Future Wheels II:

A Survey of Expert Opinion on the Future of Transportation Fuel Cells and Fuel Cell Infrastructure

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Northeast Advanced Vehicle Consortium
Boston, Massachusetts
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Submitted to

Defense Advanced Research Projects Agency
Electric and Hybrid Electric Vehicle Program

by

Northeast Advanced Vehicle Consortium

September 2003

About DARPA

The Defense Advanced Research Projects Agency (DARPA) was created in 1958 to ensure technological superiority for U.S. military forces by fostering innovation and pursuing high-payoff, frequently high-risk projects. DARPA serves as the central research and development organization for the U.S. Department of Defense (DOD). It manages and directs selected basic and applied research and development projects for DOD, and pursues research and technology where the payoff is very high and where success may provide dramatic advances for traditional military missions and dual-use applications.

The DARPA mission is to develop imaginative and innovative research ideas offering a significant technological impact that will go well beyond normal evolutionary developmental approaches, and to pursue these ideas from the demonstration of technical feasibility through the development of prototype systems. The DARPA Tactical Technology Office (TTO) fulfills this mission by engaging in the development of aeronautic, space and land systems as well as embedded processors and control systems. The main goal of the TTO is to create highly capable systems that enable "order of magnitude" improvement in military capabilities.

This project was developed and funded under the TTO Electric and Hybrid Vehicle Technology Program. The Electric and Hybrid Vehicle Technology Program (E/HEV), under the direction of program manager Dr. Robert Rosenfeld, was initiated to pursue research, development, and demonstration of technologies for electric and hybrid vehicles that address military missions, modernization, and cost mitigation. Established by Congress in Fiscal Year 1993, the program pursued technology development and prototype demonstrations that are essential for future military systems, enhancing national energy security, and facilitating compliance by the Armed Services with federal clean air legislation. The DARPA E/HEV program evolved into the Advanced Vehicle Technologies Program, which is administered by the U.S. Department of Transportation.

About the NAVC

The Northeast Advanced Vehicle Consortium (NAVC) is a public-private partnership of companies, public agencies, and university and federal laboratories working together to promote advanced vehicle technologies in the Northeast U.S. The NAVC Board of Directors includes appointees of the eight Northeast governors and the mayor of New York City, as well as the New England Governors' Conference and the Northeast States for Coordinated Air Use Management.

Over the years the NAVC has partnered with many advanced technology companies in a wide range of efforts to design, test and implement alternative fuel technologies. Our participants have initiated over 50 projects, spanning a wide range of technology areas including fuel cell, hybrid-electric and battery-electric systems and lightweight structural composites.

The NAVC also manages the Heavy-Duty Hybrid Bus Work Group and the Heavy-Duty Fuel Cell Vehicle Work Group, funded through the U.S. Department of Transportation. The industry-government workgroups seek to address potential barriers to commercialization of these new vehicle technologies. For example, the Heavy-Duty Hybrid Work Group collaborated with the Society of Automotive Engineers to develop J2711, the Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles, which as published in September 2002.

The NAVC has authored numerous industry reports including:

- a July 2003 report for DARPA and TACOM that analyzed the viability of electrolysis for the military
- the Hybrid Bus Work Group's *Engine Certification Recommendations Report* which summarized in-use hybrid bus engine data and outlined a pathway to certifying heavy-duty hybrid buses to federal emissions standards
- a report on the February 2000 *Hybrid Bus Emissions Testing Project*, which carried out independent testing of hybrid bus emissions and fuel economy
- a Transportation Research Board TCRP Report entitled *Hybrid–Electric Transit Buses: Status, Issues, and Benefits*

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The NAVC would also like to thank the many fuel cell experts who agreed to be interviewed for this report. Many people put aside valuable time to participate in this project.

The project was conceived by Ms. Sheila Lynch, NAVC Executive Director, and was carried out by Mr. Mark D'Amico, NAVC Finance Director and Ms. Lisa Callaghan, NAVC Project Director.

Northeast Advanced Vehicle Consortium

112 South Street, Fourth Floor

Boston, MA 02111

617-482-1770 *phone*

617-482-1777 *fax*

www.navc.org

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Executive Summary

In November 2000, the Northeast Advanced Vehicle Consortium published *Future Wheels*, a report on the results of our interviews with 44 global fuel cell experts on major issues surrounding the development of transportation fuel cells and related infrastructure. Much has changed since then. Technological advancements, industry alignments, product introductions, global political and economic circumstances – all have changed in ways that affect the industry. We thought it a good time to update *Future Wheels*. We wanted to learn what fuel cell experts think today about the future of the transportation fuel cell industry, the resolution of fuel cell infrastructure issues, the prospects for near-term commercialization and long-term market penetration in the transit and automotive markets, and many other key issues. The goal of this report is to provide a "big picture" view of the transportation fuel cell world in 2003, highlighting how it has changed over the last few years, where the industry is headed, and what challenges remain.

