**Present Status**[3] ($1,536 – 1,143 /year)	**Future Status**[3] ($1,368 – 839 /year)
0.04	1.75 – 1.05	3.85 – 2.95	3.50 – 2.30
0.06	1.90 – 1.20	4.05 – 3.15	3.65 – 2.45
0.08	2.05 – 1.35	4.20 – 3.30	3.80 – 2.60
0.10[2]	2.20 – 1.55	4.35 – 3.45	4.00 – 2.75

1. assumptions: 10 year life, 12,000 miles/year, 27.5 mpg (combined) ICE vehicle, 0.300 kWh/mile AC basis for FPBEV; costs not included: scheduled maintenance, battery markup and warranty cost not recovered by OEM, time

value of money, inflation, value of vehicle at end of 10 years
2. 2006 average U.S. residential rate ($0.0973)
3. Source: Table 6-3

Gasoline prices of $3.00 to over $4.00 have been experienced in 2006, which if they continue in the future, make battery cost much less of a barrier to commercialization of FPBEVs than in the past when gasoline was under $2.00/gallon. Since the USABC cost goals of 150 $/kWh (desired to 75 $/kWh) were developed about 10 years ago, when gasoline was much less expensive, the Panel expects that these goals may be revised upwards to be consistent with the expected higher prices, or possibly increased taxation, of gasoline. For reference, in August 2006 the Japanese Ministry of Economy, Trade and Industry (METI) published a 2015 CY battery cost goal of 40,000 ¥/kWh (336 $/kWh @ 119 ¥/$) for 1,000,000 packs/year.

However, if the “costs not included” in footnote 1 were included, with the exception of scheduled maintenance, the gasoline price payback threshold would be higher. In addition, the following cautions concerning this analysis are important to consider.

In the above example, it is assumed that the customer drives the national average of about 12,000 miles per year, or an average of 33 miles per day, every day (or commutes 46 miles per day, 5 days a week). This is an aggressive assumption for a FPBEV that is not capable of long trips. For a customer who drives less, the fuel savings would not be as much. If the customer drove half as much, the gasoline prices for customer breakeven would be significantly higher than those prices shown in Table 6-14 (e.g., for a $1,536/year battery and $0.10 electricity rate, the breakeven gasoline price rises from $4.35 to $7.90; or for a $839/year battery and $0.04 electricity rate, the breakeven gasoline price rises from $2.30 to $4.20).

OEMs in total are probably not likely to commit to very high annual volumes of battery systems, given their recent experience with FPBEVs. Furthermore, a battery system is usually unique for each new vehicle program, and it is highly probable that the various OEMs would not all use the same cell suppliers, further reducing volume and increasing unit costs for individual battery system suppliers and cell manufacturers.

An analysis of FPBEV fuel cost savings potential based on the net present value (NPV) of the customer’s future energy cost savings is included in Appendix I. It varies annual mileage (10,000 to 14,000 miles), gasoline price ($2.50 to $4.00/gallon), conventional vehicle fuel economy (27 to 36 miles/gallon), electricity price ($0.06 to $0.12/kWh), and vehicle energy economy (3 to 4 miles/kWh). For four combinations of assumptions it shows NPVs of $4,055, $7,056, $7,239, and $10,933. Assuming the customer pays for the battery, these values can be compared to his/her battery system cost shown above that range from $8,395 to 15,360, depending on type and volume (Table 6-3). Only in the case of high volume Li Ion and the most optimum vehicle assumptions does the NPV exceed the initial cost of the battery.

In France, the commercial goal of the Cleanova II program is to both (1) demonstrate the feasibility of producing a FPBEV that fully meets the customer’s requirements and is priced – *excluding the battery* – equivalent to a conventional vehicle, while still achieving a positive profit margin for the vehicle manufacturer – and (2) produce a battery system that is priced low enough, while still achieving a positive profit margin for the battery manufacturer, such that the customer’s fuel savings over the life of the vehicle recovers the customer’s cost of the battery system (possibly on a lease basis) over the life of the vehicle. Fueling in France with inexpensive “clean” electricity vs. expensive gasoline/diesel, combined with relatively low speeds and short daily driving distances, should provide an optimum scenario for FPBEV commercial success.

Battery Business Case Alternative

Because of the prospective high cost of FPBEV batteries, business models other than straight ownership of FPBEVs and their batteries by customers deserve consideration as a way of capturing the substantial propulsion energy cost savings of BEVs that could be realized. Electric utility ownership of batteries and lease-back to customers is one such model that has been proposed and discussed. Several business models have been proposed that go beyond utility ownership of batteries and include use of these batteries to provide specific utility functions that may have sufficient value to offset part of battery ownership costs. These include (1) availability of the power and energy delivery and acceptance capacity of batteries connected to the electric grid through the BEV-charger interface, to provide functions such as spinning reserve (i.e., energy system production capacity that is “idling”, or is ready and available to accommodate an rapid surge of demand), voltage regulation, emergency power, and peak shaving/load leveling on a local and system basis, and (2) use of batteries no longer meeting BEV requirements as distributed energy storage subsystems on the electric grid to provide some or all of the functions listed under (1). The analysis of the cost and economic feasibility of every one of the many possible configurations and functions is very complex since they are dependent on the values of these different functions which will be different for different utility systems. Moreover, for each utility system these values change as a function of time-of-day, over historic time, and as a function of system “saturation” with battery storage. Overlaid over this fundamental complexity are uncertainties regarding statistical availability of the batteries and of customer behavior, issues for which there are neither experience data nor credible models. However, because of the potential attractiveness of one or more of these applications, the Panel encourages this type of analysis.

Customer Acceptance

Major OEMs with FPBEV experience have found that customer acceptance of FPBEVs varies considerably, ranging from very high to very low, due to a complex combination of vehicle characteristics and societal norms. Many customers who rate them highly do so because of their beliefs in the electric vehicle’s cutting edge technology that leads to important societal benefits – pollution reduction, greenhouse gas reduction, and energy independence. Most customers are interested in the direct FPBEV attributes – lower fuel cost, smooth quiet operation, reduced maintenance requirements, fueling at home, “instant” heat, and/or fun to drive because of high torque at launch. Customers who rate the FPBEV low do so because of real or perceived inconvenience factors: limited driving range (especially in cold weather), the need to plug in at night, fear of forgetting to plug in, fear of running out of fuel/energy, long recharging time, limited availably of public charging infrastructure (including incompatible connectors), and/or the high cost of the battery system (if not subsidized by manufacturers or governments).

Based on market research studies of early BEV users and potential users, some OEMs have concluded that FPBEV requirements for real world driving range, reflecting all of the conditions mentioned above, is a minimum of 100 miles per overnight charge, with acceptable range of about 150 miles and preferred range of at least 200 miles. Although General Motors indicated that from their experience with the EV-1, 150 mile range was not acceptable for a mass-market vehicle. Others have found that for mass-market retail customers anything less than the typical 300 to 350 mile range of a conventional vehicle implies a functional degradation and an expected reduction in vehicle price, despite the fuel cost savings.

Ideally, the size of a FPBEV battery should not be any larger than necessary in order to keep the vehicle as affordable as possible. The Panel's perspective is that for people willing to consider a FPBEV, refueling frequency must be taken into account when making range comparisons, although this does not seem to be widely understood or accepted by mass-market customers. When plugged in every night, an EV driving range of 100 miles provides 350 miles per week, using, on average, just half the available range of the EV per day – 50 miles. This allows the EV driver flexibility to drive nearly double an average daily distance of 50 miles when necessary – thus providing day to day driving range flexibility similar to, but not as great as, that of a conventional ICE vehicle. This range and flexibility is comparable to a 350 mile range conventional ICE vehicle, which is typically refueled not more than once a week. Also, one must realize that when plugged in daily an average of 50 miles per day could provide a generous 18,250 miles/year.

While 100 miles daily driving range should be considered adequate for most urban usage, it is not sufficient for occasionally taking long trips, and thus the vehicle will have limited practicality for many customers. This limitation is especially critical for customers who have only one vehicle available to them.

Charging Infrastructure

The Panel considers charging infrastructure to be a major factor in customer acceptability – and therefore the potential commercial viability of FPBEVs. High power fast charge (e.g., 40 to 80% SOC of rated energy capacity in 15 minutes using an off board DC charger) provides an opportunity to extend driving range for unanticipated or long trips, and if fast charge infrastructure were convenient and widely available to the public, could improve the customer acceptability of FPBEVs. It could allow downsizing the battery more toward the average daily driving range and thus reduce the customer's battery cost and improve his payback rate.

However, several issues would have to be overcome before fast charge could become widely available. Electricity rates in many places are much higher during peak hours of the day, when most fast charging would take place, so FPBEV drivers would be encouraged to use fast charging only in an emergency or when taking a long trip. Special electricity rates for fast charge infrastructure could help mitigate the FPBEV range issue and possibly encourage the use of more FPBEVs but are not known to exist. Moreover, fast charging equipment is expensive, so the owner of the equipment would need to add on a significant cost premium to the electricity rate to recover his investment. Coupled with limited use by the customer, because of the resulting high cost per kWh, the business case for installing fast charge equipment becomes very difficult, unless it is intended to support a dedicated fleet operation or is subsidized by a broader utility plan to encourage FPBEVs and the associated sale of night time electricity. Finally, some battery technologies are less capable of fast charge than others (for example, some lithium systems cannot accept fast charge), and there is very little deep discharge life cycle test data of battery systems subjected to both normal overnight and (randomly used) fast charging.

e) Prospects for Advancement

Mitsubishi has announced they are developing a mini-car sized FPBEV in Japan – the 4 passenger, 1080 kg, "i MIEV", with a 16-20 kWh Li Ion battery and 47 kW motor, and that they plan to bring an EV to the U.S. in the future. Subaru is also investigating a Li Ion version of their R1 mini-car in Japan. Nissan recently announced that they plan to launch a "test" electric vehicle early in the next decade. No other major OEM is producing, or known to be developing, a FPBEV. The reasons these automakers give for either not developing FPBEVs, or proceeding very cautiously, are primarily high battery system cost and additional battery issues associated with deep discharge cycle life, robustness, gravimetric energy density and volumetric energy density, and their concerns about limited driving range and customer acceptance of FPBEVs.

Based on their past experience, and the inherent limitations of FPBEVs, most major OEMs seem convinced they will not become accepted by the mass-market and thus consider them to be niche market products with limited volume potential. Vehicles with lead acid battery packs had very limited driving range (especially in cold weather), and short battery life, and vehicles with more advanced batteries, including NiMH and Li Ion, had very high battery costs, resulting in high vehicle prices and/or unsustainable manufacturer subsidies. Long battery recharge times, and lack of convenient public fast charge infrastructure, made FPBEVs impractical for unanticipated travel or long trips. While acknowledging that they are closely monitoring energy battery developments, with a focus on cost and life improvements, most of the ten automakers that the Panel visited have not disclosed that they are actively developing next generation FPBEVs.

The major barrier to commercially viable FPBEVs is the energy battery system's high initial and life cycle cost. Volumetric and gravimetric energy densities are also concerns, although Li Ion promises gravimetric energy density meeting or approaching vehicle requirements. With the exception of the Li Ion batteries for Mitsubishi, Subaru and Nissan mentioned above, the Panel has found very little effort underway at the present time to advance the technology of batteries for FPBEV applications; however the potential for the introduction of PHEVs, discussed below, could stimulate efforts to develop and improve energy batteries that would benefit battery technology for FPBEV applications (as discussed in the VESS section (3. C) above). Relatively small FPBEVs with Li Ion batteries are most likely to be successful, due to cost issues.

Several small companies, have recently introduced, or plan to introduce, FPBEVs in very low volumes as discussed in the two examples above. Although prices are very high, these vehicles make capable retail products available to enthusiasts, and their development could help advance FPBEV technology. Also, they may help familiarize and educate the public on the various benefits of an electric vehicle and how drivers might adapt to the range limitation issues. Moreover, it will be important to track progress and market acceptance of the recently announced Javlon FPBEV from Miles Automotive, given it's expected price ($32,000).

Europe and Japan's significantly higher fuel prices, shorter driving distances, and in many cases little or no urban freeway driving requirements, provide easier hurdles for successful commercialization of small FPBEVs. If the technical and commercial goals of the Cleanova II program are met, the French Post Office may buy a substantial number of FPBEVs in 2008. If this happens, it could be the start of a commercially viable FPBEV program -- without using direct subsidies from either manufacturers or governments. Mitsubishi's "i MIEV" project, Subaru's R1e, and Nissan's recently announced plan to launch a "test" electric vehicle early in the next decade will be important to monitor.

f) Introduction Timing

Given current market conditions, combined with the high cost and other issues associated with batteries, most major OEMs do not see a viable business proposition in the next 5 to 10 years to produce FPBEVs for the U.S. market.

In the U.S. FPBEVs have achieved pre-commercialization (1,000s/year) but the Panel's projection is that they will not reach early commercialization (10,000s/year) until energy batteries that approach the DOE/USABC goals become commercially available and/or the price of gasoline increases substantially. With very little work presently underway to develop improved energy batteries, availability of suitable FPBEV batteries is not foreseen within the next 5 years. However, if energy battery development for PHEVs (discussed below) is successful, advanced energy batteries could become available after that time. Once a major OEM concludes that a battery is technically capable for the intended application, the purchase price is deemed to be acceptable, and there is sufficient long-term market demand to support a business case, it will take them another 3 or 4 years to design, develop and validate a truly commercial FPBEV. Thus early commercialization (10,000s/year) of FPBEVs in the U.S. is probably at least 8 or 9 years away at the earliest.

On the other hand, the outlook for small FPBEVs in Japan and Europe may be more promising. Nissan's outlook is that the development of battery technology indicates continued and promising progress in obtaining a future cost effective electric powered vehicle. These vehicles are likely to be introduced in limited fleet tests in the 2010 timeframe while cost reduction and performance gains continue. Test markets are expected to include both Japan and Europe based on green electric power generation, high petroleum prices, government support, and compatible usage patterns.

2. Fuel Cell Electric Vehicle (FCEV)

A fuel cell electric vehicle (FCEV) is similar to a FPBEV in that it contains an electric motor propulsion system and electric accessories, but instead of an electrochemical storage device – a battery, it stores a gaseous or liquid fuel onboard, and converts the fuel into electric power with an electrochemical conversion device – a fuel cell system. Some FCEVs also have a regenerative brake system, like FPBEVs, to capture kinetic energy during braking and deceleration, thus improving overall vehicle efficiency, and in this case they also have a small high voltage battery.

FCEVs that use hydrogen fuel have zero exhaust emissions, and on a vehicle basis do not consume any hydrocarbon based fuel (gasoline, diesel, CNG, propane, ethanol, etc.) that would create CO2 emissions.

a) Manufacturers/Vehicles/Specifications/Performance

Most major OEMs are actively engaged in fuel cell vehicle research and development and many of them are making very major financial and resource commitments. In addition to many "one-off" prototypes, FCEV fleets from seven OEMs that have been introduced or publicly announced are:

Table 6-5: FCEV Specifications[1]

Vehicle	**FC System** - stack developer - system power[2] (kW)	**Hybrid System** - type - power[3] (kW)	**Fuel System** - type - capacity[4] (kg)	**Curb Weight** (pounds)
DaimlerChrysler F-Cell	Ballard 68/72	NiMH 15/20	CH2 – 350 bar 1.8	3307
Ford Focus FCV	Ballard 68/n.a.	NiMH n.a./20	CH2 – 350 bar 4.0	3527
Ford Explorer TDV2	Ballard 68/n.a.	NiMH n.a./40	CH2 – 700 bar 10	5645
General Motors HydroGen3	GM 94[5]/94[5]	n/a 60/60	CH2 – 700 bar 3.1	3505
General Motors HydroGen3	GM 94[5]/94[5]	n/a 60/60	LH2 4.6	3505
General Motors Equinox	GM 93/93	n/a 90/100	CH2 – 700 bar 4.2	4431
2003 Honda FCX	Ballard 78/78	Ultra capacitor n/a	CH2 – 350 bar 3.3	3704
2006 Honda FCX	Honda 86/86	Ultra capacitor n/a	CH2 – 350 bar 3.6	3682
Hyundai Tucson FCEV	UTC Power n/a/80	Li Ion n/a/n/a	CH2 – 350 bar n/a	n/a
KIA Sprotage FCEV	UTC Power n/a/80	Li Ion n/a/n/a	CH2 – 350 bar n/a	n/a
Nissan X-Trail FCV	Nissan 90/90	Li Ion n.a./25	CH2 – 700 bar 3.6	4101
Toyota FCHV	Toyota 75/90[6]	NiMH n.a./25	CH2 – 350 bar 3.2	4145

1. Source: manufacturer data, most recent version deployed
2. Net continuous power/net maximum power
3. ETS continuous power/peak power
4. Actual customer usable capacity
5. Fuel cell stack power
6. Gross power

The performance of these FCEVs is shown below:

Table 6-6: FCEV Performance[1]

Vehicle	**Payload** (pounds)	**0-60 mph** (seconds)	**Range** (miles)	**Economy[2]** (mi/kg H2)	**Consumption[3]** (kWh/mi)
DaimlerChrysler F-Cell	705	13.8	110[10]	58[10]	0.520/0.440
Ford Focus FCV	605	17.2	191[6]	48/53	0.624/0.490
Ford Explorer TDV2	600	18	350[9]	35[9]	0.950[9]
General Motors HydroGen3[4]	792	16.0	168[9]	54	0.610
General Motors HydroGen3[5]	792	16.0	249[9]	54	0.610
General Motors Equinox	750	12.0	200[9]	48	0.700
2003 Honda FCX (Ballard stack)	n/a	15.0	170[0]	51/48	0.588/0.541
2006 Honda FCX (Honda stack)	n/a	13.0	210[0]	62/51	0.483/0.509
Hyundai Tucson FCEV	n/a	n/a	186[0]	n/a	n/a
KIA Sportage FCEV	n/a	n/a	n/a	n/a	n/a
Nissan X-Trail FCV	783	14.0	234[7]	58/53	0.513/0.492
Toyota FCHV	n/a	11.8	193[7]	52/46	0.574/0.565

1. Source: manufacturer data
2. City label (FTP x 0.9)/highway label (HFET x 0.78)
3. FTP/HFET dynamometer vehicle consumption “tank to wheels”, hydrogen LHV: 33.3 kWh/kg
4. CH2 version
5. LH2 version
6. FTP
7. UDDS
8. HFET
9. Combined unadjusted
10. Combined adjusted
0. Footnote 6, 7, 8 or 9 N/A

It can be seen from the tables above that some of these OEMs have introduced or announced successive generations of FCEV on-road test fleets, and the successive generations are demonstrating continuous performance improvement. Unlike “one-off” prototypes or concept vehicles typically seen at auto shows, the vehicles in these fleets are very similar to production vehicles in that they are fully engineered and tested to ensure they will perform well, will display a high level of feature comfort and function, and will be safe and reliable in the hands of the general public when driven on public roads. Achieving all of these attributes is not only very costly, but it requires dedicating a large number of highly skilled technical employees. Development of the vehicles shown in Table 6-6 thus is a good indicator of the OEM’s’ conviction regarding the future potential of FCEV technology and the seriousness of their commitment.

The National Renewable Energy Laboratory (NREL), in Golden, Colorado, is continuing to collect key FCEV data from the DaimlerChrysler F-Cell, Ford Focus FCV, General Motors HydroGen3, Hyundai Tucson FCEV, and KIA Sportage FCEV. This data includes stack durability, vehicle fuel economy (dynamometer and on-road), vehicle range, fuel cell system efficiency, maintenance and safety events, vehicle performance (maximum speed, acceleration, grade climbing capability), maximum power and time at 40°C ambient conditions, freeze start capability (time and energy required), and continuous voltage and current from FC stack, motor/generator, battery and key auxiliaries (dynamometer and on-road).

The individual vehicle test data is confidential; however, NREL has published composite data for 63 first generation vehicles which reflects efficiency and fuel economy results:

Table 6-7: FCEV National Renewable Energy Laboratory Fall 2006 Results[1]

Attribute	**DOE Target – 2015**[2]	**Fleet Status**
In-Vehicle Fuel Cell System Efficiency (%)	60 [4]	52.5 – 58.1 [5]
Fuel Economy – Dynamometer (miles/kg H2)		49 – 67 [6]
Fuel Economy – Window Sticker (miles/kg H2)		42 – 57 [7]
Fuel Economy – On-Road (miles/kg H2)		31 – 46 [8]
Vehicle Range – Dynamometer (miles)		125 – 225 [6]
Vehicle Range – On-Road (miles)	300	80 – 155 [8]
Range of Ambient Temperature (^{o}C)		-15 – 47

1. Source: Hydrogen Learning Demonstration Project: Fuel Cell Efficiency and Initial Durability, presented at Honolulu, Hawaii Fuel Cell Seminar, Nov 15, 2006, http://www.nrel.gov/hydrogen/proj_tech_validation.html
2. Source: Figure 3 (page 10), Technology-Specific 2010 and 2015 Research Goals, FreedomCAR and Fuel Partnership Plan, U.S. Department of Energy, March 2006
3. Unused
4. Peak power
5. Dynamometer data at ~25% net power
6. Unadjusted combined city/highway per SAE J2572
7. adjusted combined city/highway (label)
8. Excluding trips <1 mile, calculated from FC stack current or mass flow readings

Due to the lack of complete public availability of the NREL information, it is not possible to explain the large reduction from adjusted dynamometer results (“label”, “window sticker”) to on-road results, which for the data shown in the chart above ranges from 19 – 26%. Since this is consolidated data taken from four different vehicle designs, four different fuel cell system designs, at least four different hybridization levels, and three types of hydrogen storage systems, it is not clear whether this is representative of all of the vehicles or just some of the vehicles. Furthermore, all of these vehicles are at early stages of system design maturity.

The on-road data is taken from a wide variety of uncontrolled drive cycles. Factors which can degrade fuel economy include a high frequency of severe operating conditions typical of demonstration vehicles, such as drive cycles with excessive idling (more than 18% of time) that require significant amounts of hydrogen purging for water management, abnormally high number of passengers/heavy payload, aggressive “full throttle” driving, many starts and stops, and many short trips. Also, use of the climate control system, which has a more severe impact on a high fuel economy powertrain, cold weather operation, unrefined dynamometer test procedures for fuel cell vehicles (the highly accurate conventional carbon emission method cannot be used), unrefined measurement of road fuel economy by calculation from stack current or mass flow readings, and hydrogen boil off from the liquid hydrogen fueled vehicles in the fleet.

The Environmental Protection Agency (EPA) has issued a new standard for fuel economy labels

(5-cycle method), which will be used in vehicles from model year 2008 onwards[6], which tries to account for higher speeds, more aggressive driving (higher acceleration rates and higher top speeds), the use of air conditioning, and the effect of cold temperature. By using EPA's "mpg method" of adjusting FTP/HFET dynamometer data to obtain 5-cycle label values, a range of 49 to 67 mpg on the dynamometer equates to 5-cycle labels of roughly 36 to 47 mpg[7]. This would lower the reduction from labels to on-road results from 19 – 26% with the present method to 2 – 14% using the new method. This remaining lower reduction could be due to the higher frequency of severe operating conditions typical of demonstration vehicles explained above.

No fundamental safety problems with the vehicles have been encountered. Future NREL reports will include fuel cell durability and cold start up times.

b) Units in Operation

The number of FCEVs in operation is shown below:

Table 6-8: FCEV fleet vehicles in operation[1]

Vehicle	**California**	**North America**[3]	**Europe**	**Asia**	**Other**	**Global**
DaimlerChrysler F-Cell	--	--	--	--	--	64[5]
DaimlerChrysler Sprinter FCEV	--	--	--	--	--	3[5]
DaimlerChrysler Bus FCEV	--	--	--	--	--	33[5]
Ford Focus FCV	8	26	4	0	0	30
Ford Explorer TDV2	0	3	0	0	0	3
General Motors HydroGen3	2	8	1	3	0	12
General Motors Equinox[4]	n/a	n/a	n/a	n/a	n/a	n/a
Honda FCX	22	26	0	14	0	40
Hyundai FCEV	n/a	n/a	n/a	n/a	n/a	n/a
KIA FCEV	n/a	n/a	n/a	n/a	n/a	n/a
Nissan X-Trail FCV	16	16	0	23	0	39
Toyota FCHV	25	25	0	37	0	62
Total	varies	varies	varies	varies	varies	286+

1. Source: manufacturer data, includes company test vehicles in 2006
2. Includes vehicles planned to be deployed in 2007
3. Includes California
4. 1 engineering development vehicle currently deployed in California. Fleet of over 100 will be deployed beginning in September 2007, with approximately half in California.
5. For DaimlerChrysler, vehicles have been moved among all the areas listed including Australia and South America.

These vehicles are being deployed in a wide variety of locations to gather data from different climatic conditions, road conditions and customers.

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[6] Final Technical Support Document, Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates, U. S. EPA, December 2006; http://www.epa.gov/fueleconomy/420r06017.pdf

[7] Detailed FTP/HFET NREL data is not available to the public, precluding a more precise calculation.

c) *Technical Issues/Goals*

Vehicle Fuel Alternatives

All OEMs are now focusing on hydrogen fuel for FCEVs. In the past, methanol and gasoline fuel cell vehicles were developed by several OEMs, due to the significant fuel infrastructure advantages relative to hydrogen. However, most, if not all, manufacturers have abandoned these efforts because of major problems with system complexity, efficiency, and cost. Reformer system transient response during rapid and unpredictable changes in propulsion system load requirements and contaminants in the reformer product hydrogen also made achieving durability goals challenging. Other factors contributing to abandonment of hydrocarbon fuels for automotive fuel cell systems included increasing emphasis on petroleum independence and CO2 emissions, concerns about methanol toxicity, and the fact that these vehicles were not ZEVs.

Fuel Cell System

Major technical issues with fuel cell systems are associated with cold start performance, gravimetric power density, volumetric power density, durability and cost. Many companies are working on this technology, and have different priorities in terms of meeting challenging goals, such as power density, below freezing start capability, and durability. Usually advanced technology engineers first develop a design that can meet the key functional objectives, and, if judged successful, then work on revising the design to meet the cost objectives. At this early stage of development, while one company may be further along on one of these aspects, others may be further along on other aspects, so it is hard to determine if all of the goals can be reached simultaneously.

However, some of the leading developers of fuel cell systems expect that the technical issues will be resolved by the 2010 time frame, which could support volume production by the 2015 time frame. A detailed discussion of the goals, status, major issues and future potential of vehicle fuel cell systems is discussed in section 5.

Onboard Hydrogen Storage

Most OEMs are convinced that high pressure gaseous storage is the only practical solution for onboard hydrogen storage for the next decade. Beyond that, some manufacturers say that the only promising long term storage technology appears to be a combination of hydrides and pressure.

The major vehicle technical issues with the onboard hydrogen storage system are high cost, low volumetric energy density, and low gravimetric energy density. Low volumetric energy density makes it difficult to find a suitable location in the vehicle for the large tank(s) needed to achieve acceptable driving range (300 to 350 miles), and low gravimetric energy density makes it difficult to accommodate the weight of the tank in the vehicle. A detailed discussion of the goals, status, major issues and future potential of vehicle hydrogen storage systems is contained in section 4.

Architecture (“Conversion” vs. “Ground Up”)

Most FCEVs have been conversions of existing vehicles, in order to conserve resources and focus efforts on developing the fuel cell propulsion system technology, but conversions are difficult because of the large volume and weight of the present generation fuel cell systems and hydrogen storage systems. This has resulted in passenger and cargo space compromises, driving range compromises, and expensive weight reduction actions (e.g., carbon fiber composites, titanium, aluminum, etc.).

Heat rejection in a FCEV has been a major design constraint. Although current PEM fuel cell systems are more efficient than a conventional ICE, they (1) reject about 80% of their waste heat into the cooling system as opposed to about 33% in an ICE, and (2) to achieve acceptable stack durability operate at a lower fuel cell stack and coolant temperature than an ICE, typically about 75 to 90 °C (167 to 194 °F) versus an ICE's 120 °C (248 °F), which reduces the rate of heat transfer to the ambient air. This means that a FCEV must have a much larger radiator than a similar size ICE vehicle, and, since space is usually limited in the vehicle, especially in the case of conversions, the radiator size can constrain the maximum continuous power of the fuel cell system in the vehicle. Although the coolant temperature can be allowed to rise for a short period of time, this constraint is most critical on long steep hill climbs, at full payload, with full accessory load, in high ambient temperatures. Dedicated vehicle architectures and higher fuel cell system operating temperature are some approaches to help overcome this issue.

Present generation FCEVs typically are about 500 lbs heavier than similar sized conventional ICE vehicles, primarily due to the fuel cell system, hydrogen storage system, and large radiator and increased amount of coolant. This added weight reduces fuel economy and vehicle performance, and in the case of derivative platforms, requires a combination of weight reduction measures and vehicle upgrades to meet requirements for safety (e.g., barrier crash performance) and vehicle dynamics (e.g., braking and handling performance).

In the pursuit of cost and volumetric energy density goals, fuel cell systems are being simplified and downsized as next generations are developed. By the 2015 timeframe some systems are expected to be packaged under the hood, along with the traction motor and power electronics, within the same space as conventional front wheel drive ICE powertrain systems.

However, even next generation 700 bar compressed hydrogen storage systems capable of providing vehicle driving ranges greater than 300 miles will still require a large space within the vehicle. Some manufacturers consider a promising solution to be an under hood FC system and electric drive with a single hydrogen cylindrical tank mounted in the vehicle tunnel area (FCEVs do not require a conventional rear wheel drive transmission and driveshaft, and the FC exhaust system runs much cooler). Using a single tank instead of multiple tanks is likely to be less costly, as duplication of expensive parts is eliminated. Also, extending the length of a single cylindrical tank is a cost effective way to increase storage capacity of a compressed H2 tank.

Two examples that demonstrate progress in dealing with the challenge of onboard vehicle Hydrogen storage, are the next generation FCEVs from Ford and Honda, which have driving ranges that approach customer expectations of 300 to 350 miles,.

Ford unveiled their next generation fuel cell fleet vehicle, which is based on a modified Explorer, at the December 2006 Los Angeles Auto Show. It seats 6 passengers and has an under hood FC system and electric drive motor, and a separate rear wheel electric motor to provide all wheel drive. A large 700 bar compressed hydrogen tank is mounted in the tunnel. The tank contains 10 kg of hydrogen and at 35 mi/kg (combined, unadjusted), provides 350 miles of driving range.

Honda has announced that their next generation FCX will start limited marketing in both Japan and the U.S. in 2008 – and it will have a driving range of 270 miles (combined, adjusted). They say the range increase of about 30% versus the prior FCX is attributed to improved system efficiency and replacement of ultra capacitors with a Li Ion battery system. This is a new dedicated vehicle which seats 4 passengers and has no obvious package compromises. It packages the FC system in the tunnel, and has an under hood mounted electric drive motor and two wheel motors in the rear to provide all wheel drive. Two hydrogen storage tanks are placed laterally between the rear wheels. It maintains the prior generation FCX storage pressure of 350 bar, which can utilize the Honda Energy Station III home-based hydrogen production and refueling system, while awaiting deployment of a hydrogen infrastructure. The Panel notes that if this vehicle were modified to use 700 bar storage tanks, packaged in the same outer envelope as the 350 bar tanks, and if the additional weight of the tanks (~50% more) could be accommodated, the driving range could be increased by about 50% – to 400 miles (combined, adjusted). (Sources: Honda, 9/25/06 Press Release; Dutch Mandel, Autoweek, 10/23/06 Honda FCX Review; and VHSS; 4 G i)

Other Technical Issues

Many FCEVs are configured as HEVs, incorporating a power battery (or ultra capacitor) to store regenerative brake system energy for improved efficiency and to supply supplemental power for improved performance and to lessen the severity of load transients on the fuel cell system for improved durability. However, fuel cells do not achieve their highest efficiency at high loads as ICEs do, so the battery assist strategy is different than for “full” HEVs which lug the ICE powertrain to achieve more efficient operation. In addition, the present generation of FCEVs does not yet take advantage of start-stop capability, which is standard on virtually all conventional HEVs.

d) Commercial Issues

Vehicle Cost

As part of the FreedomCAR program, the U.S. Department of Energy (DOE), in collaboration with the U.S. Council for Automotive Research (USCAR) partners (DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation), has published goals for the three most challenging FCEV systems – the electric propulsion system, the fuel cell power system (including hydrogen storage) and the hydrogen storage system. These include goals for commercial viability in 2015 as well as interim goals and are intended to achieve costs comparable to conventional ICE systems. The Panel focused on the fuel cell power system and the hydrogen storage system as the most difficult of the three. Ongoing development of HEVs will drive down the cost of the electric propulsion system and the Panel reviewed some excellent progress in this area. The costs for the remainder of the vehicle systems are not considered to be a major issue at high volumes, and the electric accessory systems and power batteries are expected to decline in cost as HEVs continue to mature.

The goals and status of the fuel cell power system, which also includes the hydrogen storage system, are:

Table 6-10: FreedomCAR Fuel Cell Power System[1] Goals and Status

Fuel Cell Power System Parameter[1]	**FreedomCAR Goals** – 2010/2015[2]	**Present Status** – Best Case[3]	**Forecasted 2015 Status** – Best Case[3]
Type		PEM	PEM
Life (years)	15	2 – 3	10 – 13
Peak Efficiency (%)	60	50 – 60	60
Gravimetric Power Density[4] (W/kg)	325	300 – 500	700 – 1100
Volumetric Power Density[4] (W/l)	220	n/a	n/a
Cost[5] ($/kW)	45/30	75 – 600	30 – 75

1. Consists of the fuel cell stack, the fuel cell stack auxiliary sub-systems (e.g., sub-systems for air supply, fuel supply, thermal management, and any other necessary functions, such as water management), the hydrogen storage system, the high voltage energy storage system (if used), and all enclosures and connections.
2. Source: Figure 3 (page 10), Technology-Specific 2010 and 2015 Research Goals, FreedomCAR and Fuel Partnership Plan, U.S. Department of Energy, March 2006, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf
3. See VFCS (section 5) for detailed discussion and Figures 5-8, 5-9, 5-13, and 5-18
4. Excluding hydrogen storage
5. Direct material/labor and production facility costs. Indirect costs, marketing and profit not included. Design level assuming 250,000 units per year

The data shown above in Table 6-10 is a highly condensed summary of the material contained in the VFCS section (5). The Panel considers the forecasted status data to be a best case scenario, since much of the data shown in this table was derived from cell level testing, with limited full system level testing. Also, the Panel questions whether the status levels shown can all be achieved simultaneously, as discussed in detail in the VFCS section.

The goals and status of the hydrogen storage system are:

Table 6-11. FreedomCAR Hydrogen Storage System Goals and Status:

Hydrogen Storage System Parameter[1]	**FreedomCAR Goals** – 2010/2015[2]	**Present Status** – Best Case[3]	**Forecasted 2015 Status** – Best Case[3]
Type		Compressed, 350 Bar	Compressed, 700 Bar
Gravimetric Energy Density - (kWh/kg) - (weight %)	 2.0/3.0 6/9	 1.1 to 2.2 6 to 6.7	 1.9 to 2.1 6 to 6.3
Volumetric Energy Density (kWh/l)	1.5/2.7	0.6 to 0.8	0.9 to 1.3
Fill Time[4] (minutes)	2.5	<6	n/a
Cost[5] ($/kWh)	4.00/2.00	10.00 to 12.00	13.00 to 15.00

1. Based on usable hydrogen capacity, the hydrogen storage system consists of all sub-systems from the vehicle fuel inlet to the connection for the fuel cell system supply line, as well as all enclosures and connections
2. Source: Figure 3 (page 10), Technology-Specific 2010 and 2015 Research Goals, FreedomCAR and Fuel Partnership Plan, U.S. Department of Energy, March 2006, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf
3. Sources: VHSS Tables 4-4 and 4-7, see VHSS (sections 4 F and 4 H) for discussion
4. For >300 mile range (status assumes 5 kg)
5. Assuming 250,000 units per year

As discussed in the VHSS section, gravimetric energy density of both 350 and 700 bar compressed storage can meet the 2010 DOE target of 2.0 kWh/kg and 6% weight fraction, but cannot meet the 2015 targets of 3.0 kWh/kg and 9%. For volumetric energy density, 700 bar compressed storage can approach the 2010 target of 1.5 kWh/l but cannot meet the 2015 target of 2.7 kWh/l (350 bar cannot come close to either target). Cost for either type of system is significantly higher than the DOE targets by factors ranging from to 2.5X for a 350 bar system compared to the 2010 target up to 7.5X for a 700 bar system compared to the 2015 target. Unfortunately, without a major breakthrough, no major improvement in these cost levels is foreseen at this time.

Customer Acceptance

From a purely vehicle perspective, there appear to be no expected issues with customer acceptance of fuel cell vehicles, if they can meet the FreedomCAR goals and become available at prices competitive with comparable conventional vehicles. Several manufacturers expect future generations of vehicles to meet all their technical objectives, including 15 year life, 300/350 miles driving range and -30/40^{o}C cold start capability. Assuming that all of these goals and expectations are met, these FCEVs should provide essentially equivalent functionality with conventional vehicles, with no compromises, and will have added advantages in smoothness, quietness and a positive environmental image.

As has been the experience with other “alternative” fuels, customer acceptance will be highly dependent on the availability of reasonably priced, conveniently located, easily accessible, simple to operate hydrogen fueling stations, that are not dissimilar from conventional self service gasoline stations. In addition, the customer must perceive hydrogen (hydrogen fuel, hydrogen fueled vehicles and hydrogen refueling) to be as safe as gasoline, which is likely to require consumer education programs.

Hydrogen Infrastructure

Many OEMs say that the most significant issue with fuel cell vehicles is the lack of a hydrogen infrastructure, and the lack of a firm commitment to deploy a hydrogen infrastructure. They have had generally bad experience in trying to deal with the very difficult “chicken and egg” problem associated with “alternative” fuels, and have said that energy companies and/or governments must take a strong leadership role in making the case for hydrogen as an automotive fuel, and in the planning and deployment of a hydrogen infrastructure – otherwise it will not happen.

Even if OEMs are able to successfully develop a technically viable and cost competitive FCEV, they will not be able to develop a viable business case for, nor commit to, volume production of FCEVs without a hydrogen infrastructure, or a firm commitment to deploy one.

ARB has indicated that the hydrogen infrastructure issue will be addressed in more detail in a separate report.

e) Prospects for Advancement

Almost all major OEMs appear to be in agreement that hydrogen fuel cell powered vehicles will eventually replace a portion of conventional light duty ICE vehicles, and many of them have invested heavily, for ten or more years, in a major effort to develop commercially viable fuel cell vehicles. The primary motivation is ensuring the long term success of providing light duty personal transportation on a global basis – which is their core business.

These companies see hydrogen fuel cell vehicles as the best known technology to simultaneously solve the three challenges of (1) zero exhaust, evaporative and greenhouse gas emissions, (2) high efficiency, and (3) diversification of automotive fuel supply in the long term – with minimum customer compromises versus conventional ICE vehicles. To achieve these goals, hydrogen must be produced on a sustainable basis, with no greenhouse gas emissions or use of fossil based feedstock.

Many automotive companies continue to commit hundreds of engineers, large well equipped dedicated facilities, and budgets approaching hundreds of millions of dollars per year – all devoted to developing commercially viable hydrogen FCEVs. In addition to the vehicles identified above, most of them are researching and developing next generation fuel cell propulsion systems and vehicles.

At some OEMs, there is a concern about the time between the introductions of successive generations of fuel cell propulsion system technology and vehicles. It takes several years after finalizing a design concept to fully engineer the vehicle systems, build prototypes, complete validation testing, build the production tooling, and launch the vehicle. If the design concept for a next generation vehicle program must be finalized before the present generation has been evaluated by customers, and not enough improvements leading toward the technical and cost goals have been identified and validated to make the next generation worthwhile, inefficiencies are incurred that waste precious resources and slow the overall rate of progress. Advanced engineering organizations normally consider that achievement of a major portion of the shortfall of current status below the goals (often 50%) is necessary to make a next generation vehicle program worth not only the time and cost, but also worth dedicating a large number of scarce technical employees who possess the necessary qualifications and skills.

Several of the leading major OEMs who have massive efforts underway note that FCEV technology has been progressing at a rapid rate and they do not foresee any insurmountable technical barriers. In their view, it is only a matter of the time needed to develop several more generations of fuel cell system technology until the vehicles become commercially viable.

Some of the major OEMs have said they are responding to global customer concerns and are likely to first introduce FCEVs wherever support for them and the associated hydrogen infrastructure materializes.