In writing the report, we sought to portray the collective opinion of our interview subjects without editorializing or analyzing their responses, and to allow readers to draw their own conclusions.

We found that the following key themes arose during the course of the interviews:

- The debate over fuel choice has ended. Three years ago, opinions about onboard reformation vs. direct hydrogen were decidedly mixed. Since then, a consensus has formed around the use of direct hydrogen, with a small number of dissenters.

- Over the past three years, transportation fuel cells began to move from the laboratory to field trials. This has lead to a greater focus on manufacturing techniques, increased competition among suppliers, and consolidation among industry players.

- The predicted commercialization timeframe has slipped, with a majority of experts saying that the inception of market penetration is still a decade or more away.

- Onboard hydrogen storage has moved to center stage, with major challenges remaining to resolve trade-offs in vehicle range, packaging, weight and cost. There was no clear consensus on how this issue would be resolved.

- Fuel cell vehicles could usher in a revolution in vehicle design. Vehicles tailored to the fuel cell, like the General Motors Hy-wire, demonstrate that a fuel cell vehicle can be conceived in a completely new way that maximizes the advantages of the fuel cell and introduces entirely new concepts for the personal automobile.

- Micro-power applications such as laptops and handheld PDAs are likely to be the first market where fuel cells are commercialized, with commercial products using direct methanol fuel cells scheduled for introduction in 2004. Direct methanol fuel cells have fallen out of favor for transportation applications.

- The military market offers great potential for near-term fuel cell deployment as battery replacements in small portable applications or in non-tactical vehicles.

- Hydrogen ICEs are an intriguing application, but are seen primarily as an interim step that may help spur early hydrogen infrastructure deployment.

- President Bush's high-profile commitment to fuel cells and hydrogen is seen as important by many experts because it signals that the U.S. government is committed to a long-term hydrogen strategy.

- Government and industry need to commit themselves to establishing appropriate codes & standards to ensure that this issue does not become a barrier to commercialization.

Introduction

Background

In November 2000, the NAVC published "Future Wheels," a report on the status and future of fuel cell transportation infrastructure, as seen by world experts on fuel cell technology. Our goal was to explore critical issues surrounding the development of a technology and infrastructure to support fuel cells for transportation. The NAVC interviewed 44 representatives from automobile manufacturers, energy companies, fuel cell technology companies, U.S. federal and state government agencies, alternative fuel suppliers, environmental organizations, and transit agencies.

At the time the interviews were conducted, fuel cell vehicles were receiving a significant push toward commercialization, but many issues surrounding infrastructure for this new technology seemed unresolved and unclear. *Future Wheels* reported the results of these expert interviews in order to shed light on how these issues were being addressed and how the experts in the fuel cell world saw them being resolved. The report was made available at www.navc.org, where it can still be found. It stands as a record of the transportation fuel cell industry in 2000, highlighting the debates over key issues such as fuel sources and onboard reformation, and the perception of how the fuel cell industry would progress.

Overview of Future Wheels II

Since the publication of *Future Wheels*, there have been many changes in the fuel cell world. There have been technical advancements, new industry alignments and collaborations, and introduction of new prototype products. In addition, political and economic circumstances have changed in ways that have had an effect on the fuel cell industry. Therefore, expert opinion regarding the original set of issues may have changed, and whole new questions must be asked. The NAVC undertook this update of *Future Wheels*, again interviewing a wide range of experts on fuel cell technology and infrastructure to see how the landscape and future outlook have changed. Our goal was to understand what the experts think about what direction the fuel cell industry is taking, how fuel cell infrastructure issues are being resolved, what the prospects are for near-term commercialization and long-term market penetration in both the transit and automotive markets, and other key issues. This report provides the results of this latest round of interviews.

Ground Rules for the Interviews

As with the first *Future Wheels*, the NAVC conducted phone interviews with the participating experts, asking a set of 16 questions which were provided in advance. In the report, the experts are identified only by their industry sector, not by name. For example, experts are referred to as a representative of an auto company or of a governmental agency. This was done to allow more freedom of expression, and participation by experts who may not have wanted their company or organization aligned with certain views.

The NAVC is not expressing its own opinion in this report, nor do we analyze or editorialize about the interviews. We simply report what our interview subjects told us, and allow readers to draw their own conclusions.

Note: The NAVC invited other fuel cell experts who did not take part in the interviews. We recognize there are many more global fuel cell experts beyond those we interviewed, but due to time constraints and the length of interviews, it was necessary to limit the number of interview subjects.

List of Fuel Cell Experts

Air Products	Venki Raman, Business Director
	Alfred Meyer, Consultant
American Methanol Institute	Gregory Dolan, Vice President, Communications & Policy
Ballard Power Systems	Michael Rosenberg, Director, Corporate Relations
California Air Resources Board	Shannon Baxter, Alternative Energy Specialist
DaimlerChrysler	Reginald Modlin, Dir., Environmental & Energy Planning
	Andreas Schell, Senior Manager Fuel Cell System
	Max Gates, Mgr, Design, Technologies and Quality Communications
Energy Visions, Inc.	Doug James, Vice President & General Manager, Fuel Cell Div.
Environmental Defense	John DeCicco, Senior Fellow, Automotive Strategies
Fuel Cells Canada	Ron Britton, President & CEO
General Motors	Greg Ruselowski, Director of Finance, Fuel Cell Activities
Hydrogenics	Kevin Harris, Business Development
HydrogenSource	Larry Holland, Vice President, Marketing, Business Development and Strategy
	Mark Mauss, Transportation Program Manager
	Ignacio Aguerrevere, Marketing Manager
Infinity Fuel Cell and Hydrogen	William F. Smith, President
Imperial Centre for Energy Policy and Technology	David Hart, Head of Fuel Cells & Hydrogen Research
Methanex	Michael MacDonald, Senior Vice President, Technology
Natural Resources Defense Council	Mary Jean Burer, Transportation Policy Analyst
	Roland Hwang, Senior Policy Analyst
Praxair	Ed Danieli, Director of Clean Fuels
Proton Energy Systems	Thomas Maloney, Product Manager
Renewable Fuels Association	Mary Giglio, Director, Congressional & Public Affairs
Rocky Mountain Institute	Amory B. Lovins, Chief Executive Officer
Shell Hydrogen	Chris de Koning, External Affairs and Communication Manager
Toyota	William Reinert, Alternate Fuel Vehicles Manager
U.S. Army TARDEC	Erik Kallio, Deputy for Fuel Cell Development
	Harold Sanborn, Business Development
U.S. Department of Energy	Steven Chalk, Program Manager, Office of Hydrogen, Fuel Cells & Infrastructure
U.S. Department of Transportation	Shang Hsiung, Program Manager, Federal Transit Administration
U.S. Fuel Cell Council	Anthony A. Androsky, Deputy Executive Director
Union of Concerned Scientists	Jason Mark, Clean Vehicles Program Director
UTC Fuel Cells	Gordon Boggie, Manager, Fleet Vehicle Programs

Interview Questions

- Since *Future Wheels* was published in November 2000, what major changes have occurred in transportation fuel cell technology, from materials to design and production of the fuel cell to the vehicles themselves? What about source-to-destination hydrogen production and distribution?

- In which market will fuel cell technology first be commercialized on a large scale? Possible options to consider: stationary auxiliary power, stationary household power, compact/portable power, transit vehicles, passenger vehicles, other vehicles. Has your opinion on this issue changed in the past two years?

- What kind of "synergy" is there between development of transportation fuel cells and fuel cells for stationary, portable, or other applications?

- How would you rate the long-term commercial viability of fuel cells for passenger vehicles? For transit buses? For other medium- or heavy-duty vehicles or off-road vehicles?

- What is the viability of fuel cells for military applications?

- When do you think fuel cells will capture a significant share of the market for transit applications? For passenger vehicles? Has your opinion of this changed in the last two years?

- What type of fuel cell do you expect to be used for transportation? Will this depend on whether the fuel is reformed onboard or off board? What new fuel cell types are possible?

- What are the outstanding technical issues associated with the fuel cell stack for transportation applications? When and how do you see these issues being resolved?

- What are the major cost barriers to development of a commercially viable fuel cell stack for transportation? What are the barriers for developing a cost-competitive fuel cell vehicle (passenger and/or transit)?

- What are the major outstanding issues with regard to fuel cell transportation infrastructure?

- Will hydrogen be used by ICE vehicles, such as in the prototype Ford U vehicle, before being used with fuel cells? Are fuel cells superior to the pairing of a hydrogen ICE with a hybrid electric drivetrain? How? Are commercialized fuel cell vehicles likely to be hybridized?