Some OEMs have said that substantial government assistance will be required to overcome the near term and longer term business risks/costs associated with FCEV market introduction, including financial incentives for OEMs, suppliers and customers, fleet purchases at meaningful volume levels, and support for uniform vehicle codes and standards.

In the Panel’s view, sustaining the high level of effort underway by many of the major OEMs to develop commercially viable FCEVs will be dependent on whether they can continue to make acceptable progress in overcoming the technical, cost and fuel availability problems, and to what extent the general public becomes more knowledgeable, interested and concerned about issues of pollution, greenhouse gas emissions and energy independence.

As discussed in the VFCS section (5), the Panel is concerned that the FreedomCAR $30/kW fuel cell power system cost goal may not be feasible, given the difficulty of simultaneously achieving adequate FC stack durability with lower MEA catalyst loading, higher current density and the upward trends in the price of platinum. Continued engineering innovation and additional scientific invention will be necessary to successfully reach commercialization, in the Panel’s opinion.

A major issue will be the availability of adequate hydrogen fueling infrastructure and hydrogen fuel at affordable costs, as discussed above. California's infrastructure efforts are a good start, but other states are not as far along. It may be that the first commercially successful hydrogen infrastructure will be developed outside the United States, especially given the high prices of gasoline in other countries, in which case the introduction of the first commercially viable FCEVs could occur outside the United States.

f) Introduction Timing

Several major OEMs have stated that the FCEV will be ready for volume production by 2015 but have serious doubts about the hydrogen infrastructure. They have indicated that as with other alternative fuels, there is a "chicken and egg" issue that must be resolved – and, as can be seen with today's far simpler ethanol or E85 availability issue, they have not been able to single-handedly resolve "alternative" fuel infrastructure issues.

Some major OEMs have suggested that there is very little technical or economic benefit associated with each of them building more than a few 10's of vehicles for engineering evaluation, or at most perhaps a few 100's of vehicles for market development, or public relations, until the goals are met. That is until FCEV technical maturity achieves the key goals for performance, durability, and cost (assuming high volume), and a firm hydrogen infrastructure plan is agreed to by all the key stakeholders. Producing larger numbers of pre-commercial vehicles could be counterproductive since it could require manufacturers to divert resources from the FCEV research, development and engineering urgently needed to attain the goals for commercially viable technology – thus slowing technical advancement and the eventual introduction of commercially viable FCEVs.

FCEVs have achieved demonstration volume levels (100s/year), and the Panel's view is that given the massive effort underway, are likely to reach pre-commercialization (1,000s/year) within the next 5 years, as long as the leading major OEMs and fuel cell suppliers continue to make substantial progress toward solving the technical and commercial issues, and can see a path toward availability of a hydrogen infrastructure. However, FCEVs will not reach early commercialization (10,000s/year) until achievement of the technical and cost goals is considered within reach at several OEMs and a suitable hydrogen infrastructure becomes available in some region of the world.

B. Advanced Technology Vehicles (ATVs) – Non-ZEV

The Panel also investigated five types of Advanced Technology Vehicles (ATVs), which utilize advanced technology also used in FPBEVs and/or FCEVs. Besides helping to accelerate the introduction of FPBEVs and/or FCEVs, these ATVs are playing or could play a significant supporting role in attaining the environmental and energy-strategic goals addressed by ZEVs.

Although not discussed in detail in this report, ICE vehicles that run on compressed natural gas (CNG) also provide some of these benefits. The extensive experience gained by OEMs in developing and producing CNG vehicles over many years has made important contributions to both ZEVs and ATVs. From a vehicle standpoint, CNG technology was used in developing onboard gaseous hydrogen storage systems (FCEVs and H2ICVs) and in developing ICE modifications necessary for running on hydrogen (H2ICVs). In addition, experience with gaseous fuel infrastructure has been gained that is applicable to a hydrogen infrastructure.

1. Neighborhood/Utility/City Electric Vehicle (NEV-UEV-CEV)

Several types of BEVs have been developed that have limited performance compared to conventional vehicles, allowing smaller motors and inverters and less powerful batteries in order to achieve lower manufacturing costs and better customer affordability. In particular, they have slower acceleration and lower top speed compared to conventional vehicles, making them marginal for safely or comfortably operating with conventional vehicle traffic on high speed roads that require those capabilities. They are not suitable for use on all roads and thus have limited ability to serve as a replacement for a conventional vehicle.

California ZEV classifications of BEVs are based on driving range, and not on performance. These classifications are NEVs (neighborhood electric vehicles), Utility Electric Vehicles (UEVs), City Electric Vehicles (CEVs) and Full Function Electric Vehicles as shown below:

Table 6-12: California ZEV Definitions[1]

ZEV Tier	**Common Description**	**ZEV Range[2]**
NEV	NEV	no minimum requirement
Type 0	Utility Electric Vehicle	< 50 miles
Type I	City Electric Vehicle	50 – 99 miles
Type II	Full Function Electric Vehicle	100 + miles
Type III	Fuel Cell Electric Vehicle	100 + miles[3]

1. Source, page 89, The California Low-Emission Vehicle Regulations, January 1, 2006, http://www.arb.ca.gov/msprog/levprog/cleandoc/cleancompletelev-ghgregs11-7.pdf
2. Urban dynamometer driving schedule
3. Also must be capable of refueling in <10 minutes (95% of rated energy capacity)

Some NEVs are similar to an electric golf car but can achieve top speeds between 20 and 25 mph. Vehicles that can travel 20 mph or faster are considered motor vehicles and are subject to federal regulations. In 1998 the National Highway Traffic Safety Administration (NHTSA) established a new classification for low speed motor vehicles, to (1) eliminate conflicts between local, state and federal regulations for these types of vehicles, and (2) standardize requirements for manufacturers and therefore encourage efficient production of small vehicles (including BEVs) for use in controlled locations (e.g., planned communities, college campuses, etc.) as well as certain public roads.

In about 45 states NEVs can operate on public roads with posted speed limits of 35 mph or less if they meet Federal Motor Vehicle Safety Standard 500[8] (FMVSS 500) for low speed vehicles. FMVSS 500 defines low speed vehicles as those that have 4 wheels, are capable of 32 km/hr (20 mi/hr), are speed limited to 40 km/hr (25 mi/hr), and have a Gross Vehicle Weight Rating (GVWR) less than 1,361 kg (3,000 pounds). The standard requires that these vehicles be equipped with headlamps, turn signal lamps, tail lamps, stop lamps, reflectors, rear view mirrors, parking brake, automotive windshield, seat belts, and VIN number.

In this section, all BEVs with lower performance (i.e. acceleration and top speed) than conventional vehicles are considered to be either NEVs if they meet FMVSS 500 or CEVs if they have a maximum speed of over 25 mph. CEVs can operate on all public roads and must meet crash requirements and all other Federal Motor Vehicle Safety Standards (FMVSS), but

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[8] Source: NEV; http://www.nhtsa.dot.gov/cars/rules/rulings/lsv/lsv.html and http://avt.inl.gov/pdf/nev/changes.pdf

compared to FPBEVs, they may be smaller, have less driving range, and/or fewer features and passenger comforts. As the name suggests, they are intended for urban driving and are particularly well suited to European and Japanese city centers. They are not well suited to freeway driving due to their performance limitations.

a) Manufacturers/Vehicles/Specifications/Performance

Examples of NEVs include Club Car Pathway, Columbia Par Car, Dynasty IT, Frazer-Nash City Car, TH!NK Neighbor (Ford Motor Company), and GEM (Global Electric Motorcars, DaimlerChrysler). Several recent NEV entries into the US market are the ZX40 and ZENN. The ZX40 is being imported from China by the Miles Automotive Group. It is available in either 2 or 4 passenger versions. The specifications and performance of many of these vehicles are shown in Appendix K.

The manufacturer's suggested retail price (MSRP) for the GEM ranges from $6,795 for the standard e2 two-passenger model to $12,495 for the standard e6 six-passenger model. The MSRP for the ZX40 is $14,800 and the ZX40s is $16,500. The MSRP for the ZENN is between $12,500 and $14,995. For reference, some of these NEV prices approach the price of a Honda Civic Coupe, which has a MSRP of $15,610, achieves 30 mpg city/40 mpg highway labels, and is a full function vehicle meeting all FMVSS requirements (Sources: manufacturer's websites, Automotive News, NADA Price Guide).

Drivers who can use NEVs for short trips instead of conventional vehicles reduce exhaust emissions significantly. This is because a conventional vehicle cold start contributes a very large proportion of the total exhaust emissions on a short trip. On a vehicle basis NEVs do not consume any hydrocarbon based fuel (gasoline, diesel, CNG, propane, ethanol, etc.) and create CO2. However, their limited performance means that they are not likely to be driven as many miles and thus the improvement in fuel consumption and CO2 production is not as great as the improvement in exhaust emissions, since fuel consumption and CO2 production are nearly proportional to mileage (e.g., if they substituted for half of the trips of a conventional vehicle, they would have half as many cold starts, and therefore almost half the exhaust emissions, but they would be more likely to be used for the short trips and not for the long trips, and thus the NEV probably would be driven much less than half of the mileage of the substituted conventional vehicle).

NEVs use simpler electric drive technology than FPBEVs and are usually less efficient, but as can be seen by the excellent consumption results of NEVs compared to FPBEVs (see Appendices J and K, Tables J-2, J-3, and K-2) this lower efficiency is offset by lower road loads (i.e., less mass, lower speeds, slower acceleration), and lower accessory loads, and thus they consume less energy per mile driven than most FPBEVs.

CEVs include the previous Toyota e-Com, Nissan Hyper-mini, Honda City-Pal, and the Ford TH!NK City.

b) Units in Operation

Annual NEV volume surged in 2001-2003, during the time they could earn four ZEV credits (2001-2002) and manufacturers tended to subsidize the cost of the vehicles to earn credits, but volume fell back when credits for NEVs were significantly reduced. GEM estimates there are more than 15,000 NEVs on the road in California and that this fleet represents the largest concentration of electric vehicles in the world.

c) Technical Issues

NEVs and CEVs have no major technical issues. They have major performance limitations and lack features compared to conventional vehicles, but these limitations are inherent in the design concept of these types of vehicles, which is to limit performance and feature content in order to achieve low costs and an affordable vehicle for the intended use of the product.

d) Commercial Issues

NEVs have no commercial issues, and GEM appears to have successfully created a profitable business with this technology. Although barriers to entry into the NEV market are very low, there is not an over abundance of competitors, since many weaker entries have dropped out. This situation has enabled GEM to achieve an adequate volume to sustain and grow their business, as the market naturally develops and the technology matures.

CEVs have not been successful in the U.S. despite several attempts, such as the Ford TH!NK City, Honda City-Pal, Nissan Hyper-mini, PIVCO Citi, and Toyota e-Com. As with FPBEVs, relatively high manufacturing costs combined with a small base of interested customers are the most likely reason why these types of vehicles failed to become commercially viable.

e) Prospects for Advancement

GEM is the major manufacturer of NEVs in the U.S. and it has become a successful stand alone business. Their vehicles presently use PbA batteries but the company continues to evaluate more advanced battery types. However, the cost of advanced batteries is still too high for use in NEVs. GEM continues to refine the technologies in their products to remain competitive in the marketplace.

GEM supports the creation of a next level CEV FMVSS standard, similar in concept to FMVSS 500 for low speed vehicles, to encourage the development of commercially viable CEVs, possibly with a maximum speed of 55 mph.

The Panel’s assessment of the advancement of NEVs is that they will continue to evolve and mature, but the rate of change will be paced by the cost of available electric vehicle technology. With the small size of the market for NEVs, there will not be much research and development funding available to support the advancement of NEV technology.

Given the difficulty of overcoming the cost challenges facing the development of commercially viable FPBEVs, as discussed above, the Panel agrees that the creation of standards, similar in concept to FMVSS 500, but applicable to CEVs, could help stimulate the development and introduction of CEVs. The Panel supports using a consensus standard process, ensuring all stakeholders have input. Possible ways to help keep CEV costs as low as possible, and therefore maximize the chance of achieving commercial success, are (1) restrict CEVs from operating on freeways and other high speed roads, (2) leave determination of an acceptable minimum driving range to the marketplace, and (3) encourage development of a standard that is universally accepted (maximum global harmonization).

f) Introduction Timing

NEVs have achieved early commercialization (10,000’s per year), but probably will not achieve mass commercialization (100,000's per year) until more low speed vehicle friendly communities are created, either "from the ground up" or by adapting existing communities.

CEVs might be reintroduced in the U.S. if the projects to commercialize limited performance city cars in Europe and Japan are successful, but this could be 10 or more years away. If a FMVSS for CEVs were developed, along the lines of the suggestion above, it might help stimulate interest in CEVs, but this process could take a long time.

g) Significance to ZEV Commercialization

DaimlerChrysler considers NEVs to be potentially significant relative to the commercialization of full performance FPBEVs for several reasons; (1) NEVs are sustainable – they are a commercially viable product without requiring manufacturer or government subsidies, although as with any new technology introduction, incentives would help to expand the market, (2) NEVs are conditioning customers – to learn to accept limited range and the requirement to plug the vehicle in, and (3) NEVs could lead to successful CEVs – as more sophisticated vehicles are demanded by customers and battery technology and cost gradually improve.

NEVs are helpful in solving the issues of emissions, greenhouse gas, and energy independence, but they use very simple technology. Most NEVs have DC motors and lead acid batteries, and they are not full function vehicles, so they have little direct synergy with the advancement of FPBEV technology.

However, they are the highest volume battery electric vehicles on the road today, they are affordable, and they are commercially viable. Thus, they can serve to condition and educate the public on the attributes of BEVs, and possibly stimulate interest in PHEVs discussed below.

The Panel envisions that CEVs could be more helpful in solving the issues of emissions, greenhouse gas, and energy independence, and they use more advanced technology, in some instances including advanced batteries. However, CEVs are not likely to be developed soon and/or far enough in advance to help FPBEV technology within the next 10 years. Longer term, CEVs could serve as a viable alternative to FPBEVs, especially as environmentally compromised and restricted access urban areas become more widespread.

2. Hybrid Electric Vehicle (HEV)

Hybrid electric vehicles (HEVs) are important to consider in the context of ZEVs and ATVs because (1) they are the only electric drive vehicles being sold in significant numbers and (2) they could become a basis for early PHEVs. A HEV contains a battery or ultra capacitor RESS, in order to be able to store electrical energy created during driving and selectively use it at a later time, as well as a conventional liquid or gaseous fuel tank. Most HEVs improve efficiency and reduce fuel consumption, especially in stop and go, low speed driving, which is typical of urban conditions, and as a result they have reduced exhaust emissions and produce less CO2.

The addition of the RESS and electric motor/generator(s) allows achievement of the HEV's efficiency improvement by one or more of several primary methods; (1) stopping the ICE when the vehicle is stationary (and during low speed braking or deceleration with some systems) and rapidly restarting it when needed (stop-start system), (2) capturing kinetic energy during braking or deceleration for use later (regenerative brake system) (3) forcing the ICE to operate at a more fuel efficient load point (as well as speed point with some systems) by simultaneously making it generate electricity for use later, and/or (4) adopting a less powerful but more efficient

ICE (e.g., downsizing and/or Atkinson cycle). Depending on the complexity of the hybrid system, energy that has been stored in the RESS by methods (2) and (3) can be used to: (A) rapidly restart the ICE, (B) provide torque smoothing to allow fuel shut off during braking or deceleration with the ICE rotating, (C) provide power to a planetary gear set to stop the ICE during braking or deceleration, or operate the ICE at a desired speed, (D) operate electric accessories when the ICE is stopped (e.g., climate control system, electric steering, etc.), (E) provide electric drive power assist to the ICE when needed, (F) provide an electric drive reverse, and/or (G) provide limited range low speed electric drive propulsion with the ICE stopped (EV mode). A sophisticated hybrid control system is used to determine the optimum combination of the available operating modes listed above during driving in order to achieve maximum fuel economy and provide performance and smoothness equal or better than a conventional ICE powertrain.

There are a wide variety of HEVs, either on the road today, being developed, or invented, ranging from simple 14 volt belt driven alternator systems to complex ~300 volt power split systems[9] capable of a few miles of low speed electric drive propulsion ("full" hybrids). These different types of HEVs have been described by many different names, including Series, Parallel, Split, Integrated Starter Generator (ISG), Mini, Mild, Full, Power Split, Two Mode, Type A, B, C, D, E, etc..

a) Manufacturers/Vehicles/Specifications/Performance

HEVs are, by far, the most successful electric drive vehicle technology on the road today in terms of availability and customer demand and are presently being produced by Ford, General Motors, Honda and Toyota as summarized in Appendix L.

Some of these HEVs have been certified as California ATPZEVs, which means they have electric drive capability and have met the Super Ultra Low Emission Vehicle (SULEV) tailpipe standard which is 90% cleaner than the average new 2003 automobile. In addition, they have near-zero evaporative emissions and their emission control equipment has a 15-year/150,000 mile warranty.

b) Units in Operation

There are nearly 1,000,000 HEVs on the road today around the world.

In the U.S., HEV growth accelerated rapidly in the 2003 – 2005 time frame, as new entries were introduced and existing entries were improved, but growth declined significantly in 2006 as shown below:

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[9] How an electric CVT power split hybrid works: http://eahart.com/prius/psd/

Table 6-13: HEV U.S. Sales[1]

Calendar Year	2003	2004	2005	2006
Ford Escape		2,566	18,797	19,228
Honda Accord		653	16,826	5,598
Honda Civic	n/a	25,586	25,864	31,253
Honda Insight	n/a	587	666	722
Lexus GS 450h[2]				513
Lexus RX 400h			20,674	20,161
Mercury Mariner			998	3,375
Toyota Camry[3]				27,336
Toyota Highlander			17,989	31,485
Toyota Prius	n/a	53,761	107,897	106,971
Total	47,525	83,153	209,711	246,642
Annual Growth	32%	75%	152%	18%[4]
Share of Industry	0.3%	0.5%	1.3%	1.5%

1. Sources: HEV volume, Electric Drive Transportation Association, http://www.electricdrive.org/index.php?tg=articles&topics=7, industry volume, Automotive News
2. Not including October – December 2006 sales
3. Not including December 2006 sales
4. 28% based on R.L. Polk & Co. data (254,545 vs. 199,148); source: Automotive News, March 5, 2007

Since the Panel was asked by ARB to forecast future volumes of ZEVs and AVTs, this successful real world experience of commercializing electric drive technology provides some interesting and relevant background.

Much has been written about the appeal of HEVs and what motivates a customer to pay a price premium to buy one, in addition to the usual factors involved in choosing a vehicle, such as brand reputation, perceived quality, status/image conveyed by ownership, dealer experience, appearance, comfort, features, safety, performance, utility and function. There seem to be several distinct HEV factors which can be involved in the purchase decision, besides the fact that there are no compromises versus a conventional vehicle. Depending on the views of the individual customer and the attributes of the specific vehicle being considered, these can include, (1) expected fuel cost savings (highly influenced by gasoline prices at the time of consideration, as noted in the next paragraph), (2) newness of the technology, (3) societal benefits (improved air quality, reduced greenhouse gas, and/or more energy independence), (4) tax incentives, (5) preferential treatment (HOV lanes, tolls, parking, etc.), and (6), ability of others to identify the vehicle as a HEV. Should these factors diminish or increase in importance, it remains to be seen how future HEV growth and market share will be affected.

Regarding the sensitivity of HEVs to fuel prices, CNW Marketing Research recently reported that a year ago (2005), when fuel prices were high, 30% of car shoppers considered buying a HEV and said they were willing to pay a premium of $2,500 over a conventional vehicle. In December 2006 consideration was only 12% and the price premium had dropped to only $1,153. Directionally consistent with this market research, HEV sales were 19,000 in November 2006, compared to 32,000 in August 2006 when gas prices nationally peaked. (Source: Rick Popely, Chicago Tribune, December 20, 2006).

c) Technical Issues

There are no technical issues that preclude HEVs from being an acceptable product for the customer. However, most OEMs have said that cost must be reduced to make HEVs viable, or more viable, from a commercial standpoint.

Remaining issues are vehicle package constraints and the vehicle weight increases from adding the HEV battery, motor(s) and inverter. Although the present NiMH battery-based systems perform quite well, greater SOC operating range for a given battery capacity would allow use of smaller-capacity and thus lower-cost and -weight batteries. The higher gravimetric power density and “stiffer” discharge and charge power characteristics of the high power Li Ion batteries currently being evaluated for HEV applications is expected to enable advances in this area beginning within a few years (see the VESS section (3C) for a more detailed discussion.). Determining power battery calendar life when combined with cycle life is a complicated and challenging task that can vary considerably based on temperature.