- Will fuel reformation take place onboard or off board fuel cell vehicles? If off board, will it be at a refueling service center or at a more central location and then distributed? Has your view of this issue changed in the past two years?

- What are the major challenges to onboard hydrogen storage? Are there any viable advanced storage technologies (such as metal hydrides, carbon nanotubes, others)?

- What are the most promising sources of hydrogen for fuel cells in the transportation sector? Has your view of this changed in the past two years?

- What factors are currently driving the development, or lack of development, of fuel cells for transportation? (Factors to consider may include oil supply concerns, climate change, air pollution.) Has your view of this changed in the past two years?

- What, if anything, should government do to support or advance fuel cells for transportation use? Compare government efforts to advance fuel cell technology in the U.S., Canada, Europe and Japan.

Major Changes in the Fuel Cell World Since November 2000

The fuel cell is far from a new technology. Since its discovery in 1839, interest in it as a highly efficient, environmentally friendly propulsion technology has waxed and waned. Concentrated research and development of the fuel cell reached a peak during the 1960's when fuel cells became an integral part of the U.S. space program. Fuel cells also attracted the interest of automobile manufacturers at this time, but through the 1980's and early 1990's, they remained laboratory-bound as only one of many R&D efforts. Not any more. Fuel cells have risen to prominence as the "holy grail" for creating a clean, efficient transportation sector. In the late 1990's, fuel cells became the focus of major R&D efforts by automobile manufacturers, with a small number of prototypes being introduced. By the year 2000, the investment community had begun to take notice, as did governments around the world and environmental advocacy groups. Fuel cells also became the subject of increasing media attention and public curiosity. It was at this point that the NAVC published *Future Wheels*, which served to highlight some of the key issues surrounding the development of fuel cells and a hydrogen infrastructure.

We have chosen to begin this report by reviewing progress since then. The fuel cell experts that we interviewed were asked for their take on the major developments in fuel cell technology and hydrogen infrastructure. The experts were asked specifically about changes in fuel cell technology, from materials to the design and production of the fuel cell, to the vehicles themselves. They were also asked about changes in source-to-destination hydrogen production and distribution. However, many chose to highlight other changes that are external to the fuel cell and hydrogen technology itself, such as political changes or changes in the automobile market.

Changes Relating to Fuel Cell and Vehicle Technology

The range of opinion as to how fuel cell technology has changed since 2000 shows that progress is truly in the eye of the beholder. While there has been much time, money and energy invested in the development of fuel cell technology and fuel cell vehicles, the general consensus is that the last three years have not produced any major breakthroughs. This does not mean that there haven't been changes and advancements, just that there have not been any major transformative changes. Rather, the technology has undergone incremental improvements. Whether this is seen as a reality check, a disappointment, or a positive trend forward seemed to depend on the respondent's inclination to see the glass as half full or half empty. Respondents' viewpoints also depended in part on how close they are to fuel cell R&D activities. To many looking in from the outside, such as government agencies and "supporting players" in the fuel cell industry, there have been no major breakthroughs in the technology.

Perhaps not surprisingly, the fuel cell companies were the most enthusiastic about the advances that have been made in the technology. They noted that, over the last three years, they have been working on the next generation of their fuel cell technology and making significant design changes. The last few years have given the fuel cell companies a chance to work on a variety of engineering issues – they are still using the same basic materials, but are improving the fuel cells in terms of robustness, cost, and efficiency.

The automotive manufacturing companies offered differing opinions about the progress of the technology. One company was very enthusiastic about the progress of technical developments. As this representative put it, "*in comparison to the progress made in battery technology during the 80's and early 90's, fuel cells are showing a significantly faster rate of development.*" On the other hand, another company said they were disappointed with the incremental progress over the last few years.

For those that did cite progress on the fuel cell technology front, they cited the following technical areas: rapid start-up, operation in freezing temperatures, operation in high temperatures, efficiency, packaging, system integration, durability, power density and cost.

Clarity Regarding Fuel Choice

In striking contrast to the results of our survey three years ago, there was consensus around the focus on direct hydrogen fuel cell vehicles. As one respondent said, "*the debate over fuel choice is over.*" Respondents generally agreed that no one is pursuing onboard reformation anymore, although there were a few significant outliers in this respect. Most respondents said that onboard reformation hadn't shown the progress that some had hoped three years ago. Many noted that they had never supported the concept because of the added complexity and cost, and because the reformer takes away the "zero emission" benefit of fuel cell vehicle. However, some respondents believe that the automakers simply decided that getting an onboard reformer to work would be too complex and costly, and decided to focus their time and money on the one complicated concept, a workable fuel cell vehicle. A few respondents felt that the move away from onboard reformation was temporary, and that interest would revive as commercially viable reformers were introduced and the problems of developing a widespread hydrogen refueling infrastructure became more evident.