Different types of HEV architectures tend to result in different costs, fuel economy benefits, towing capabilities, reverse grade climbing ability, and/or all electric drive capability/range. The leading manufacturers of HEVs are taking different approaches in attempting to optimize one or more of these attributes in their commercial and developmental HEV products.

d) Commercial Issues

Vehicle Cost

Despite widespread availability and initial success, cost is still a major issue facing commercialization of HEVs. Design maturity, increased component standardization and high volume manufacturing processes are expected to further reduce cost, but additional cost reductions are required to make HEVs cost competitive with modern fuel efficient ICE technologies (e.g., direct injection gasoline and common rail turbo diesel).

On an incremental unit cost basis, there are significantly different perspectives among the OEMs. For example, Toyota executives have stated that the Prius is profitable. Based on this, the Panel would have to conclude that Toyota’s incremental cost (labor, material, and direct overhead) required to produce another Prius is less than their revenue from selling the Prius to the dealer. Many other OEMs who either produce HEVs, or have studied HEVs, say that this cost is equal or greater than vehicle revenue, and therefore HEVs must be sold at breakeven or a loss. In this case, the manufacturer may have to subsidize the loss on the HEV, as well as the lost profit on his conventional vehicles for which some portion of the HEVs substituted. The Panel envisions several possible explanations for this difference in perspective, including different volume assumptions (Toyota is the market leader), different technology, different suppliers, or favorable exchange rates (Prius’ sold in the U.S. are made in Japan).

On a fully accounted basis, where all costs in addition to incremental costs are considered, including engineering design and development, manufacturing plant and equipment, and allocated company overhead, the Panel is doubtful that “full hybrids” provide a positive return to OEMs. This is a major reason cited in the past by some automakers and why some have been slow to introduce HEVs. However, the competitive nature of the marketplace, as well as the expected high cost of diesel technology (now popular in Europe and often compared with HEVs) that can meet future U.S. emissions regulations, is pressuring almost all manufacturers into introducing HEVs into the U.S. market. In addition to “full” hybrids, other types, such as mild and mini hybrids are being pursued by several manufacturers as less costly alternatives.

Limited Component Supply Base

Many OEMs have indicated that the supply base for the majority of unique HEV components is still immature, which means that normal levels of automotive supplier competition, which drives technology advancement and cost reduction, is lacking. This situation also can allow higher than normal levels of supplier profit mark up to exist.

As the number of product offerings and volumes grow, efforts are underway by the manufacturers to increase and geographically diversify the supply base. One example is Delphi's recent announcement that it will provide battery pack and cooling systems for the 2008 Ford Fusion Hybrid and Mercury Milan Hybrid.

e) Prospects for Advancement

With four major manufacturers presently offering HEVs (Ford, General Motors, Honda and Toyota), and several more who have announced plans to offer them in the near future, including BMW, DaimlerChrysler and Nissan, it is clear that this electric vehicle technology is advancing rapidly, despite the cost issue discussed above.

The large number of vehicles being produced and sold, by many different manufacturers, will encourage the automotive supplier industry to aggressively pursue advancements in technology and cost for all unique HEV components, including power batteries, electric motors, inverters, control modules with their software control algorithms, and supporting systems, such as regenerative brake, electric steering and electric climate control.

However, variable cost remains a major issue, and gasoline prices have a significant impact on HEV volume, so as additional HEV products enter and fragment the market, tax incentives expire, and gasoline prices remain at current levels, maintaining or achieving sustainable profitability levels of individual HEV entries could be challenging. If this situation continues, implementing the needed HEV cost reductions rapidly is critical to avoid choking off growth and limiting the positive benefits this technology can have on the total vehicle fleet.

f) Introduction Timing

After the initial December 1997 introduction of the Toyota Prius in Japan, HEVs offerings expanded and quickly achieved mass commercialization volumes (100,000s/year) by 2004. In 2005 over 200,000 units were sold in the United States (over 300,000 units worldwide). In contrast to FPBEVs, the Panel considers the reasons for this success to be due to two important factors; (1) existing battery technology capability and cost levels were more suitable for the application, and (2) the mass-market customer did not have to accept vehicle performance, functional or convenience compromises.

g) Significance to ZEV Commercialization

Not long ago, manufacturer's assessment of HEV technology varied greatly, ranging from Toyota's view that all vehicles will become HEVs in the not too distant future, to some manufacturers having said HEVs don't make sense and that other powertrain technologies are more cost effective, such as direct injection gasoline engines and common rail turbo diesels.

With more and more manufacturers developing HEVs, their assessment of the significance of HEVs appears to be getting stronger. Interestingly, at a speech given at the November 2006 Los Angeles Auto Show (the 100th anniversary), General Motors' CEO Rick Wagoner stated: "I have no doubt that, when the L.A. Auto Show celebrates its 125th anniversary, it will look back at this time as a period of great change… and the formative years of the age of electrically driven vehicles."

The Panel believes HEVs are undoubtedly the most important bridging technology for ZEVs due to their success in the marketplace, besides providing rapidly growing environmental and fuel savings benefits. In the case of FPBEVs, they will contribute improvements in electric drive motors, power conversion electronics, electrically operated accessories and vehicle systems controls. They are likely to lead to plug-in hybrid electric vehicles, discussed next, which would also contribute to energy battery development. In the case of FCEVs, almost all of which are HEVs, they will contribute advancements in all areas of electric vehicle technology other than the fuel cell and hydrogen storage systems.

3. Plug-in-Hybrid Electric Vehicle (PHEV)

From the customer's perspective, a plug-in hybrid electric vehicle (PHEV) combines all the benefits of a BEV with all the benefits of a HEV. Compared to a HEV, a PHEV adds the capability to connect the vehicle to the electric grid while parked and charge an energy battery, similar to a BEV. It then depletes this stored energy during driving to displace the use of ICE fuel. The attributes of a PHEV could make it attractive to the mass-market customer – like BEVs, they can reduce fuel cost and be refueled at home, and like HEVs they can be used for long trips, they can be refueled quickly when necessary and "plugging in" is not required to operate the vehicle. Compared to a HEV, they provide reduced exhaust emissions, fuel consumption and CO2 production.

As is the case with HEVs, there can be several different types of PHEVs. The main differentiators from a customer's perspective are: (1) the quantity of electrical energy from the grid that can be stored on the vehicle, typically overnight, and be available the next day to displace the use of ICE fuel, (2) whether or not the vehicle can operate in electric propulsion mode (EV mode), similar to a BEV, and (3) for those vehicles having EV mode capability, whether EV mode has limited performance (i.e., acceleration and top speed), like "full" HEVs, or does not have performance limitations, like FPBEVs – or has performance somewhere between "full" HEVs and FPBEVs. In general, PHEVs that can operate in EV mode will have all electric range (AER) proportional to the amount of energy from the grid that can be stored in the battery system.

A PHEV with EV mode capability could function temporarily as a true ZEV if the trip length was within the vehicle's remaining AER. However, this would require that the vehicle has no performance limitations while in EV mode applicable to the trip being taken (e.g., either no freeway driving required or fully capable of safe freeway driving in EV mode) and the ICE did not start.

a) Manufacturers/Vehicles/Specifications/Performance

Presently, the only known PHEV that has been developed by a major OEM and is undergoing limited fleet testing on public roads by customers is DaimlerChrysler's Sprinter Van PHEV. EnergyCS and EDrive Systems have converted several Toyota Prius HEVs to PHEVs by replacing the original power battery system with an energy battery and adding an on board charger. Sacramento Municipal Utility District (SMUD) and Southern California AQMD are currently testing several converted Toyota Prius PHEVs. The New York State Energy and Research Development Authority (NYSERDA) is also testing various "one-off" PHEV conversions by third parties, including Toyota Prius, DaimlerChrysler Smart, Honda Civic and Ford Escape.

Table 6-14: PHEV Demo Specifications[1]

Vehicle	**ICE** --Displacement --Power (kW)	**Battery Rated Capacity**	**Battery SOC** –Depletion Mode –Sustaining Mode	**Motor**[2] (kW)	**Curb Weight** (pounds)
Sprinter Van PHEV[3]	2.3 l 150	14 kWh[4]	100 – 35%[5] 45 -- 35%	70/90	5860
Prius PHEV[6]	1.5 l 57	9.9 kWh[7]	100 – 27%[8] 31 – 23%	20[9]/50	3200

1. Source: manufacturer data
2. Continuous power rating/peak power rating (e.g., 18 seconds)
3. DaimlerChrysler conversion
4. SAFT Li Ion (102 cells, 41 Ah, derated by 7%)
5. Usable energy of 11.2 kWh versus rated capacity of 14 kWh
6. EnergyCS conversion of 2006 model for ETA
7. See Appendix H for discussion
8. Usable energy of 7.2 kWh versus rated capacity of 9.9 kWh
9. Battery – traction motor controller DCDC link – governs power delivered by battery

The performance of these vehicles is shown below:

Table 6-15: PHEV Demo Performance[1]

Vehicle	**Payload** (pounds)	**Acceleration** (seconds, 0 to 60 mph)	**Electric Range** (test cycle)	**Fuel Economy Improvement** (test cycle)
Sprinter Van PHEV[2]	2690	~22	20 miles (NEDC)	20% (NEDC) 10 – 50% ("Real World")
Prius PHEV[3]	680	<12.5	Up to 29 mi	40 – 140% (city, highway and urban driving)[4]

1. Source: manufacturer data, unless noted
2. DaimlerChrysler conversion
3. EnergyCS conversion of 2006 model for ETA
4. SMUD testing, average trip length 14.8 miles

The results of these demonstration vehicle tests show significant potential for improved gasoline fuel economy using the PHEV architecture. However, unauthorized conversions by third parties voids the original OEM's warranty, as is typically the case with any significant vehicle modification.

b) Units in Operation

DaimlerChrysler has built six Sprinter Van PHEVs and EnergyCS has built 13 Toyota Prius conversion PHEVs.

c) Technical Issues (in addition to HEVs)

Energy Battery

The major technical issue with PHEVs is the ability of the energy battery to endure the large number of deep cycles the battery must deliver over the life of the vehicle. As discussed in the

VESS section, this number is substantially higher for PHEVs than for FPBEVs and thus represents a new dimension in deep cycling requirements. The gravimetric power density of a PHEV battery also needs to be higher than that of a FPBEV battery, but it does not need to be as high as the power density of a HEV battery. Gravimetric energy density, although still important for PHEV batteries, is not as critical as for FPBEV batteries.

A PHEV can operate the battery system in four main types of modes: (1) a grid charging mode, which occurs when the vehicle is parked, is plugged into the grid and is charging the battery (2) a charge depletion EV only mode, which consists of discharging the battery during driving after being charged by the grid from a full SOC to a predetermined low SOC, allowing regenerative brake charging but not ICE charging (the ICE does not supply power to the wheels -- similar to a FPBEV), (3) a charge depletion HEV mode, which consists of discharging the battery during driving after being charged by the grid from a full SOC to a predetermined low SOC, allowing regenerative brake charging but not ICE charging (the ICE does supply power to the wheels when needed – similar to a HEV), and (4) a charge sustaining mode, which consists of continuously varying the battery SOC between an upper and lower limit during driving, allowing both regenerative brake charging and ICE charging, the same as with a HEV, but around a much lower average SOC.

Battery cycle life when first operating in a charge depletion mode and then switching to operation in a charge sustaining mode around a relatively low average SOC is not completely known at this time. However, in the first laboratory tests, both NiMH and Li Ion medium energy/medium power batteries are approaching 2000 deep cycles when cycled in this mode. Because a PHEV has an ICE to meet a portion of the vehicle's range requirement and power demand, its battery can be smaller than a FPBEV, thus reducing the battery cost, weight and volume issues. However, because of their lower capacity, PHEV batteries are more likely to be fully discharged daily than FPBEV batteries, making cycle life requirements more severe, as discussed in Sections 3.B and 3.C.

Some testing of Li Ion and NiMH batteries on a simulated PHEV cycle developed by the Electric Power Research Institute (EPRI) has been conducted by Southern California Edison with encouraging results, as presented at the ZEV Symposium and discussed in the VESS section (3.C.2 and 3.C.5). However, additional battery testing will be required and will impact the introduction timing of PHEVs. As with all components and systems in a production vehicle, OEMs will want to ensure they have a PHEV battery system test cycle that has been validated to be representative of a wide range of actual driving and climatic conditions (typically at the 90th percentile) and that the test cycle has been proven to accurately detect failure modes. Since they are responsible for customer satisfaction and vehicle warranty, they will expect their battery system suppliers to conduct cycle life testing of PHEV battery systems using validated test cycles until the end of life, or, if that is not possible, a substantial portion of life with a conservative end of life projection. Calendar life is another concern, especially for Li Ion battery technology, and it requires a long evaluation period. Battery warranty exposure for today's HEVs is 8 years, and rises to 15 years in order to qualify as an AT PZEV. The Panel was not able to obtain actual warranty costs, but OEMs have described battery warranty as "costly and a great risk for OEMs".

Other issues with a larger energy battery are the ability to find acceptable package space and accommodate the weight increase in some existing vehicle architectures, most likely existing or planned HEVs, which already may be straining to package both the ICE and electric drive systems.

Unlike FPBEVs and HEVs, USABC technical and commercial goals for PHEV battery systems are not yet available, so it is challenging to accurately compare the status of the various battery technologies to the appropriate vehicle requirements. PHEV battery chemistry alternatives, cycle life, cost and other issues are discussed in more detail in the VESS section (3 C – E).

Other Technical Issues

PHEV definitions and standards for testing emissions and fuel economy will have a major impact on the design and performance of PHEVs. For example, the design of the PHEV will depend on whether or not EV mode is necessary, and, if so, the distance of AER that may be required to meet certain goals. Also, whether AER should be measured in EV mode only, or, alternatively, a "blended" operating strategy, similar to an HEV, which specifies the equivalent electric range, sometimes called "virtual" AER, associated with charge depletion mode (fully discharging the battery after being fully charged by the grid), before switching to conventional hybrid charge sustaining mode.

Test standards that require a PHEV to follow the UDDS trace in EV mode to measure AER implies that in actual driving the vehicle can start the ICE and switch to HEV mode if the power requirement is greater than was needed to follow the UDDS trace. The UDDS test cycle contains maximum acceleration rates of 3.3 mph/sec, which are not severe, due to dynamometer capability limitations when the cycle was developed in the late 1960's, and the vehicle's air conditioning system is not operating. Since both of these conditions are not typical of actual vehicle usage, it is likely to cause a discrepancy between "tested" AER and actual AER and result in customer dissatisfaction. Customer dissatisfaction associated with actual results being less than tested results is the main reason that the 5-cycle method to establish fuel economy labels will be required with 2008 MY vehicles. The 5-cycle method includes the US06 test with acceleration rates of 8.4 mph/sec and the SC03 test with air conditioning operating.

Initially, PHEVs could be derivatives of HEVs in order to keep the manufacturer's development cost and risk at an acceptable level, and, therefore, to stimulate introduction. AER test requirements that specify acceleration, such as the one described above to follow the UDDS drive trace in EV mode only, or similar requirements with more severe cycles such those found in the 5-cycle method, could result in some, or possibly all, PHEVs having to adopt a larger electric motor and inverter than the base HEV from which they could be derived. Similarly, requirements that completely preclude starting the ICE on driver demand by simply pressing down the accelerator pedal, such as an "EV only" mode switch, will necessitate larger motors and inverters than the base HEVs to insure vehicle safety in emergency maneuvers.

Several manufacturers have said that vehicle emissions will be a difficult issue to resolve if the internal combustion engine in the PHEV is forced to perform a cold start under high load, such as in the case of a PHEV being started and driven in EV mode and suddenly needing to start the ICE to insure vehicle safety in an emergency maneuver. Today's "full" HEVs start the ICE when the driver turns the key on and operates it at low rpm, under low load, and with high exhaust gas temperature to light off the catalysts. It has been suggested that a PHEV can use grid energy while plugged in to keep the engine coolant and catalyst warm (albeit at some loss of efficiency), but there is no guarantee that the driver will always plug in the vehicle. In most places, plugging in is also not possible for a driver who starts out in EV mode and makes short trips with long stops in between while away from home during the day.

Evaporative emissions are another issue that has been raised if EV mode AER is used. If the vehicle is plugged in every day, is driven only for short trips, and the ICE does not start up and go into charge sustaining HEV mode, there is no purge method available.

A different PHEV approach is to utilize series hybrid architecture. Instead of a large ICE and relatively small energy battery in a parallel configuration, it uses a small ICE and relatively large energy battery in a series configuration. This concept, sometimes called a range extender hybrid, is basically a FPBEV with a small ICE powered generator (or fuel cell system) to periodically recharge the battery when necessary or to supply continuous power during long trips. Unlike parallel hybrids, the ICE has no mechanical connection to the wheels. In order to be capable of long trips and satisfy customers, the ICE/generator must be sized to provide adequate power output at the wheels for sustained cruising during maximum load conditions (e.g., 75+ mph speeds, strong headwind, higher altitude, air conditioning operating in high ambient temperature, etc.) plus some amount of battery charging to keep the battery adequately charged and allow battery assist when necessary for hill climbs and other temporary situations requiring greater power. This type of PHEV can operate as a full performance ZEV, during the times that the ICE is not operating, and can avoid the cold start emissions problem discussed above, but it requires a relatively large energy battery and a large, full performance, electric drive propulsion system, similar to a FPBEV or FCEV. Compared to a FPBEV, it can use a smaller, more affordable battery and it does not have the driving range limitation issues. Compared to a parallel PHEV, it can operate the ICE at the optimum combination of speed and load necessary to achieve maximum efficiency (except for a short time for warm up), however, this efficiency advantage is reduced to some degree by a combination of generator, battery charging, battery discharging, and electric drive system efficiency losses before reaching the wheels. Compared to some other parallel hybrid systems, it is probably not suitable for vehicles intended for trailer towing.

Agreed upon definitions and standards for testing emissions and fuel economy of PHEVs are likely to be complicated and do not yet exist. Ideally they will maximize commonality with existing standards and will need to be established before serious design and development of PHEVs can begin. In addition to modeling efforts underway, manufacturers will need to deploy PHEV demonstration fleets with a variety of operational characteristics to gather real world on-road customer data in order to provide meaningful input to proposed definitions and standards prior to being finalized. Furthermore, truly representative battery cycle life testing, which takes a long time to conduct, cannot be started until agreement is reached on definitions and standards for PHEVs.

d) Commercial Issues

Vehicle Cost

A PHEV battery must have a much higher energy capacity than a HEV, which makes the cost issue more challenging. As is the case with FPBEVs, battery system costs are the major issue; however, compared to a FPBEV the customer payback of the battery is improved significantly. This is due to (1) being able to use a smaller battery and (2) being able to discharge the battery fully, because of the capabilities provided by the ICE, which results in a higher proportion of the battery capacity being used every day to displace conventional fuel.

If vehicle operational requirements require a higher power electric drive system, such as to operate the vehicle safely in EV mode, without ICE assist, larger, more costly motors and power electronics than the base HEV from which the PHEV is derived, will be required. Also, fixed costs will increase due to the need for these unique components, a significant redesign of the vehicle to accommodate the larger system and the associated validation testing.

Commonality and standardization of components would help keep fixed costs down for PHEVs, such as commonality of motors and power electronics with the base HEV from which early PHEVs could be derived. A less likely, but significant, cost opportunity is energy battery standardization, at least at the cell level, which would allow much higher volumes per cell manufacturing facility and reduce battery costs.

Customer Acceptance

The Panel expects customer interest and acceptance of a PHEV to be good. Depending on the final label methodology, high fuel economy numbers are likely to get mass-market customer's attention, and this could be particularly effective coupled with the significant 2008 MY reductions in label values. Fuel costs can be reduced by plugging into the grid, and unlike FPBEVs, the vehicle does not have range issues and does not need to be plugged into the grid to be able to operate. Customers can also have the satisfaction of knowing they are helping to reduce exhaust emissions, petroleum consumption and the creation of CO2. Other advantages are fewer trips to the service station, and if the vehicle has EV mode, quiet electric drive and the security of being able to do some limited driving during a fuel shortage. Ultimately, however, vehicle price will be a major factor in establishing mass-market customer appeal and therefore market success of the PHEV.