Moving From R&D to the Real World

Several respondents' comments focused on the fact that the fuel cell and hydrogen industry is moving away from the laboratory and early R&D efforts and taking initial steps toward making a real, commercial product. This means that the fuel cell developers are working on the manufacturing processes for the fuels cells, and are starting pilot production instead of creating "handmade devices." Moving to volume production means learning how to make many identical products, with real quality control, and ensuring that customer expectations are met. This also leads to cost reductions, which are critical to the drive to commercialization.

This also means that competition is beginning to emerge around the potential suppliers for the fuel cell industry. A few respondents noted that there has been consolidation and contraction of fuel cell players in the past three years, indicating that unsuccessful or unsustainable technologies or business are being weeded out. Experts see this as a positive development in that it is indicative of a maturation of the fuel cell industry and allows the industry to focus on viable commercial concepts and companies.

There is also increasing competition, some respondents thought, among hydrogen generation companies. Energy companies like Shell Hydrogen and BP are leading the way for other energy companies to get involved. Several respondents mentioned that the industrial gas companies seem to be more serious about becoming players in developing hydrogen infrastructure for transportation. Several mentioned that smaller companies like Stuart Energy Systems, HydrogenSource, Proton Energy Systems and H2GEN are offering commercial hydrogen appliances. Entry of these kinds of non-traditional players in the automotive refueling world will help advance the industry toward commercial viability.

Vehicle Introductions

Several respondents cited specific vehicle introductions as major events. Not surprisingly, these respondents often referred to a vehicle with which they are associated. Some respondents cited the introduction of the first commercial fuel cell vehicles from Honda and Toyota. As one respondent noted, this put fuel cell vehicles in the hands of real customers for the first time. Others mentioned the cross-country trip made by the DaimlerChrysler NECAR in the summer of 2002, which demonstrated a 300-mile range using methanol.

By far, however, the vehicles that received the most mention were the General Motors AUTOnomy and Hy-wire concept vehicles. Several respondents, from car companies to energy suppliers and others, called this a groundbreaking concept. It demonstrated that the fuel cell vehicle could be conceived in a completely new way that would offer customers a new value proposition. The Hy-wire concept shows that fuel cells can be packaged very differently than conventional internal combustion engine (ICE) vehicles, which many respondents cited as important in developing a commercially viable fuel cell vehicle. As one respondent said,

> *"This represents a maturation of thinking about design for fuel cell vehicles. Rather than adapting existing vehicles to fuel cells, we can start with a clean sheet of paper, which will allow us to maximize the advantages of the fuel cell, gain benefits in hydrogen storage and range, and introduce completely new concepts with the fuel cell vehicle."*

External Changes

President Bush's State of the Union address in January 2003 was seen by many as a major development for the fuel cell and hydrogen world. Some cited it as the most significant event over the last three years – surpassing any technological developments that have occurred. They noted that it signaled the U.S. government's commitment to hydrogen for the long haul, and that the U.S. intends to "stay the course" until hydrogen has become a widespread commercial transportation fuel. One respondent noted that the President's announcement attracted much more attention to fuel cells, with the public and other policymakers showing greater interest in understanding and supporting this technology. The U.S. Government's commitment is also driving the cultivation of potential hydrogen sources, in particular, among the coal and nuclear industries. Respondents outside the U.S. also indicated that the public commitment of the U.S. Government is an important driver for the development of fuel cell and hydrogen infrastructure around the world. However, some respondents were suspicious of the Administration's high-profile commitment to hydrogen. They felt that the focus on such long-term R&D rather than near-term regulatory policy would delay rather than accelerate an ultimate transition to clean transportation technologies.

Transportation Fuel Cell Market Development

Fuel Cell Market Development

Fuel cells have already been introduced in a variety of applications, but primarily as prototype products in limited demonstrations. We wanted to find out in which market respondents think fuel cells will first reach commercialization, with the fuel cell being sold as a mass-produced product that can compete with the incumbent technology and meet customer expectations. Respondents were asked to consider all fuel cell markets – not just transportation, but also stationary and micro-power applications.

What became clear is that there are three primary competing theories of the fuel cell commercialization pathway. One theory says that commercialization will follow a cost curve. One says that the development of the fuel cell's durability will determine which market launches first. One says that volume will be the key driver for companies to enter a particular market.

- **Following the cost curve:** Cost is one of the big challenges for fuel cell developers in the effort to make fuel cells commercially viable. The "cost curve" theory says that fuel cells will enter a particular market as a commercialized product once the cost of the fuel cell hits the "price point" of the incumbent technology and therefore becomes cost-competitive. If you follow this theory, then fuel cells will first be commercialized in the premium stationary power market and in micro-applications such as portable PCs and handheld PDAs, where battery costs are quite high. Fuel cells will next be introduced in transit and other commercial fleets, and later in the automotive market, where fuel cells have to come down to $50/kW to compete.

- **Durability will determine the pathway:** Durability is another major technical challenge that fuel cell developers are working to address. Current fuel cell technology allows for a useful life of less than 5,000 hours. Private automobiles have a useful life of about 5,000 hours while most other transportation applications have life-cycle requirements that are significantly longer. So, according to this theory, fuel cells could be commercially introduced in the passenger vehicle market first. Primary stationary power needs devices that run for over 40,000 hours. Until fuel cells can be designed and manufactured to meet this operational lifetime, they will not be viable in the stationary primary power market. Back-up stationary power would also be viable earlier, as durability requirements are around 5,000 hours.

- **Volume as the key driver:** According to this school of thought, only the automotive market provides sufficient volume to attract the level of investment that will be required to make a commercially viable fuel cell. For example, in the U.S., the new passenger vehicle market in the U.S. is roughly 17 million units per year. By contrast, roughly 5,000 new transit vehicles are purchased in a year. Stationary application markets are similarly limited. The anticipated payback from such a small market is not sufficient to justify the required initial investment.

It should be noted that most respondents did not, and were not asked to, specify whether they were talking about the U.S. market or the world market. A few expressly commented on the differences between the U.S. market and other countries, and their comments are noted below. Otherwise, it is safe to assume that respondents are commenting primarily on the U.S. market.

Premium/Back-Up Power, Micro-Power Are the First Likely Markets

A substantial majority of respondents chose either premium or micro-power as the first market where fuel cells will be commercialized. (Many thought it would happen first in both this market and micro/compact power.) Here the two key factors of durability and cost come together to create a powerful argument for early commercialization. For premium power applications, the cost of losing power is very high; therefore, the fuel cell will be cost competitive in this market before it is in other, lower cost markets. As for durability, back-up power applications don’t have the very long lifetime requirements that primary stationary power does, so fuel cells will hit the required durability target for back-up power sooner than for primary power. With micro-power applications, i.e., laptop computers or handheld PDAs, the fuel cell will replace expensive battery technology and will face limited lifetime requirements.

This was somewhat different than the common view three years ago. At that time, micro-power applications did not receive much attention. Respondents were more focused on the early opportunities provided by the transit market, which seemed to offer lower barriers-to-entry and is motivated more by societal concerns including environmental impact.

Definitions of Fuel Cell Applications

Fuel cells can be used as power sources in a wide range of applications. This section gives a brief definition of the fuel cell applications referenced in this report. In our questions, we focused on a limited number of applications that are the focus of serious commercial development efforts or that have received attention as showing potential for commercial success. We also used broad, overarching categories that might comprise several different applications; for example, we referred to “commercial” stationary applications, which could include small backup power and large power plants. This should not be taken as a comprehensive list of all potential fuel cell applications; it is intended simply as a guide for understanding the terminology used in this report.

Stationary Power Applications: The stationary market comprises many applications that are quite different in power and operational requirements. In this report, we refer to the following broad categories:

Primary power, as distinguished from small-scale backup power, comprises large utility, commercial or industrial applications where the fuel cell system is the “primary” source of power. Examples would be any major public or commercial building such as a school, hospital, or office building, where the fuel cell system is the primary power plant. An important subset of this category is combined heat and power (CHP) or cogeneration plants, which provide heat and electricity.

Premium backup power refers to a market where it is critically important to avoid any power interruptions, such as hospitals, or where power interruptions result in extremely high economic losses, such as credit card companies, brokerage houses, and telecommunications centers. These markets typically have multiple back-up installations to ensure uninterrupted power, and fuel cells are considered viable for the back-up systems. A backup power installation is much smaller than primary power and has lower kilowatt requirements.

Residential systems are small-scale systems that can provide either primary or auxiliary power. They can be connected to the electric grid to provide supplemental power or be installed as a grid-independent generator in remote areas that are inaccessible by power lines.