The fuel economy improvement of a PHEV varies with trip length, and, as can be seen from Table 6-15, varies greatly. From the customer's standpoint a direct way to assess the fuel savings value provided by the PHEV, and enable him/her to determine how that relates to the price premium of the vehicle, is to compare the cost of electric energy stored overnight and used the next day with the cost of the petroleum fuel displaced in normal HEV charge sustaining mode.

As with fuel economy, there are too many variables involved to make it possible to determine precisely what results a particular individual will achieve, but it is useful to make some assumptions and give an example. Using the Prius PHEV data shown above as a baseline, 7.2 kWh of usable electric energy would provide about 29 miles of electric drive range. This would cost the customer about $0.55 for the electricity and save him/her about $1.85 in gasoline (assuming $3/gallon) for a net fuel cost savings of about $1.30 per day or about $475 per year, assuming the battery is completely discharged every day.

From Table 3-13 in the VESS section, a 30 Ah cell Li Ion battery for PHEVs having a 10 year life and rated capacity of 9.9 kWh is projected to cost about $7,300 at a reasonable initial vehicle introduction volume level of about 14,000 vehicle batteries/year. Assuming comparable vehicle volume, a 10 year, 2 kWh, 7 Ah cell Li Ion HEV battery is projected to cost about $4,400. Adding a provision of $200 for other vehicle components (e.g., added onboard charger, upgraded thermal management system, etc.), the incremental cost of the PHEV at these volumes is therefore about $3,100. Assuming no additional profit mark up from the OEM to recover incremental development, warranty, and marketing costs, the customer payback would be about 6+ years. The payback is highly sensitive to the price of gasoline; at $2/gallon the payback period increases to 12+ years, and at $4/gallon it declines to 4+ years. This analysis assumes that the electric drive system does not need to be upgraded for increased power to achieve AER, as discussed above.

A major unanswered question is how many customers would actually pay the full $3,100 incremental cost of the PHEV in this example versus a HEV. There would need to be enough paying customers for the OEM to achieve a viable business case. Although the per mile fuel cost savings is much greater on a PHEV than a HEV, given the price premium resistance of HEVs over comparable conventional vehicles discussed in the HEV section above (6. B. 2. b.), this could be a major issue. If the customer is not willing to pay the full incremental cost over the base HEV, the OEM would have to absorb the remaining portion of the cost difference and this would make the manufacturer's business case for a PHEV program less viable than what may already be a marginally profitable HEV program. This may be acceptable to the automaker for an initial low volume marketing or public relations effort, but it is not likely to be acceptable at higher volumes, nor is it sustainable.

Average customers will need to be educated on how a PHEV differs from a HEV and many are likely to be confused for a while. Communications efforts by manufacturers to convince potential HEV customers that HEVs do not need to be plugged in will be complicated by the existence of PHEVs.

Charging Infrastructure

The charging infrastructure requirements for PHEVs are much simpler than for FPBEVs because the AER (either actual or virtual) will be significantly less than the range of a FPBEV. Standard 120 volt, 15 amp circuits could provide about 30 to 40 miles AER with batteries capable of being completely charged in 6 to 8 hours. However, this would require circuits which are dedicated, or see only minor additional loads, and these are not always available. Since the PHEV, like a HEV, has an ICE and associated rapid fill fuel tank, high power fast charging infrastructure is unnecessary.

e) Prospects for Advancement

While acknowledging that PHEVs in principal have a high degree of synergy with FPBEVs, with respect to energy battery development and conditioning customers to plug in, many OEMs have been suggesting that the high life cycle cost of the energy battery, on top of the high cost of the base HEV, precludes commercial viability of both the PHEV and FPBEV in the foreseeable future.

These manufacturers' pessimistic views may be tied to an assumption that PHEVs will be required to have an EV mode in which the vehicle must provide both a long AER and full function performance capability. This assumption, in turn, may be based on the expectations being generated from statements such as the one President Bush made in an April, 2006 speech; "And we're pretty close to a breakthrough. We believe we're close to a technology that will make it possible to drive up to 40 miles on electricity alone. And then if you have to drive more than 40 miles, then your gasoline kicks in."

However, interest in PHEVs seems to be growing rapidly among major OEMs. DaimlerChrysler has deployed a small demonstration fleet of Sprinter Van PHEVs. Last year Ford, Nissan, and Toyota announced they are actively studying PHEVs, and General Motors announced at the December 2006 Los Angeles Auto Show that they will produce a Saturn VUE PHEV when advanced battery technology is ready.

At the January 2007 Detroit Auto Show, two interesting PHEV concept vehicles were shown. General Motors introduced the Chevrolet Volt, which uses series hybrid architecture with no mechanical connection from the ICE to the wheels. It consists of a full performance electric drive propulsion system, a Li Ion battery system, a battery charger for overnight charging, and a small gasoline ICE powered generator, used to recharge the battery if necessary during driving. As with the Vue PHEV, General Motors said that production of the Volt PHEV will begin when battery technology is ready. Ford introduced the Airstream, which uses a fuel cell system from their Focus FCV and adds a Li Ion battery system and battery charger. It does not appear this vehicle is intended for production, but it is the first time Ford has shown a PHEV.

Ford also introduced a plug-in series hybrid drivable prototype, based on the Edge, at the February 2007 Washington DC Auto Show. It has a 130 kW Li Ion battery, a 120/240 volt onboard charger, a 35 kW fuel cell auxiliary power unit, a tunnel mounted, 350 bar, 4.5 kg, hydrogen tank, and a 4 wheel, 130 kW, electric drive system. They say that the powertrain reduces the size, weight, cost and complexity of a conventional fuel cell system by more than 50 percent and promises to more than double the lifetime of the fuel cell stack. They also mentioned that one of the benefits of this concept is that it can extend the time between hydrogen refueling, which is an important consideration during the early deployment of a hydrogen infrastructure.

The architectures of both the Chevrolet Volt and Ford Edge are envisioned by the respective manufacturers to be able to use a variety of ICE engines and fuels, such as gasoline, diesel, ethanol, or bio-diesel, as well as fuel cells, to generate electricity to recharge the battery.

The Panel considers battery cost the largest issue for successful introduction of PHEVs. As costs come down, and gasoline prices go up, PHEVs will become increasingly viable. However, several important issues will impact the future of this technology – AER probably the most important among them. Like FCEVs, OEMs are expected to need to conduct on-road customer fleet trials of demonstration vehicles to fully understand and address consumer acceptance, battery development and cost reduction.

As long as issues associated with AER, EV mode, and testing, discussed above, do not overly complicate vehicle operational requirements, force larger motors/power electronics, or require very large and costly energy batteries, the Panel anticipates that one or more OEMs may try to be the first to introduce a PHEV derivative of an existing HEV as a marketing competitive advantage.

Initial introduction and subsequent advancement of PHEVs will be highly influenced by the required battery capacities. Larger batteries are more costly, more difficult to package, and it is more difficult to offset the associated vehicle weight increase. A smaller battery, and consequently more affordable vehicle pricing, can increase the likelihood of early market introduction of PHEVs. The primary enabler of using smaller batteries is reducing or eliminating AER. This would help directly by reducing the usable energy storage required and indirectly by allowing manufacturers more flexibility in designing PHEV batteries and battery operation for shallower depth of discharge, to extend battery life and reduce warranty risk. From such a beginning, marketplace and technology competition, driven by the quest for customer satisfaction, are likely to eventually yield vehicles with greater AER (actual or virtual).

The Panel envisions that after demonstration fleets are deployed to gain real world information, definitions and standards are debated and agreed upon, and initial PHEV derivatives of HEVs with small energy batteries become available in the market, it is likely that as batteries improve and the market develops, vehicles with series hybrid architectures will eventually be introduced which have ZEV operating capability with 25 to 40 miles of AER, as demonstrated by the Chevrolet Volt and Ford Edge PHEVs.

f) Introduction Timing

Given the rapid success and increasing mass-market awareness of HEVs, the high level of national publicity about PHEVs, recent auto show PHEV concept and prototype vehicle announcements, and the need for OEMs to gain real world fleet experience in order to participate effectively in PHEV standards development, the Panel projects that demonstration level volume (100's/year) could be on the road within the next 5 years. A key requirement to enable successful introduction of PHEVs are definitions and standards developed through a formal process and consensus among the key stakeholders. Some manufacturers may introduce expensive and/or limited numbers of PHEVs within the next 5 to 10 years, probably as marketing or public relations initiatives. When a battery becomes available that is technically capable for the intended application and the purchase price is low enough, or gasoline prices rise significantly, or some combination of the two, mass commercialization (100,000's/year) is likely to be achieved within five years thereafter. Until then, however, volumes of PHEVs will not progress beyond the level of pre-commercialization (1,000s/year) or, at most, early commercialization (10,000s/year).

g) Significance to ZEV Commercialization

PHEVs have several desirable attributes from a customer perspective; they reduce fuel cost, they can be fueled at home (reducing the frequency of fueling at service stations), and they are not range limited. They also have several favorable attributes from a societal perspective (also desirable to many customers); they reduce exhaust emissions, and, including infrastructure, they reduce net petroleum fuel consumption and the associated production of CO2 and other greenhouse gases. PHEVs are making the news regularly and more OEMs have begun to evaluate them and publicly express a serious interest in their development.

If they become commercially successful, the Panel considers PHEVs to be an important technology for helping to enable FPBEVs, as they would stimulate more rapid development and commercialization of energy batteries, which are more similar to FPBEV batteries than power batteries for HEVs. Unlike FPBEVs, which must have large expensive batteries to achieve the customer's minimum acceptable 100 miles range, PHEVs are capable of starting out with much smaller, more affordable batteries because the ICE system gives them adequate range. In addition, they could serve to condition customers to plugging in, and to educate them on the advantages of using the electric grid, or homeowner supplied photovoltaic electric energy to help power their vehicle.

However, if significant AER and high performance while in EV mode are required in the early phases of PHEV development and introduction, the Panel is concerned that these initiatives and the required investments by potential manufacturers of batteries and vehicles could be slowed significantly due to cost issues. The key challenge is for the key stakeholders to encourage, guide, and carefully pace the introduction of PHEVs, consistent with the development of suitable energy battery life cycle costs.

If suitable batteries become available, PHEVs may support earlier introduction of FCEVs by providing a vehicle architecture solution to help resolve some of the most difficult fuel cell system challenges, such as meeting cold start, durability and cost objectives. A plug-in series hybrid FCEV with a relatively small fuel cell stack and a relatively large energy battery would allow the fuel cell stack to operate under more readily controlled conditions – those that have been found to be most ideal for simultaneously achieving higher efficiency and longer durability with lower catalyst loading (e.g., elimination of idling, constant power, gradual transients, gradual cold start off-plug, coolant heaters on-plug, etc.). The fuel cell system could be simplified by requiring it to operate in only three steady state conditions; (1) off, (2) an optimum efficiency point for battery charging, and (3) an optimum power point for long distance cruising. Following dynamic vehicle loads would not be required, so transitions from one steady state to another could be highly controlled to optimize efficiency and durability.

Plug-in series hybrid FCEVs could also provide benefits supporting implementation of a hydrogen infrastructure, including reducing the quantity of hydrogen needed and making the customer's cost of hydrogen less of an impediment. A series PHEV with a fuel cell running on hydrogen is always a ZEV and would not need to be subjected to AER requirements. In this case the OEM might chose to establish one or more optimum battery sizes tailored to match the potential PHEV customer's expected daily driving range.

4. Hydrogen Internal Combustion Vehicle (H2ICV)

A hydrogen internal combustion vehicle (H2ICV) is basically a conventional ICE powered vehicle that has been converted to operate on hydrogen fuel, very similar to vehicles converted to operate on CNG fuel. Like CNG vehicles, some H2ICVs are "dedicated" (use only hydrogen fuel) and some are capable of operating on multiple types of fuel (e.g., bi-fuel – gasoline or hydrogen). When operating on hydrogen, H2ICVs have near zero exhaust emissions (primarily low levels of NOx), and on a vehicle basis do not consume any hydrocarbon based fuel (gasoline, diesel, CNG, propane, ethanol, etc.) and create CO2.

a) Manufacturers/Vehicles/Specifications/Performance

Only two major OEMs appear to be pursuing hydrogen internal combustion engine vehicles (H2ICV) at the present time – BMW and Ford. Some other manufacturers have studied this technology in the past but are not actively pursuing it at present.

BMW and Ford have announced limited volume demonstration fleets:

Table 6-16: H2ICV Specifications[1]

Vehicle	**Engine**	**Power** (hp/kW)	**Hydrogen Storage** (kg/type)	**Curb Weight** (kg)
BMW 7 Series – Bi Fuel	6.0L V12	256/191	~7.8 / liquid	2460
Ford E-450 Bus – Hydrogen	6.8L V10 (supercharged)	235/175	29 / compressed @ 350 bar	n/a

1. Source: manufacturer data

Table 6-17: H2ICV Performance[1]

Vehicle	**Emissions**	**Performance** (sec. 0-60 mph)	**Driving Range** (miles/km)	**H2 Consumption** (kg/100 km, cycle)
BMW 7 Series – Bi Fuel	ECE compliant	9.5	127/205 (hydrogen) 311/500 (gasoline)	3.6, NEDC
Ford E-450 Bus – Hydrogen	2010 Phase II Heavy Duty compliant	n/a	150/241 to 200/320	8.0 – 10.0, real world shuttle bus

1. Source: manufacturer data

BMW believes hydrogen is the energy carrier of the long term future and that it will play a major role in resolving energy security and global CO2 issues. BMW is convinced that a solution for future sustainable mobility has to be defined on the basis of a technical standard fostering the competition between different technologies, in order to find commercially viable solutions fulfilling customers' needs. Therefore, BMW is focusing on H2ICVs and have developed a series of 100 units of 7 series hydrogen bi-fuel vehicles which they plan to loan to selected users in different countries starting in 2007. Compared to the SULEV II standard, the BMW hydrogen vehicle emissions are less than 1% of the NMOG and CO limits, and NOx is significantly lower than this standard, when operating on hydrogen.

Ford sees H2ICVs as a legitimate transitional product to move from today's fossil fuel dominated powertrains to a pathway that is powered by renewable fuels which have the potential to be environmentally benign. They have focused on high use shuttle vans which consume large quantities of hydrogen and thus help the business case for hydrogen fueling stations. They have developed a 12 passenger E-450 shuttle bus pilot/demonstration program which utilizes a 6.8L supercharged V-10 engine and 350 bar compressed hydrogen storage tanks holding 29 kg of hydrogen. The vehicle has a 150 to 200 mile driving range. In terms of regulated emissions, the E-450 shuttle bus is capable of meeting the 2010 heavy duty NOx standard with no after treatment and has significantly lower CO (3%) and THC (21%) compared to the standard.

For light duty H2ICVs, Ford has achieved the SULEV standard for NMHC and significant reductions in NOx (80 % below SULEV standard) and CO (500% below SULEV standard) with a lean NOx trap after treatment system purged by hydrogen.

b) Units in Operation

Until recently, there have been no fleets of H2ICVs, other than a few "one-off" concept vehicles. During the fourth quarter of 2006, Ford began leasing their E-450 hydrogen bus to customers and in the first quarter of 2007 BMW started production of their 7 series hydrogen bi fuel vehicles.

BMW plans to place up to 25 units in California and another 35 to 50 vehicles in Europe. Ford plans to deploy 30 E-450 H2ICV shuttle busses in 2006 – 2007.

c) Technical Issues

Onboard storage of hydrogen for use in an ICE is more difficult than with a FCEV. Although the efficiency of a H2ICV is about 15-20% better than a gasoline ICE, it is less than the FCEV, and thus for equivalent driving range, more hydrogen must be stored. BMW addresses this by using a liquid hydrogen storage system while Ford is developing large compressed hydrogen storage systems packaged in large shuttle vans.

A detailed discussion of the goals, status, major issues and future potential of onboard vehicle hydrogen storage is discussed in the VHSS section (4).

There are a number of powertrain issues remaining to be overcome in converting conventional engines to operate successfully and durably on hydrogen, however, they are steadily being resolved and none of them are seen by BMW or Ford to be barriers to the successful development of H2ICVs.

d) Commercial Issues

Vehicle Cost

Modifications are required to the ICE to operate successfully on hydrogen fuel and meet durability requirements. Also, direct injection, supercharging, turbo charging and hybrid electric systems are being investigated to offset the lower power output of a hydrogen ICE and improve efficiency. These are conventional automotive technologies and the associated costs are not considered to be an issue.

The cost of the hydrogen storage system is a major issue, as it is with FCEVs. For a more detailed discussion of hydrogen storage costs see section 4 above.

Customer Acceptance

From a vehicle perspective, there appear to be no expected issues with customer acceptance of hydrogen internal combustion vehicles, assuming they can achieve acceptable driving range and become available at prices competitive with comparable conventional vehicles. These vehicles would provide essentially equivalent functionality with conventional vehicles, with no compromises, and have added advantages of a positive environmental image.

Hydrogen Infrastructure

As with other “alternative” fuels, customer acceptance will be highly dependent on the availability of reasonably priced, conveniently located, easily accessible, simple to operate hydrogen fueling stations, which are not dissimilar from conventional self service gasoline stations. In addition, the customer must perceive hydrogen fuel as safe.

e) Prospects for Advancement

BMW and Ford are presently deploying first generation demonstration programs and are continuing to investigate H2ICV technology and possible next generation vehicles.

If a hydrogen infrastructure begins to be deployed on a large scale, before commercially viable FCEVs become widely available, it is possible that more OEMs will begin development of the less costly H2ICVs, especially if FCEV advancement slows due to unresolved technical or commercial issues, or significant government incentives for H2ICVs are introduced. The technology provides near zero exhaust emissions, does not rely on imported petroleum, and, compared to FCEVs, is less costly to develop. Questions of relatively low efficiency remain, however, and could preclude advancement.

f) Introduction Timing

With the BMW and Ford H2ICV fleets now starting production, demonstration (100s/year) will be achieved in 2007 or 2008. However, H2ICVs are not expected to be produced in much higher quantities until a suitable hydrogen infrastructure becomes available in some region of the world.

g) Significance to ZEV Commercialization

Despite the fact that conversion of their existing ICE manufacturing facilities to make H2ICVs is far less costly than ZEV alternatives, most manufacturers have said they are not pursuing

H2ICVs because FCEV technology is a better long term solution from an efficiency standpoint and that a FCEV is a true ZEV. Therefore, they say they are focusing their efforts on FCEVs and some of them are becoming convinced that FCEVs will achieve commercially viable by the 2015-2020 time frame. Although availability of a hydrogen infrastructure is a significant issue, it is necessary in either case.

Both BMW and Ford see H2ICVs as having high degree of significance on stimulating hydrogen infrastructure development, although the Panel questions how significant this can be based on the very low vehicle volumes and consumption expected from just two manufacturers. On the other hand, experience gained from both BMW and Ford's H2ICV demonstration programs could help in the effort to condition customers to accept hydrogen as an automotive fuel.

H2ICVs could help commercialization of FCEVs by development of onboard hydrogen storage systems. Although BMW is very active in developing onboard hydrogen storage systems for light duty vehicles, their vehicles utilize liquid hydrogen storage. Most FCEV developers have chosen compressed hydrogen over liquid hydrogen fuel storage systems and believe this will be the technology used by FCEVs for quite some time.

Some OEMs who are developing FCEVs, but not H2ICVs, have noted that if H2ICVs are given government incentives, and if that results in more availability of H2ICVs by their competitors, they could be forced to divert scarce R&D budgets away from their FCEV technology development to fund H2ICV development. In this case the synergy of H2ICVs with FCEVs would actually be negative.

H2ICVs have no known synergistic benefits for FPBEVs.

5. Fuel Cell Auxiliary Power Unit Vehicle (FCAPUV)

A fuel cell auxiliary power unit vehicle (FCAPUV) adds a small fuel cell to an ICE vehicle, primarily to produce electric power for electrically operated accessories. APUs can also be combined with an HEV system as an efficient supplementary power source under certain vehicle operating conditions. Some APU systems with reformers for use in petroleum fueled vehicles are being developed that also use the reformer's hydrogen rich gas for regeneration of particulate and NOx traps, primarily to meet future diesel emissions regulations.

There has been interest in APUs for heavy duty applications, such as long haul diesel trucks, to produce power for driver resting periods without requiring the ICE to idle for long periods of time. This type of application also makes sense for chauffer driven vehicles which spend a significant amount of time parked with the ICE running to power the climate control system and electronic accessories.

So called "fuel cell auxiliary power units" that are used in series hybrid vehicle architectures are discussed in the PHEV section above.

a) Manufacturers/Vehicles/Specifications/Performance

BMW is investigating a 5 kW United Technologies PEM fuel cell auxiliary power unit for their H2ICV. They are also investigating ways to use it as one option to capture the energy usually lost in the boil off hydrogen from the on board liquid hydrogen storage tank. The Panel knows of no other OEMs actively studying FCAPUVs at this time.

b) Units in Operation

There are no units in operation at this time other than a few engineering prototypes.

c) Technical Issues

Fuel Cell System Related

Fuel cell systems used in a FCAPUV do not have the same demanding start-up time and dynamic response requirements as in the case of a FCEV, which permits use of a wider variety of fuel cell technologies in addition to quick starting PEM, such as slower starting solid oxide.

To simplify vehicle fueling for the customer, these systems typically would be designed to use the same fuel as the ICE, and for gasoline or diesel vehicles, they require a reformer system to produce hydrogen for the APU's fuel cell stack. If the ICE uses hydrogen fuel, the small fuel cell or APU can be much simpler by avoiding the need for a reformer to produce hydrogen.

BMW's experience with the development of FCAPUVs is described in more detail in the FCS section (5. B. 1. b.).

Architecture Related ("Conversion" vs. "Ground Up")

In the case of a conversion of an existing ICE vehicle, there is usually no unused space to package the addition of a FCAPU, especially one which includes a high temperature reformer and its associated insulation and heat shielding. One solution is to package it in the spare tire well and adopt run flat tires. A FCAPU that runs on hydrogen is easier to package but the hydrogen storage system itself is a major packaging problem, as discussed in the H2ICV section.

d) Commercial Issues

Vehicle Cost

The Panel did not obtain any information on the cost of a FCAPU or a FCAPUV.

Customer Acceptance

A vehicle with an APU which uses the same fuel as the ICE will provide improved fuel economy and can eliminate long ICE idle time. It will be transparent to the customer and should require no compromises, except if it requires run flat tires and the customer does not want run flat tires. If the addition of an APU increases the price of the vehicle substantially, there will be customer resistance, especially in mass-market vehicles. A vehicle with an APU that uses a fuel different from the ICE will be difficult to market, due to the inconvenience of having to refuel with two different fuels.

e) Prospects for Advancement

BMW is studying FCAPUs for use with their H2ICV and is continuing their investigation. The Panel knows of no other OEM investigating FCAPUVs.

As BMW is the only known OEM pursuing FCAPUVs, therefore, prospects for advancement are limited to BMW's plans.

Several companies now offer battery powered APUs for vehicles, which are fuel independent and serve existing customer needs for auxiliary power to avoid long periods of ICE idling. This commercially available competitive technology makes it more difficult to establish a market for FCAPUs.

f) Introduction Timing

BMW is considering adding an APU to their H2ICV in the future, but they have not made a decision on their next program. If they decide to proceed, demonstration level (100s/year) could be possible in 5 or more years. Volumes beyond that level are not possible to predict.

g) Significance to ZEV Commercialization

As BMW is the only OEM investigating FCAPUVs, and they apparently do not have a major effort in FCEVs underway, there appears to be little synergy between the two technologies at the OEM level. To the extent UTC Power is developing FC systems for both FCAPUs and light duty propulsion, there is some synergy possible.

The Panel has no assessment on FCAPUVs synergy with ZEVs. Although PEM APUs are similar to fuel cells in FCEVs, the Panel does not expect that FCAPUVs will have much synergy with FCEV technology. The units are usually small (e.g., 5 kW) and the duty cycle is significantly different than fuel cells used for vehicle propulsion. BMW is investigating hydrogen APUs, but their use is predicated on successful introduction of H2ICVs discussed above.

Some of the suppliers that were working on APUs in the past were focused on high temperature systems (e.g., solid oxide). This technology is suitable for use with petroleum fuels and therefore for use in conjunction with ICEs running on gasoline or diesel, but are not suitable for vehicle propulsion due to their long start up time.

C. Vehicle Integration Discussion

Customer demand, intense competition, stockholder expectations, and increasingly stringent global regulations force all automotive manufactures to improve their conventional powertrain systems and to diversify their powertrain offerings. Most automotive manufactures agree there is no single technology that solves all the issues. Advanced technologies such as E85 flexible fuel vehicles, CNG vehicles, common rail turbocharged diesels, direct injection gasoline engines, and dual-clutch, continuously variable, and 6 speed (or more) automatic transmissions must be developed and introduced at a rapid rate. These efforts require major engineering efforts and capital expenditures.

Major resources are also necessary to develop ZEVs and ATVs, but the payback on these investments is usually far longer and much more uncertain. Costs to produce larger than necessary for learning volumes of demonstration fleets with immature design levels (designs that still would not achieve competitive cost levels even if they were produced at high volumes) takes resources away from the basic research and development efforts necessary to advance the technology.

However, there are urgent and compelling reasons for ZEV and ATV technologies to be developed as rapidly as possible, and eventually to become commercially successful –

improved air quality, reduced greenhouse gas emissions and increased energy independence.

Electrification of mass-market light duty vehicles is steadily progressing, ranging from increased electrification of accessories on conventional ICEs to the introduction of more and different types of HEVs. With several PHEVs being announced at recent auto shows, the Panel contemplates an eventual convergence of advanced electric drive technologies – merging HEV and BEV technology to create PHEVs and merging PHEV and FCEV technology to create plug-in FCEVs.

D. Vehicle Integration Summary

In summary, significant progress is being made on ZEVs and ATVs, but there appears to be no agreement among the OEMs on whether and when the designs can mature enough to satisfy all the functional requirements and reach cost levels low enough to become commercially viable mass-market products and therefore achieve the societal benefits described above.

A brief summary of the ten major OEMs input is shown below:

Table 6-18: Summary of Major OEMs' and Suppliers' Input

	Present status of technology[1]:		**Range of assessment of potential:**	
Technology	**Function**	**Cost**	**Low**	**High[6]**
FPBEV	Major Issues	Major Issue	Not viable[2]	Promising for urban
FCEV	Major Issues	Major Issue	Not viable[3]	Commercial by 2015-18
NEV	No Issues	No Issue	Low volume	Commercial now
CEV	Some Issues	Major Issue	Not viable[2]	Promising for urban
HEV	No Issues	Still an Issue	Cost too high	Commercial now
PHEV	Still an Issue	Major Issue	Not viable[2]	Commercial by 2012-15
H2ICV	Minor Issues	Medium Issue	Not viable[4]	Promising
FCAPUV	Some Issues	Major Issue	Not viable[5]	Uncertain

1. Views of majority of automakers, detailed discussions of function and manufacturing cost (goals, status, issues and potential) is included in the report, along with minority views
2. Due to lack of an affordable battery in the foreseeable future
3. Due to lack of an affordable fuel cell system in the foreseeable future and hydrogen storage issues
4. Due to low efficiency, hydrogen storage issues and high cost
5. Due to dependency on H2ICV and high cost
6. "Promising" – manufacturer is investing in the technology but say it is too early to predict commercialization

Also, several manufacturers consider FCEV, H2ICV and FCAPUV technology "not viable" due to lack of a suitable hydrogen infrastructure in the foreseeable future.

7. Report Summary and Conclusions

In the Panel's scope of work, the ARB specifically requested that the Panel make projections as to when the various ZEV and ATV technology vehicles would achieve certain volume milestones.

Given the uncertainty surrounding the future of major factors that will contribute to the success, or lack of success, of these technologies, especially the cost and performance of the key vehicle systems (batteries, fuel cells and hydrogen storage), the price of petroleum, the mood of the general public regarding global warming and energy independence, the level of government incentives (e.g., fleet purchases, tax credits, ZEV credits, etc.), and the implementation of a hydrogen infrastructure in the case of FCEVs and H2ICVs, it is not really possible to make predictions with a high degree of confidence.

However, since being formed, the Panel has reviewed a great amount of public information, and confidential information from many OEMs, automotive suppliers and others, most of whom were very cooperative and forthright, and the Panel is comprised of diverse individuals, with a wide variety of relevant experience and knowledge, so at this point in time, as a group, is willing to make an educated "best guess" projection.

The chart below reflects the Panel's consensus projection on global volumes, based on what they know today, including the present ZEV regulations, and barring any sudden and unanticipated major trigger events (e.g., scientific breakthrough, public and/or political outcry, increase in gasoline taxes (U.S.), petroleum supply destabilization, climate change, war, terrorism, etc.):

Table 7-1: Panel's Projected Achievement of Global Volumes (ARB defined milestones)

Vehicle Technology	**100s/year** (Demonstration)	**1,000s/year** (Pre-Commercialization)	**10,000s/year** (Early Commercialization)	**100,000s/year** (Mass Commercialization)
FPBEV	*1996*	*2002*	**2015**	**2030**
FCEV	*2004*	**2009**	**2020**	**2025**
NEV	*1998*	*2001*	**2010**	**2040**
CEV	*1998*	*2001*	**2010**	**2030**
HEV	*1998*	*1999*	*2000*	*2004*
PHEV	**2008**	**2010**	**2012**	**2015**
H2ICV	**2007**	**2020**	**2025**	**2030**
FCAPUV	**2010**	**2015**	**2030**	**2050**

Note: For years prior to 2006, the year when the technology achieved the stated volume is approximate and is shown in small italics.

The Panel suggests that these projections while probably not very confident in terms of the exact year of achievement carry somewhat greater confidence in terms of the relative timing of these technologies, for the reasons outlined in this report and briefly summarized here:

> *The Panel's projection is that PHEVs with modest energy storage capacity will be derived from HEVs and will proliferate rapidly, stimulating further development and cost reduction of energy batteries and leading to commercially viable PHEVs and, in the longer term, FPBEVs. While PHEVs will continue to grow rapidly, as they have no functional limitations, FPBEVs will grow more slowly due to customer acceptance of limited range and long recharge time. NEVs are commercially viable now and will continue to grow, but will grow slowly due to limited functionality. CEVs will become commercially viable in Japan and Europe in the not too distant future due to lower hurdles for BEVs to overcome. CEVs may be offered in the U.S. as energy batteries continue to mature, but growth will be slow due to functional limitations of BEVs in general, and the specific limitations of CEVs, especially urban freeway driving. The intense effort on FCEVs will result in technically capable vehicles by the 2015 to 2020 time frame, but successful commercialization is dependent on meeting challenging cost goals and the availability of an adequate hydrogen infrastructure. If that happens, FCEVs will grow rapidly, followed by some H2ICVs, and some H2ICVs with FCAPUs.*

The Panel's can envision as a long term outcome - plug-in hybrid FCEVs, powered by sustainable electricity for shorter trips and sustainable hydrogen for longer trips.

8. Appendix A: Questions for Lithium Ion Battery Manufacturers

A. Company Views on HEVs, EVs and PHEVs; Company Battery Strategy

- How do you view the commercial prospects of hybrid electric vehicles (HEVs)?
- Is your company engaged in development of batteries for HEVs? In manufacturing of batteries for HEVs?
- How do you view the commercial prospects of battery-powered vehicles (EVs)? Does your company strategy include development of batteries suitable for EVs? Future manufacturing of EV batteries?
- How do you view the commercial prospects of plug-in hybrid electric vehicles (PHEVs)? Does your company strategy include development of batteries for PHEVs? Future manufacturing of PHEV batteries?
- If your company is not now engaged in EV or PHEV development, which events or developments might lead to your company becoming engaged?

B. Company Li Ion Technologies Suitable for EV Applications

- Has your company developed (or under development) Li Ion technologies in cell sizes suitable for EV applications (for example, 40-100 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?
    - Cell chemistry (composition of positive electrodes, negative electrodes, electrolyte)
    - cell and/or module specific (pulse) power
    - cell and/or module specific energy and energy density (e.g.@c/3)
    - cycle life (e.g., at 80% depth of discharge; at which temperature?)
    - safety characteristics in abuse tests?
    - special characteristics unique to your company´s technology?
- What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Safety issues? Other?)
- What are the most important non-technical barriers to commercial production?

C. Company Li Ion Technologies Suitable for PHEV Applications

- Has your company developed (or under development) Li Ion technologies in cell sizes suitable for EV applications (for example, 15-50 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?
    - Cell chemistry (composition of positive electrodes, negative electrodes, electrolyte)
    - cell and/or module specific (pulse) power
    - cell and/or module specific energy and energy density (e.g.@c/3)

        - cycle life (e.g., at 80% depth of discharge; at which temperature?)
        - safety characteristics in abuse tests?
        - Special characteristics unique to your company´s technology?
    - What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Safety issues? Other?)
    - What are the most important non-technical barriers to commercial production?

D. *Cost of your company´s Li Ion technology for EV applications:*
(cell size 30-100Ah, capacity 20-40 kWh)
Capacity, voltage and estimated cost of modules:
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year
Cost of balance of battery system (BMS, case/tray, wiring, other hardware)
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year

E. *Cost of your company´s Li Ion technology for PHEV applications*
(cell size 15-50Ah, capacity 5-20 kWh)
Capacity, voltage and estimated cost of modules:
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year

F. *Cost of balance of battery system (BMS, case/tray, wiring, other hardware)*
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year

G. *Technology Improvement and Advancement Prospects*

- Which technology advances are most likely to reduce Li Ion battery cost? When does your company expect these cost reductions to become part of commercially available technology?
- Which technology advances are most likely to increase Li Ion battery safety?
    - When does your company expect these safety increases to become part of commercially available technology?

9. Appendix B: Questions for Nickel Metal Hydride Battery Manufacturers

A. Company Views on HEVs, EVs and PHEVs; Company Battery Strategy

- How does your company view the commercial prospects of hybrid electric vehicles (HEVs)?
- Is your company engaged in development of NiMH batteries for HEVs? In manufacturing of batteries for HEVs?
- How do you view the commercial prospects of battery-powered vehicles (EVs)? Does your company strategy include development of NiMH batteries suitable for EVs? Future manufacturing of EV batteries?
- How do you view the commercial prospects of plug-in hybrid electric vehicles (PHEVs)? Does your company strategy include development of NiMH batteries for PHEVs? Future manufacturing of PHEV batteries?
- If your company is not now engaged in EV or PHEV battery development, which circumstances might lead to your company becoming engaged?

B. NiMH Batteries Suitable for EV Applications

- Has your company developed (or under development) NiMH technologies in cell sizes suitable for EV applications (for example, 40-100 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?
    - Cell chemistry (composition of positive electrodes, negative electrodes, electrolyte)
    - cell and/or module specific (pulse) power ?
    - cell and/or module specific energy and energy density (e.g.at c/3) ?
    - cycle life (under which testing conditions were cycle life data obtained (charge/discharge profile, temperature, cell/module/pack)
    - safety features and cell/module/pack characteristics in abuse tests?
    - special characteristics and advantages that are unique to your company´s technology?
- What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Other?)
- What are the most important non-technical barriers to commercial production?

C. NiMH Batteries Suitable for PHEV Applications

- Has your company developed (or under development) NiMH technologies in cell sizes suitable for EV applications (for example, 15-50 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?

    - Cell chemistry (positive electrodes, negative electrodes, electrolyte)?
    - cell and/or module specific (pulse) power ?
    - cell and/or module specific energy and energy density (e.g.at c/3) ?
    - cycle life (under which testing conditions were cycle life data obtained (charge/discharge profile, temperature, cell/module/pack)
    - safety features and cell/module/pack characteristics in abuse tests?
    - special characteristics/advantages of your company´s technology?
- What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Safety issues? Other?)
- What are the most important non-technical barriers to commercial production?

D. Cost of your company´s NiMH technology for EV applications:
(cell size 30-100Ah, capacity 20-40 kWh)

- Capacity and voltage of modules and of the complete battery
- Estimated cost of modules:
    - at maximum current production rate (please indicate the current rate)
    - at 30,000 kWh per year
    - at 300,000 kWh per year
    - at 3,000,000 kWh per year
- Cost of balance of battery system (BMS, case/tray, wiring, other hardware)
    - at maximum current production rate (please indicate the current rate)
    - at 30,000 kWh per year
    - at 300,000 kWh per year
    - at 3,000,000 kWh per year

E. Cost of your company´s NiMH technology for PHEV applications
(cell size 15-50Ah, capacity 5-20 kWh)

- Capacity and voltage of modules and the complete battery
- Estimated cost of modules:
    - at maximum current production rate (please indicate the current rate)
    - at 10,000 kWh per year
    - at 100,000 kWh per year
    - at 1,000,000 kWh per year
- Estimated cost of balance of battery system (BMS, case/tray, wiring, other hardware, battery assembly)
    - at maximum current production rate (please indicate the current rate)
    - at 10,000 kWh per year
    - at 100,000 kWh per year
    - at 1,000,000 kWh per year

F. Technology Improvements and Advancement Prospects

- In your company´s view, which are the most important improvements of NiMH battery technology (materials, design, manufacturing) over the past five years? Which of these improvements are likely to be applicable to EV batteries and/or to PHEV batteries?
- Which are the most important NiMH technology improvements that your company predicts for the next five years?
- Which technology advances are most likely to increase NiMH battery calendar and/or cycle life? When does your company expect such life improvements to become part of commercially available technology?
- Which technology advances are most likely to reduce NiMH battery cost? When does your company expect such cost reductions to become part of commercially available technology?

10. Appendix C: Hydrogen Storage Questionnaire

Note to the respondent: This same questionnaire will be presented to different groups with different involvements in hydrogen storage. Not all questions are necessarily applicable to each of these groups, so please respond to the ones that you feel comfortable in answering. Respondents please include information requested below. Thank you.

Respondents name and/or organization ____
Contact person if additional questions arise ____
Contact person telephone number ____________________

There is a perception that consumer acceptance of hydrogen-fueled vehicles will be greatly influenced by both the normal driving range and refueling convenience. There are many other factors which will also be of considerable importance in the decisions to produce or purchase such vehicles including costs, safety concerns, and effects of the hydrogen storage system physical characteristics (e.g., weight and volume) on vehicle utility.

- Do you think vehicle range and refueling convenience are major factors for consumer acceptance?
- If so, what do you think, for the first generation of hydrogen-fueled vehicles (produced in at least thousands), the minimum acceptable normal driving range will be for consumers? The maximum acceptable refueling time?
- DOE has established 2010 and 2015 performance and cost targets for vehicle hydrogen storage systems to help movement towards mass-manufactured and consumer-acceptable, hydrogen-fueled vehicles. Some of the 2010 and 2015 key <u>system</u> targets are shown below:
        - <u>2015</u>
        - • Volume ~ 1.5 kWh/l 2.7
        - • Weight ~ 2.0 kWh/kg 3.0
        - • Cost ~ $4/kWh $2
        - • Refueling time ~ 3 min for 5 kg
        - • Discharge ~ 0.02 g/s/kW
        - • Durability ~ 1000 cycles

    - Do you think that overall the targets are
    - reasonable for 2010? for 2015?
    - too ambitious for 2010? for 2015?
    - too lax for 2010? for 2015?
- Are there specific targets which you think are not appropriate? If so,
    - which are too ambitious for 2010? for 2015?
    - which are too lax for 2010? for 2015?
- Do you think that some or all of the targets for 2010 will be met? If not, which ones are most likely <u>not</u> to be met?
- Do you think that hydrogen storage issues will be major or minor factors in determination of the time scale for the introduction of hydrogen-fueled vehicles?
- If you think that hydrogen storage issues will be major, which of the following do you think is more likely to occur?

- Hydrogen storage technology will continue to advance sufficiently to resolve major issues. If so, when?
- A reduced range requirement will be accepted by OEMs and consumers for early generations of hydrogen-fueled vehicles.
- The energy efficiency of hydrogen-fueled vehicles will reach sufficiently high levels to provide adequate range without significant advances in hydrogen storage technologies.
- A combination of the above.
- None of the above. Hydrogen storage will continue to be a major problem and delay the introduction of hydrogen-fueled vehicles.

A number of categories of storage technologies are being pursued by many different groups, including:

- High pressure gaseous storage tanks
- Chemical hydrides
- Metal hydrides
- Carbon/sorbents

and, referring the 2010 key DOE targets,

Which category of technology (or technologies) do you think are most likely to meet <u>each</u> of the various 2010 targets:
Volume?
Weight?
Cost?
Refueling time?
Discharge?
Durability?

Which category of technology do you think has the most promise for meeting <u>all</u> of the 2010 targets?
High pressure gaseous storage tanks?
Chemical hydrides?
Metal hydrides?
Carbon/sorbents?
Some combination of the above?
None of the above?

Please give brief comments on your overall impression of each of the technologies above for which you would like to express opinions. Please include your thoughts concerning the practicality and acceptability of gaseous storage pressures up to 700 bar (~ 10,000 psi).