Transportation Applications: Fuel cells are being evaluated for a multitude of vehicle applications. We limited our discussion those applications that are receiving serious attention for commercial development, and used two broad, overarching categories that encompass many vehicle types. In these applications, the fuel cell can be used either as the primary propulsion device, as part of a hybrid system, or as an auxiliary power unit (APU) that provides supplemental electricity for non-motive power needs (e.g., electrical systems).

Passenger or private vehicles simply mean the commercial automotive market. These are the sedans, SUVs, minicars, or other vehicles that are the focus of the automakers’ fuel cell development efforts.

Heavy-duty or medium-duty commercial fleet vehicles encompass transit buses, long-haul trucks, and delivery vehicles. These are all fleet vehicles that would be housed at a central depot and operated by professional drivers.

Micro-applications: Also referred to as portable power applications, these are devices with relatively low power requirements, from handheld electronic devices such as laptops and cell phones to portable generators used to provide electricity for portable equipment.

Sources:
U.S. Fuel Cell Council, www.fuelcells2000.org

U.S. Department of Energy’s Office of Renewable Energy and Energy Efficiency, www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html

Prospects for Stationary, Transportation and Micro-Power Markets

The following is a summary of opinions regarding each market proposed for consideration during our interviews.

Stationary – premium power, back-up power: As noted above, this was one of the two applications cited most often as the likely first market for fuel cell commercialization. The high cost of premium power means that fuel cells will be able to compete on cost earlier in this market than in others. These applications also require fewer hours of operation over the lifetime of the energy device, so the durability concern for fuel cells will be easier to overcome. One respondent also noted that fuel cells are a "good neighbor" because they are quiet and have low emissions. This provides potential customers with a better value proposition than they would have with conventional diesel generators.

Stationary – primary: Views were mixed on the likelihood of early commercialization for stationary primary power. The biggest barriers are the lifetime issue. Primary power requires tens of thousands of hours, which will require a significant increase from current fuel cell systems' lifetime. One respondent noted that primary power will benefit from the same value proposition noted above, namely that fuel cells are a good neighbor. Nevertheless, the durability issue is likely to remain a barrier until fuel cells can come close to the lifetime of the incumbent technology or possibly until costs come down such that replacement is not a costly proposition.

For those respondents that felt cost was the major driver in commercialization, stationary was cited as an earlier market than transportation due to the higher cost of current stationary power generation. There were a few respondents who noted that they had supported this theory three years ago, but felt that stationary had not made as much progress as they had expected. As one respondent noted, "…*the wheels seem to have come off*" the stationary fuel cell movement. These respondents questioned whether there was still a viable pathway to commercialization.

Stationary – residential: Views tended toward pessimism regarding the commercial viability of fuel cells for residential power. A few respondents were emphatic that this market had no chance to succeed. As one respondent put it, "*this is a dead business model*." This respondent cited the high cost of building a complete fuel cell system, and said that, while a utility could spread the costs over many customers, an individual customer would not recoup the extra cost in a timely fashion. There would be no incentive, therefore, to invest in a risky new technology that offered no clear payback. A few respondents noted that the outlook for residential power was much more favorable in Japan, where the price of power is very high.

Micro-power: As already noted, a clear majority of respondents thought this market would be the first to materialize. Two companies in Japan, NEC and Toshiba, have already announced plans to introduce laptops powered by direct methanol fuel cells in 2004. Three years ago, many fuel cell experts felt that the promise of DMFCs was uncertain, and much of the attention was focused on their potential as a vehicle fuel cell. This view has changed over the last three years, with the focus having shifted to these micro-applications, where the DMFCs replace high-cost batteries. One respondent warned against becoming too confident of the pending commercial success of DMFCs; this respondent commented that some safety issues remained unaddressed (for example, whether it will be possible to bring a methanol container on an airplane).

Transportation – transit or commercial fleets: Three years ago, the clear consensus from fuel cell experts was that transit and other fleet operations would be the first transportation market for fuel cells. While many respondents still cited transit as a likely early market, there were quite a few who thought the prospects looked less promising than they did three years ago.

For those that believed cost would be the major driver for fuel cell commercialization, transit will come before the private vehicle market because the comparative costs of conventional transit technology is higher than for the auto market. Also, the federal government heavily subsidizes public transit purchases, and they offer a revenue stream to offset the initial outlay. It is easier to address the infrastructure issue with transit, as they return to a central depot each night and therefore do not depend on an existing network of fueling stations. However, many respondents noted that, in spite of the rosier cost and infrastructure picture, transit presents a significant hurdle in terms of durability. Transit operators require a sturdy vehicle with high reliability and a usable life beyond 10,000 hours. Meeting the tough transit requirements could delay commercialization for this market significantly. A few respondents also noted that, at under 5,000 new vehicles per year in the U.S., the transit market is just too small to allow fuel cell manufactures and vehicle OEMs to recoup their investment.