Within each of the various storage technology categories, there are many investigations and projects involving many different materials and processes. Some specific technologies mentioned as examples of significant progress include (but are not limited to):

- ·**Advanced Metal Hydrides** such as Li Mg Amides, Alane, Li Borohydrides, Destabilized Binary Hydrides, and LiMgAlane, M-B-N-H.
- ·**Chemical H2 Storage** such as Phenanthraline/Organic Liquids, and Ammonia Borane/Scaffolds.
- ·**Carbon/Sorbents/New Materials** such as Metal/Carbon Hybrids, Metcars; Bridged Catalysts, IRMOF-8; and Metal-Organic Frameworks, IRMOF-177.

What do you think is the most promising (not necessarily from those mentioned above) specific technology?

- For gaseous storage tanks?
- For chemical hydrides?
- For metal hydrides?
- For carbon/sorbents?

What do you think the current state of the art is for the one specific technology you think is most promising overall?

For volume?
For weight?
For cost?
For refueling time?
For discharge?
For durability?

What hydrogen storage technology do you expect to be on the first generation of mass-produced (at least thousands) hydrogen-fueled vehicles? If you think that it will be high pressure gaseous storage, what pressure do you think will be used?

When do you think the first generation of hydrogen-fueled vehicles will be available?

What do you expect the range of these first-generation vehicles to be?

What do you expect the cost penalty, associated only with the hydrogen storage system, of the vehicle to be?

Are there other important issues associated with vehicle hydrogen storage that you think should be discussed? If so, please list them and include your comments.

11. Appendix D: Automotive Fuel Cell System Questionnaire

This Fuel Cell questionnaire is intended to assist the Independent Expert Panel to assess the technical status of fuel cell systems, especially with regard to technology development, performance, timing of commercialization, and likely costs. The questionnaire pertains to:

- Fuel cell technology your company is working on
- Technical goals for automotive fuel cell systems
- Technical issues impeding introduction of automotive fuel cell systems
- Commercialization challenges for automotive fuel cell systems

Not all questions are applicable to each company or organization to which this questionnaire will be presented. Please respond to the questions appropriate to your development and/or commercialization program. Any comments and suggestions not covered or omitted from the technical questionnaire are welcomed.

A. Fuel Cell Technology Your Company is Working On?

- Are you working as a vehicle system integrator or specific component supplier that others will integrate into an automotive system?
- Is the fuel cell application for primary propulsion power, auxiliary power, other?
- Fuel cell type and general characteristics, e.g. PEM, SOFC, gross/net power, expected efficiency etc.
- Will your automotive fuel cell system application be hybridized with energy storage, e.g. battery?
- Will the on-board automotive fuel be hydrogen or other?
- What are the expected first and subsequent automotive applications, e.g. cars, SUVs, trucks, buses?
- Do you anticipate non-automotive applications of your fuel cell technology?

B. Technical Goals for Automotive Fuel Cell Systems

The US Department of Energy (DOE) has determined fuel cell power train performance and cost targets based on direct comparison with conventional internal combustion engine/automatic transmission system vehicles.

- What do you think of the US DOE fuel cell power train goals?
- Considering the continued advances in ICE vehicles, is it possible for a fuel cell power train system to achieve parity in performance, durability and cost with a conventional internal combustion engine power system in the 2010 to 2020 time frame?

- Which of the following is most difficult in achieving parity with a conventional internal combustion engine power system? Also, consider what characteristics of the fuel cell system can exceed parity with conventional internal combustion engine power systems.
    - Performance (functional characteristics of power, efficiency, general operation, emissions, driving characteristics)
- Durability and life
- Initial vehicle cost and operating cost
- Please comment on any trade-offs to achieve goals.
- Is it necessary to utilize light weight chassis materials, and/or advanced aerodynamics to achieve parity?
- Is it necessary to hybridize a fuel cell system with energy storage to achieve parity? If your company is planning to hybridize the fuel cell, what are desired characteristics of the energy storage system?

C. Technical Issues of Automotive Fuel Cell Systems

What is the most important technical issue to be overcome before automotive fuel cell systems can be commercialized?

Please provide comments regarding:

- Energy efficiency at rated and expected average power
- Fuel consumption on standard driving cycles and expected customer experience
- Parameters effecting durability
- Balance of Plant requirements e.g. thermal management, humidification, air and fuel, control system
- Start up, shutdown and storage issues
- Operational ability in extreme hot and cold ambient conditions
- Cold start time
- The ability to change output power to match vehicle drive requirements
- Storage survivability in extreme hot and cold ambient conditions
- Necessary H2 storage and purity requirements
- Noise, harshness and vibration (NHV)

What are the technical advantages and disadvantages of Fuel Cell Vehicles compared to the following vehicle types? How are the technologies complementary or competitive in development and commercialization?

- Hybrid Electric Vehicle, e.g. Toyota Prius, Ford Escape
- Plug-In HEV e.g. a full hybrid type vehicle that can be plugged-in for limited EV range (20 to 40 km).
- Battery Powered Electric Vehicle e.g. EV1, RAV4 EV
- Hydrogen Fueled Internal Combustion Engine Vehicle

D. Commercialization of Automotive Fuel Cell Systems

Does your company have a commercialization plan for your automotive fuel cell technology?

Please describe.

The ARB fleet size definitions to achieve a level of maturity is described in terms of:

- Demonstration (100’s of vehicles)
- Pre Commercialization (1000’s of vehicles)
- Early Commercialization (10,000’s of vehicles)
- Full Commercialization (100,000’s of vehicles per year)

Are the above transition numbers reasonable considering the need for field experience compared to the resources expended at each step on service and support?

Given no infrastructure barriers, when will it be technically possible to reach early and full commercialization of fuel cell vehicles?

What is the expected retail vehicle cost compared to conventional internal combustion engine power system vehicles at time of market entry? Consider also, 10 years after market entry.

Is there adequate support to establish an OEM supplier base for a fuel cell industry?

Please provide comment on any obstacles.

12. Appendix E: Auto Manufacturers Questionnaire

A. Vehicle technologies – please include each type in answers to sections below:

- Zero Emissions Vehicles (ZEVs)
- Battery Electric Vehicle (BEV)
- Fuel Cell Electric Vehicle (FCEV)
- Advanced Technology Vehicles (ATVs)
- Neighborhood Electric Vehicle (NEV)
- Hybrid Electric Vehicle (HEV)
- Plug-in-Hybrid Electric Vehicle (PHEV)
- Hydrogen Internal Combustion Engine Vehicle (H2ICV)
- Fuel Cell Auxiliary Power Unit Vehicle (APUV)

What is the status of the Company's existing ZEVs/ATVs (demo/prototype/production) ?

- Name/Model Year(s)/Purpose Built or Conversion/Price – if Sold or Leased
- Specifications
- Major Differences – versus similar non-ZEVs/ATVs
  - Brief Description of Powertrain/Propulsion System
  - Brief Description of Energy Storage System
  - Brief Description of Other Major Differences
- Passenger, Luggage and/or Cargo Capacity
- Vehicle Weight (curb)
- Maximum Power (hp, kW, etc.)
- Fuel Storage Capacity (actual customer usable)
    - Energy Battery – based on kilowatt hours (kWh)
    - Hydrogen Fuel – based on kilograms (kg)
    - Fossil Fuels – liquid measurement
- Performance
- Emissions (specify test cycle)
- Fuel Economy
  - City/Highway (specify test cycle)
    - Energy Battery – based on kilowatt hours (kWh)
    - Hydrogen Fuel – based on kilograms (kg)
    - Fossil Fuels – liquid measurement
  - Comparison to Company's similar non-ZEVs/ATVs
- Acceleration (seconds, 0-60 mi/h or 0-100 km/h)
- Driving Range – from 0% to 100% of II-B-5 usable capacity
- Refueling Time – from 0% to 100% of II-B-5 usable capacity
- Crash Results (specify test, or if not tested – capability)
- Limitations (e.g., climatic, hill climb, start time, etc.) – versus Company standards
- Present Units in Operation
- North America
  - California
  - Other North America
- Europe
- Asia
- Other Global

What are the remaining unresolved issues of the Company's ZEVs/ATVs ? *

- Technical Issues
- Performance Related
- Reliability/Durability Related
- Other Technical Issues
- Commercial Issues
- Company Manufacturing Cost Related – versus similar non-ZEVs/ATVs
    - Unit Incremental Variable Cost (present automation/volume levels)
    - Potential Reduction of Cost (design/material revisions)
    - Potential Reduction of Cost (high automation/volume levels)
- Customer Cost of Ownership Related – versus similar non-ZEVs/ATVs
- Other Commercial Issues (e.g., infrastructure, codes and standards, etc.)

What are the prospects for advancement of ZEVs/ATVs within the Company ? *

- Company and Supplier Resources Committed (management priority, number of dedicated engineers/scientists, annual budget, dedicated facilities, number of patents, etc.)
- Present Status
- Future Plans
- Company Goals
- Technical Goals
- Commercial Goals
- Company Plans for Evaluation/Demonstration and Commercialization

When will ZEVs/ATVs become commercially viable ? *

When will total U.S. industry volume reach the following Levels (Phases) ?

- 100s (demonstration)
- 1,000s (pre-commercialization)
- 10,000s (early commercialization)
- 100,000s (mass commercialization)

What requirements/achievements are necessary to reach each Level (Phase) in V-A ?

- Technical Maturity Required
- Manufacturing Cost Required
- Other Requirements (e.g., infrastructure, subsidies, firm vehicle orders, etc.)

For ATVs only – what is the significance of each advanced technology toward enabling earlier ZEV (BEV and/or FCEV) commercialization ?

- Technical Synergies
- Affordability Synergies
- Other Synergies
- ATV volume necessary to provide benefit to ZEV commercialization
- Degree of significance to ZEV commercialization (high/medium/low/none)

13. Appendix F: Companies and Organizations Visited or Interviewed by the Panel

A123 Battery
AC Propulsion
Altair Nanotechnologies
Argonne National Laboratory
Ballard
BMW
Bosch
CalStart
DaimlerChrysler – Michigan
DaimlerChrysler – Stuttgart
DCX/GM/BMW
Department of Energy
EdF
Electrodyne
Electrovaya
EPRI
Ford (Twice)
GAIA Akkumulatorenwerke
General Motors – California
General Motors – Mainz
General Motors – Michigan
General Motors – New York
GS/Yuasa
Hitachi Vehicle Energy
Honda
Hydrogenics
Hyundai
Japanese NEDO
Matsushita
MES-DEA (ZEBRA Battery)
Mitsubishi Motors
Mitsubishi Motors/Litcell
NECLamillion
Nissan
Panasonic EV Energy (PEVE)
Quantum
SAFT
Sanyo
Toyota
UC Davis
UTC Fuel Cells
Volkswagen

14. Appendix G: From DOE Hydrogen Contractors Meeting

A. *Summary of Hydrogen Storage Oral Presentations*

1. "Chemical Hydrogen Storage in Ionic Liquid Media," Larry G. Sneddon (Penn), et al.
   " … Work has now shown that ionic liquids provide advantageous media for ammonia borane dehydrogenation in which both the extent and rate of dehydrogenation are significantly increased."

2. "From Fundamental Understanding to Predicting New Nanomaterials for High Capacity Hydrogen Storage and Fuel Cell Technologies," T. Yildirum (Penn), et al.
   " … focus on achieving fundamental understanding of the chemical and structured interactions governing the storage and release of hydrogen …"

3. "Addressing Grand Challenges through Advanced Materials," M.S. Dresselhaus (MIT), et al.
   " … The elements of the hydrogen initiative are reviewed with particular emphasis given to hydrogen storage …"

4. "Atomistic Transport Mechanisms in Reversible Complex Metal Hydrides," Peter Sutter (BNL), et al.
   "The long-term goal of this project is to develop an atomistic understanding of the interaction of hydrogen with metal and alkali metal surfaces and nanostructures …"

5. "Basic Research for the Hydrogen Fuel Initiative: Control of Hydrogen Release and Uptake in Condensed Phases," Nancy Hess (PNNL), et al.
   " … knowledge that will provide the basis for the development of new materials …"

6. "*In-Situ* Neutron Diffraction Studies Of Novel Hydrogen Storage Materials," William B. Yelon (Univ. Missouri-Rolla), et al.
   " … to study the decomposition reactions of systems of the type AMH_4 where A is an alkali metal (Li,Na,K) and M is either Al or B …"

7. "*In Situ* NMR Studies of Hydrogen Storage Systems," Mark S. Conradi (Washington Univ.), et al.
   " … focuses on *in situ* NMR studies of solid-state hydrogen systems."

8. "High Throughput Screening of Nanostructured Hydrogen Storage Materials," Gang Chen (MIT), et al.
   " … project combines high throughput combinatorial materials synthesis, high throughput screening along with fundamental studies to identify high capacity hydrogen storage materials …"

9. "Complex Hydrides – A New Frontier for Future Energy Applications," Vitalij K. Pecharsky (Iowa State Univ.), et al.
   " … to achieve a fundamental understanding of the relationships between the chemical composition, bonding, structure, microstructure, properties and performance of hydrogen-rich solids."

10. “Molecular Hydrogen Storage in Novel Binary Clathrate Hydrates at Near-Ambient Temperatures and Pressures,” L.J. Rovetto (Colorado School of Mines), et al.
    “ … a fundamental understanding of the structure, molecular-level dynamics, and H_2 formation/release rates and mechanisms in these novel crystalline compounds is the main objective …”

11. “Atomistic Mechanisms of Metal-Assisted Hydrogen Storage in Nanostructured Carbon,” Nidia C. Gallego (ORNL), et al.
    “ … directed towards the development of a broad science foundation to identify and understand the atomistic mechanisms of metal-assisted storage in nanostructured carbons.”

12. “A Synergistic Approach to the Development of New Classes of Hydrogen Storage Materials,” A. Paul Alivisatos (UC Berkeley), et al.
    “ … emphasis is on exploring the possibilities for nanoporous polymers, nonoporous coordination solids, destabilized high-density hydrides, nanostructured boron nitride, and magnesium and light alloy nanocrystals …”

B. Summary of Poster Presentations

1. “Elucidation of Hydrogen Interaction Mechanisms with Metal-doped Carbon Nanostructures,” Ragaiy Zidan (SRNL), et al.
   “ … aimed at obtaining a better understanding of the nanoscale level of hydrogen sorption behavior of metal-doped carbon nanostructures.”

2. “Characterization of Carbon Nanostructures in Pd containing Activated Carbon Fibers using Aberration-Corrected STEM,” Klaus van Benthem (ORNL), et al.
   “ … to obtain an in-depth characterization of atomic structures in Pd-doped activated carbon fibers (ACF) using sub-angstrom resolution electron nicroscopy, and to correlate these structures with their hydrogen storage properties.”

3. “Theoretical Investigation of the Energies of Hydrogen Interaction with Graphene Layers: The Effect of Interlayer Spacing on Hydrogen Storage,” Rachel S. Aga (ORNL), et al.
   “ … to understand the interactions of hydrogen with graphite-like structures and the role of metal particles on the intercalation of hydrogen on grapheme surface.”

4. “Neutron Scattering Aided Studies of the Design, Synthesis and Thermodynamics of Molecular Hydrogen Adsorption Materials,” J.Z. Larese (ORNL), et al.
   “ … focuses on the development of accurate potential energy surfaces to describe the interaction of molecular hydrogen with solid surfaces and within porous media to ultimately achieve predictive powers to tailor-make new materials.”

5. “First Principles Studies of Phase Stability and Reaction Dynamics in Complex Metal Hydrides,” Mei-yin Chou (Georgia Tech), et al.
   “With the simulations, we will explore and screen the possibilities of forming new complex hydrides with high hydrogen contents from various lightweight metals.”

6. “Crystal and Electronic Structures of $LiNH_2$ and Related Compounds,” J.B. Yang (Univ. of Missouri-Rolla), et al.
   “ … we report the revised crystal structure for $LiNH_2$ and show data for $LiNH_2$-$LiBH_4$

compounds, using neutron powder diffraction with high sensitivity."

7. "Understanding the Role (and Controlling Behavior) of Transition Metal Dopants in $NaAlH_4$ Systems," Tabbetha A. Dobbins (La. Tech), et al.
   " … will develop the fundamental materials science and engineering surrounding the behavior of transition metal catalysts added to complex metal hydrides using synchrotron x-ray studies …"

8. "Integrated Nanoscale Metal Hydride-Catalyst Architectures for Hydrogen Storage," Yiping Zhao (Univ. of Georgia), et al.
   " … goal is to use a novel nanofabrication technique, glancing angle deposition (GLAD), to design and produce metal hydride nanorods and nanowires with different topography, structure, and composition, and probe how hydrogen interacts …"

9. "The Molecular Design Basis for Hydrogen Storage in Clathrate Hydrides," Vijay A. John (Tulane), et al.
   " … develop new clathrate hydrates as inclusion compounds for hydrogen storage at moderate pressure (<100 bar) approaching 10 wt% hydrogen loading, and at ambient or near-ambient temperatures."

10. "First Principles Based Simulation of Hydrogen Interactions in Complex Hydrides," Qingfeng Ge (Southern Illinois), et al.
    " … to develop a multiscale approach to model desorption and adsorption of hydrogen in complex metal hydrides."

11. "Dehydrogenation of Boron-Nanoclusters," Aashani Tillekaratne (Univ. Illinois-Chicago).
    " … designed to test the hypothesis that at a certain length scale, the three-dimensional boron structural units found in certain boron-rich solids can be reversibly hydrogenated in the presence of a suitable catalyst to form boranes and/or carboranes with similar three-dimensional boron units."

12. NMR Studies of Metal-Hydrides: $MgScH_x$," Mark S. Conradi (Washington Univ.), et al.
    " … focuses on the *in situ* NMR studies of Solid-State Hydrogen Storage Systems."

15. Appendix H. Small-Cell Batteries for FPBEVs and PHEVs

Batteries consisting of thousands of Li Ion cells of the type normally used in laptop PCs and other consumer electronic products are currently used to power several prototypical electric and plug-in hybrid electric vehicles that are being sold in small numbers at high prices (see Vehicle Integration Chapter of this Report), primarily in California.

The main motivation for using multi-kWh FPBEV and PHEV batteries assembled from type 18650 Li Ion cells is the commercial availability of such cells from mass production in several Asian countries, at prices that are continuing to decline under the impact of growing competition. Li Ion batteries with cell sizes designed for FPBEV and PHEV applications, on the other hand, are available only as prototypes at very high prices.

The characteristics of currently used "small-cell" batteries and their constituent cells are summarized below:

Vehicle Manufacturer (California)	Batteries				Cells		
	Capacity[1] (kWh)	Weight (kg)	Voltage (Volt)	Number of Cells Total/Parallel/Series	Voltage (Volt)	Capacity	
						(Ah)	(Wh)
AC Propulsion	35 [37.5]	284	355	5,088T/53P/96S	3.7	2.0	7.4
Tesla Motors	50	~410	~365	6,831T/69P/99S	3.6	n.a.	7.3[2]
Energy CS	9.0 [10.5]	~110	248	2,376T/33P/72S	3.25	1.35	4.4

[1] Capacity rated by vehicle manufacturer [in brackets: nominal capacity based on cell capacity and number]
[2] Estimated from battery capacity and total number of cells

Vehicle Manufacturer (California)	Batteries				Cells		
	Capacity[1] (kWh)	Weight (kg)	Voltage (Volt)	Number of Cells Total/Parallel/Series	Voltage (Volt)	Capacity	
						(Ah)	(Wh)
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[1] Capacity rated by vehicle manufacturer [in brackets: nominal capacity based on cell capacity and number]
[2] Estimated from battery capacity and total number of cells

As shown in the table, a large number of cells need to be connected electrically in parallel to achieve the needed battery capacities at practical voltages. The 35kWh and 50kWh small-cell batteries listed in the table have energy densities of around 120Wh/kg. If cells with capacities of about 2.6 Ah (yielding nearly 200Wh/kg) are becoming available as expected by the vehicle builders, battery energy density might increase to around 150Wh/kg, the USABC goal and well within FPBEV requirements (see Table 3-2).

Peak power data for these batteries were not made available. However, with a peak power-to-energy ratio of about 4 typical for small Li Ion cells, power should be more than sufficient, as attested to by the high performance claimed for the AC Propulsion and Tesla Motors vehicles. The 9 kWh battery used in the EnergyCS Prius conversion approaches 100Wh/kg, readily meeting the energy density requirement for a PHEV.

Small-cell batteries are enabling the construction and sale of FPBEVs and PHEVs at the present time, but several uncertainties and potential issues surround such batteries. One of these is rather high cost, despite assembly of the batteries from relatively low-cost cells. While no battery cost information was made available to the Panel, a lower limit for small-cell battery cost can be estimated using the following cost factors:

- cost of single cells in mass production: $2-4
- Small Cells→ large-cell "sheets" of parallel-connected cells: factor 1.5-1.25
- Cell Sheets→ modules with distributed controls: factor 1.03 (see section 3.D, Table 3-12)
- Modules→ complete BEV battery: factor 1.2 (Table 3-12)

Applying the composite factor of 1.375 (average) x 1.03 x 1.2 to assumed cell costs of $3 results in estimates of approximately $25,000 for the AC Propulsion battery and about $35,000 for the Tesla Motors battery. For the smaller EnergyCS battery, and assuming a factor of 1.4 for module integration into batteries, the estimated battery cost is approximately $14,000. These estimates assume efficient (but not mass production) methods for the assembly of cell sheets, and large-scale assembly of modules and complete batteries. Present battery costs thus may be higher than the estimates above.

Large-scale manufacturing of small-cell batteries would likely reduce the cost ranges above by perhaps 15-20%, still not sufficient to bring costs of small-cell batteries for FPBEV or even PHEV applications down to the net present values of future fuel cost saving (see Table 3-15), or to the cost levels projected (see Table 3-13) for mass-produced Li Ion batteries with cell sizes designed for FPBEV or PHEV applications. Another major reduction of single cell costs to well less than $2 would be required to achieve this goal which is considered unlikely in the foreseeable future.

No information is as yet available on the calendar and cycle life of the small-cell batteries currently used in FPBEVs and PHEVs. It is reasonable to assume that calendar life will exceed the typical 3-year life of Li Ion cells in consumer products, possibly substantially because of the better control of cell temperature and state of charge (SoC) achieved in these batteries compared to the thermal and electric environment in laptop computers and other consumer products. Small-cell batteries should have the advantage of more effective temperature management also over batteries with cell sizes designed for FPBEV and PHEV applications which will benefit calendar life and safety.

The cycle life of small-cell batteries can be expected to depend sensitively not only on the representative cycle life of individual cells but on cell-to-cell uniformity. Differences in the capacities of cells connected electrically in parallel are less serious for Li Ion than for most other battery types because of the absence of side reactions (such as oxygen evolution at the positive electrode of NiMH batteries). However, existing differences in the capacity of parallel cells could grow with time and the number of cycles because even slightly lower-capacity cells will be fully charged somewhat sooner in each cycle and thus spend more time at high SoC which would tend to shorten life. This potential problem is being addressed by current assemblers of small-cell batteries through careful selection of cells and electronic controls of parallel blocks to maintain cell voltages within narrow ranges. It remains to be seen whether these measures, combined with high quality cell manufacturing, can assure continued cell uniformity and retention of battery capacity as small-cell batteries age.

The ultimate prospects of small-cell batteries appear rather uncertain because of their likely high costs even in volume production, and in view of the uncertainties in their calendar and cycle life capabilities. On the other hand, such batteries provide substantial packaging design flexibility in the conversion of conventional vehicles, and they enable acquisition of experience in the construction and operation of early, fully capable FPBEVs and PHEVs. Positive experience could encourage interest and involvement of Li Ion battery manufacturers in design and development of FPBEV and/or PHEV batteries. Some that experience may be directly applicable in the evolution of Li Ion batteries for ZEVs and partial ZEVs, especially if that evolution proceeded through batteries with mass produced cells in sizes between consumer product cells and cells fully optimized for FPBEV and/or PHEV applications.

16. Appendix I. Net Present Value (NPV) of Fuel Cost Savings

The table below lists calculated NPVs of the fuel savings achieved by HEVs, PHEVs and BEVs relative to ICE vehicles of comparable performance and accommodations, with the assumptions given at the bottom of the table.

Vehicle Type	Annual Mileage		Gasoline Energy		Electric Energy		NPV of Energy Savings[3] $
	Gasoline miles/yr	Electric miles/yr	Cost $/gal	Efficiency[1] miles/gal	Cost $/kWh	Efficiency[2] miles/kWh	
HEV	10,000	0	2.50	30 (40)[4]	n.a.	n.a.	1,573
	10,000	0	3.00	27 (45)	n.a.	n.a.	3,356
	14,000	0	3.50	36 (50)	n.a.	n.a.	2,878
	14,000	0	4.00	33 (50)	n.a.	n.a.	4,356
PHEV-20	7,000	3,000	2.50	30 (40)	0.10	3.0	2,318
	6,000	4,000	3.00	27 (45)	0.06	3.5	4,909
	9,500	4,500	3.50	36 (50)	0.12	3.5	4,221
	8,500	5,500	4.00	33 (55)	0.08	4.0	7,407
PHEV-40	5,500	4,500	2.50	30 (40)	0.10	3.0	2,690
	4,500	5,500	3.00	27 (45)	0.06	3.5	5,491
	8,000	6,000	3.50	36 (50)	0.12	3.5	4,669
	7,000	7,000	4.00	33 (55)	0.08	4.0	8,029
FPBEV	0	10,000	2.50	30	0.10	3.0	4,055
	0	10,000	3.00	27	0.06	3.5	7,239
	0	14,000	3.50	36	0.12	3.5	7,056
	0	14,000	4.00	33	0.08	4.0	10,933

[1] efficiency (gasoline mileage) of baseline conventional ICE vehicle
[2] efficiencies (miles per kWh of AC electricity) used by PHEVs and EVs in EV (electric drive) mode
[3] NPV calculation basis: 10 year battery life, 3% inflation rate, 8% interest rate
[4] in parentheses: efficiencies (gasoline mileage) of HEVs and PHEVs in HEV (hybrid drive) mode

The first two lines for each vehicle type in the table can be viewed as near-term scenarios in terms of annual mileage, gasoline and electricity prices, and vehicle ICE and electric drive efficiencies; the other two lines can be considered longer term scenarios. For each set of scenarios, the upper line uses assumptions is more conservative and less favorable to ZEVs and near (including partial) ZEVs in terms of propulsion energy costs and vehicle efficiencies; the lower line is more favorable.

For each vehicle type, the NPV for the favorable longer-term scenario is nearly three times the value for the conservative near term scenario, indicating the large potential for growing fuel cost savings.

17. Appendix J: FPBEV Specifications and Performance

Table J-1: FPBEV Specifications[1]:

Vehicle	Platform	Motor[2] (kW)	Battery System (Rated[3] kWh – Type)	Curb Weight (pounds)
Chevrolet S10 EV[4]	S10	n.a.[11]/85	15 PbA[4]	4200
Chevrolet S10 EV[5]	S10	n.a.[11]/85	18.7 PbA[5]	4110
Chevrolet S10 EV[6]	S10	n.a.[11]/85	26.4 NiMH[6]	4037
Chrysler EPIC[7]	Dodge Caravan	75/100	27 PbA[7]	5018
Chrysler EPIC[8]	Dodge Caravan	75/100	29 NiMH[8]	4878
Ford Ranger EV[4a]	Ranger	32/67	25 PbA[4a]	4700
Ford Ranger EV[5]	Ranger	32/67	29 NiMH[5]	4100
Ford Postal Van EV[4a]	Ranger EV	32/67	25 PbA[4a]	5000
GM Gen I EV-1[4]	Dedicated	n.a.[11]/102	15 PbA[4]	2970
GM Gen I EV-1[5a]	Dedicated	n.a.[11]/102	15 PbA[5a]	3060
GM Gen II EV-1[5]	Dedicated	n.a.[11]/102	18.7 PbA[5]	3109
GM Gen II EV-1[6]	Dedicated	n.a.[11]/102	26.4 NiMH[6]	2946
Honda EV Plus[5]	Dedicated	49/49	29 NiMH[5]	3590
Nissan Altra[9]	Dedicated	40/62	30 Li Ion[9]	3940
Nissan Altra[10]	Dedicated	40/62	30 Li Ion[10]	3940
Toyota RAV4 EV[5]	RAV4	20/50	27 NiMH[5]	3440

1. Source: manufacturer data, Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/fsev.shtml
2. Continuous power rating/peak power rating (e.g., 18 seconds)
3. Basis for measuring performance in USABC testing (e.g., depth of discharge - DOD) / established by developer or manufacturer based on best balance of power/capacity/life
4. Delphi 12 v.
4a. Delphi 8 v. (East Penn after 1999)
5. Panasonic
5a. Panasonic retrofit
6. GM Ovonic
7. Electrosource Horizon 12 N85 VRLA
8. SAFT
9. Sony July 1999
10. Shin-Kobe (Hitachi)
11. Continuous power constrained by wiring and battery pack limits

The performance of these vehicles was independently measured by Southern California Edison under a variety of real world driving conditions and is summarized below:

Table J-2: FPBEV Southern California Edison Pomona Loop Testing[1]:

Vehicle	**Payload[2]** (pounds)	**0-60 mph** (seconds)	**Driving Range[3]** (miles)	**Consumption[3]** (AC kWh/mile)
Chevrolet S10 EV PbA[4]	980	n/a	30-43	0.396-0.668
Chevrolet S10 EV PbA[5]	850	12.8	36-57	0.408-0.595
Chevrolet S10 EV NiMH[6]	920	14.4	60-84	0.667-0.906
Chrysler EPIC PbA[7]	860	n/a	46-61	0.520-0.720
Chrysler EPIC NiMH[8]	930	14.6	64-99	0.542-0.823
Ford Ranger EV PbA[4a]	960	n/a	52-72	0.400-0.500
Ford Ranger EV NiMH[5]	1220	17.4	63-81	0.391-0.503
Ford Postal Van EV PbA[4a]	960	n/a	52-72	0.400-0.500
General Motors EV-1 PbA[4]	460	8.0	60-91	0.233-0.304
General Motors EV-1 PbA[5]	447	8.0	73-114	0.223-0.331
General Motors EV-1 NiMH[6]	484[11]	8.0[11]	103-161[11]	0.233-0.304[11]
Honda EV Plus NiMH[5]	860	n/a	79-105	0.380-0.560
Nissan Altra Li Ion[9]	639	15.6	74-122	0.255-0.392
Nissan Altra Li Ion[10]	705	16.0	87-104	0.312-0.384
Toyota RAV4 EV NiMH[5]	766	16.3	69-93	0.329-0.434

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/fsev.shtml
2. Actual tested maximum payload
3. range of results for eight test conditions (urban/freeway, minimum/maximum payload, with/without auxiliary loads -- ambient temperature varied from vehicle to vehicle and test to test, but did not include cold conditions)
4. Delphi 12 v.
4a. Delphi 8 v. (East Penn after 1999)
5. Panasonic
6. GM Ovonic
7. Electrosource Horizon 12 N85 VRLA
8. SAFT
9. Sony July 1999
10. Shin-Kobe (Hitachi)
11. Source: General Motors

EV America also independently tested many of these vehicles as summarized below:

Table J-3: FPBEV EV America Baseline Performance Testing[1]:

Vehicle	**Payload** (pounds)	**0-50 mph[2]** (seconds)	**Range[3]** (miles)	**Consumption** (AC kWh/mile)
1997 Chevrolet S10 EV PbA[4]	951	9.7	43.8	0.470
Chevrolet S10 EV PbA[5]	n/a	n/a	n/a	n/a
1999 Chevrolet S10 EV NiMH[6]	920	9.9	95.3	0.794
1997 Chrysler EPIC PbA[7]	882	12.3	52	0.499
1999 Chrysler EPIC NiMH[8]	945	12.3	79.1	0.784
1998 Ford Ranger EV PbA[4a]	669	11.6	65.1	0.484
1999 Ford Ranger EV NiMH[5]	1206	10.3	82.4	0.485
Ford Postal Van EV PbA[4a]	n/a	n/a	n/a	n/a
1997 General Motors EV-1 PbA[4]	440	6.3	78.2	0.248
General Motors EV-1 PbA[5]	n/a	n/a	n/a	n/a
1999 General Motors EV-1 NiMH[6]	440	6.3	140.3	0.373
Honda EV Plus NiMH[5]	n/a	n/a	n/a	n/a
Nissan Altra Li Ion[9]	n/a	n/a	n/a	n/a
Nissan Altra Li Ion[10]	n/a	n/a	n/a	n/a
1998 Toyota RAV4 EV NiMH[5]	759	12.8	94.0	0.432

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/fsev.shtml
2. at 100% State of Charge (SOC)
3. Per SAE J1634 (two UDDS and two HFET)
4. Delphi 12 v.
4a. Delphi 8 v. (East Penn after 1999)
5. Panasonic
6. GM Ovonic
7. Electrosource Horizon 12 N85 VRLA
8. SAFT
9. Sony July 1999
10. Shin-Kobe (Hitachi)

18. Appendix K: NEV Specifications and Performance

Table K-1: NEV Specifications[1]

Vehicle	**Body Type**	**Charger** (type/voltage)	**Battery System** (voltage/Ah capacity[2])	**Curb Weight** (pounds)[3]
2002 Columbia Par Car	2-passenger open	offboard/120	48/146[4]	1205
2001 Frazer-Nash City Car	4-passenger enclosed	offboard/480 3-phase	48/136[5]	1961
2002 TH!NK Neighbor	2-passenger open	onboard/120	72/73[6]	1355
2005 GEM e-2	2-passenger enclosed	onboard/120 or 240	72/80[7]	1303

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/nev.shtml
2. C/2
3. as delivered curb weight
4. Trojan T-105 Flooded PbA
5. Electrosource Absorptive Glass Mat PbA
6. East Penn 8G31 Gel PbA
7. GEM/Deka 8G31 Gel PbA (Deka is made by East Penn)

NEV America independently tested these vehicles as summarized below:

Table K-2: NEV America Baseline Performance Testing[1]

Vehicle	**Payload[2]** (pounds)	**0-20 mph[3]** (seconds)	**Range[4]** (miles)	**Consumption[5]** (AC kWh/mile)
2002 Columbia Par Car	707	22.9	52.9	0.133
2001 Frazer-Nash City Car	633	5.8	30.9	0.201[6]
2002 TH!NK Neighbor	544	6.3	33.1	0.163
2005 GEM e-2	547	4.9	44.3	0.184

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/nev.shtml
2. as delivered payload
3. At 100% State of Charge (SOC) and 332 pounds payload; NEV America performance goal is 6.0 seconds
4. Operated at maximum speed until 18 mph could no longer be maintained
5. Drive cycle unknown, GEM states their vehicle achieves 0.200 to 0.240 AC kWh/mi in "neighborhood driving cycle"
6. Based on test result of 0.171 DC kWh/mile and assuming charging efficiency of 85% (AC kWh/mi was not tested)

Table K-3: NEV Specifications[1]

Vehicle	**Body Type**	**Charger** (type/voltage)	**Battery System** (voltage/Ah capacity[2])	**Curb Weight** (pounds)
ZX40	2-passenger enclosed	onboard/120 or 240	48/150[3]	2116
ZX40s	2-passenger enclosed	onboard/120 or 240	72/150[3]	2350
ZENN	2-passenger enclosed	onboard/120	72/TBD[4]	1280

1. Source: Miles Automotive Group, http://www.milesautomotive.com, ZENN Cars, http://www.zenncars.com/specifications/specs_index.html, Green Car Congress, http://www.greencarcongress.com/2006/05/feel_good_cars_.html
2. 10 hour rate

3. Tianjin Blue Sky Absorptive Glass Mat Sealed PbA
4. Deka Gel PbA (Deka is made by East Penn)

Table K-4: NEV Performance[1]

Vehicle	**Payload** (pounds)	**0-18.6 mph** (seconds)	**Range** (miles)	**Consumption** (AC kWh/mile)
ZX40	882[3]	11.9	40 – 50[2]	n/a
ZX40s	648[3]	3.0	60 – 70[2]	n/a
ZENN	425[4]	4.0	25-31	n/a

1. Source: Miles Automotive Group, http://www.milesautomotive.com, ZENN Cars, http://www.zenncars.com/specifications/specs_index.html, Green Car Congress, http://www.greencarcongress.com/2006/05/feel_good_cars_.html
2. 12.4 mph constant speed
3. Based on GVWR of 2998 lbs.
4. Based on GVWR of 1705 lbs.

19. Appendix L: HEV Specifications and Performance

Table L-1: HEV Specifications[1]

Vehicle	**Platform**	**Engine** (hp/kW)	**Motor/Gen**[2] (kW)[5]	**Motor/Gen**[3] (kW)[5]	**Motor/Gen**[4] (kW)[5]	**Battery** (type - voltage)
Chevrolet Silverado HEV[6]	Silverado	295/220	n.a./10	none	none	PbA 36
Chevrolet Tahoe HEV[6a]	Tahoe	n.a./n.a.	n.a./60	none	n.a./60	NiMH 288
2008 Ford Escape HEV[7]	Escape	133/99	70/n.a.	45/n.a	none	NiMH 330
Honda Accord HEV	Accord	253/189	12/21	none	none	NiMH 144
Honda Civic HEV	Civic	110/82	15/15	none	none	NiMH 158
Honda Insight	Dedicated	73/54	10/10	none	none	NiMH 144
Lexus GS450h	GS450	292/218	48[8]/147	n.a./n.a	none	NiMH 288
Lexus RX400h 4WD	RX400	208/155	32[8]/123	n.a./n.a	12[8]/50	NiMH 288
2007 Nissan Altima HEV	Altima	158/118	n.a./105	n.a./n.a	none	NiMH 245
Saturn Aura HEV	Aura	170/127	3/4	none	none	NiMH 36
Saturn VUE HEV	VUE	170/127	3/4	none	none	NiMH 36
Toyota Camry HEV	Camry	148/110	24[8]/105	n.a./n.a	none	NiMH 245
Toyota Highlander HEV 4WD	Highlander	208/155	32[8]/123	n.a./n.a	12[8]/50	NiMH 288
Toyota Prius	Dedicated	76/57	29[8]/50	n.a./n.a	none	NiMH 202

1. Source: manufacturer data, Automotive News, http://www.whybuyhybrid.com/current-hybrid-vehicles.htm
2. Traction motor/generator
3. Power split system sun gear motor/generator
4. Second traction motor/generator
5. Continuous power/peak power
6. Also GMC Sierra HEV
6a. Also GMC Yukon HEV
7. Also Mercury Mariner HEV and Mazda Tribute HEV
8. One hour rated output by Japanese Motor Output Measurement Test Procedure

HEVs have good performance and excellent fuel economy, and driving ranges that generally exceed conventional vehicles, as shown below:

Table L-2: HEV Performance[1]

Vehicle (all are HEVs)	**Payload** (pounds)	**Emissions** (California)	**0-60 mph** (seconds)	**Range** (miles)	**Economy**[2] (mi/gal)	**Consumption**[3] (kWh/mi)
2006 Chevrolet Silverado	1162	Bin 8	9	445	18/21	1.695/1.259
2008 Ford Escape 2WD	1000	ATPZEV	n/a	661	41/32[4]	0.744/0.826
2007 Honda Accord	n/a	ATPZEV	n/a	477	28/35	1.090/0.755
2007 Honda Civic	n/a	ATPZEV	n/a	554	49/51	0.623/0.518
2006 Honda Insight A/T	n/a	SULEV	n/a	534	57/56	0.535/0.472
2006 Honda Insight M/T	n/a	ULEV	n/a	601	60/66	0.509/0.401
2007 Lexus GS450h	n/a	SULEV	5.2	402	25/28	1.220/0.944
2007 Lexus RX400h 4WD	n/a	SULEV	7.6	449	31/27	0.984/0.979
2007 Nissan Altima HEV	n/a	ATPZEV	n/a	n/a	42/36	0.726/0.735
2007 Saturn VUE	n/a	Bin 5	10.2	418	27/32	1.130/0.826
2007 Toyota Camry	n/a	ATPZEV	8.9	604	40/38	0.763/0.696
2007 Toyota Highlander 4WD	n/a	SULEV	7.6	449	31/27	0.984/0.979
2007 Toyota Prius	n/a	ATPZEV	10.1	589	60/51	0.509/0.518

1. Sources: manufacturer data, and <www.fueleconomy.gov>
2. City label (FTP x 0.9)/highway label (HFET x 0.78)
3. FTP/HFET dynamometer vehicle fuel consumption “tank to wheels”, gasoline LHV: 33.9 kWh/gallon
4. Old method labels shown for data consistency; 34/30 using new 2008 MY 5 cycle method

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