Transportation – passenger or private vehicles: The prediction for automotive commercialization depends on whether the respondent considers cost, durability or volume to be preeminent. Three years ago, most of the fuel cell experts interviewed believed that passenger vehicles would happen after transit. Many of our interview subjects still think transit will happen earlier, but quite a few expressed doubts that they said they did not have three years ago. Some indicated that the automotive market is the only one that offers sufficient volume to attract the interest of, and investment by, the vehicle OEMs and fuel cell manufacturers. Others noted that only the auto market offers the economies-of-scale that will be needed to drive down the cost of the fuel cell to a competitive level.

Synergism Among Different Fuel Cell Applications

Given that fuel cells are simultaneously being developed for use in a wide range of applications, we wanted to find out if there is any synergism among these various fuel cells development efforts. In other words, if fuel cells are launched first in the back-up power or portable PC market, will this have any spin-off benefits for other fuel cell markets? Or, for example, will the massive investment in automotive fuel cells advance development of stationary or transit fuel cells? The answers to these questions were wide ranging, covering all aspects of fuel cell and hydrogen systems development. Many limited their response to technological overlaps – synergies among the fuel cells themselves or synergies at fundamental levels, such as materials, engineering and catalyst development. Others stressed that the main synergies would be in external areas, such as codes and standards development or investment in hydrogen infrastructure. Overall, there was no broad consensus regarding the question of how development of one fuel cell application might benefit other fuel cell applications, but most respondents cited some areas of synergy.

Few thought that the development of the small portable power market (i.e., laptops, PDAs) would have much applicability to other markets. Micro-applications are employing direct methanol fuel cells; few, if any, other applications appear likely to use this type of fuel cell. And, while DMFCs are a type of PEM technology, few respondents commented on any synergy between technical development of DMFCs and other PEM applications. There may be some crossover between development of DMFCs for consumer products and military applications. Regarding fuel processing synergies, as no other fuel cell applications appear likely at this time to use methanol as a hydrogen fuel source, DMFCs do not offer fuel processing benefits for other fuel cell applications either.

Is there synergy among the fuel cells developed for cars, buses, back-up power, primary power? The simple answer is, yes and no. Many respondents were emphatic that there is little crossover. Although fuel cells are valued for their modularity, it doesn’t appear possible to take a single fuel cell design and scale it up or down to create fuel cells for all transportation and stationary applications. As one respondent said, *"you don't have much overlap between a Detroit V-8 engine and a diesel generator."* Likewise, the engineering characteristics for certain fuel cell applications are quite different. Primary stationary power requires very long operation at steady full power levels, whereas the automotive market has much lower durability requirements but requires more frequent dynamic response capability. Fuel cells will have to be optimized to meet the operational requirements of the particular application.

The flipside of this is that, where there are similarities in duty cycle, developments in one application might benefit another. For example, several respondents noted that some automakers are adopting a strategy of promoting their automotive fuel cell for use in the premium and back-up power market. If the power goes out, the fuel cell needs to start up immediately; automotive fuel cells will provide this quick start up capability. So, automakers can develop fuel cells for both markets, thereby spreading the investment costs over two markets.

Many respondents were enthusiastic about the potential for overlap in the development of fuel cell components – the plates, membranes, electrodes, and platinum catalyst. Development of better, more efficient, less costly, or more durable component technologies would benefit all PEM fuel cell applications.

Many respondents noted that the development of codes and standards for the early fuel cell markets would be a boon to development of other fuel cell applications. Codes and standards issues being addressed include transport of hydrogen and other source fuels like methanol; hydrogen refueling and storage; building codes relating to hydrogen vehicles; fuel cell recycling; and many others. Some of these are specific only to transportation applications, some only to stationary. Refueling standards clearly apply to vehicles only, but the development of standards for early commercial fleet demonstrations, for example, will benefit the private auto market as well. On the other hand, vehicle safety standards may be quite different for passenger vehicles than for heavy commercial vehicles as is already the case with conventional vehicle safety standards.

Several respondents believe that important synergistic benefits will be offered through the installation of hydrogen refueling infrastructure. As early fuel cell products are introduced, hydrogen infrastructure will develop to meet the fueling needs of the market. A few respondents thought creative use of early market synergies would help develop the infrastructure. Hydrogen supply centers or corridors could be set up at locations where both stationary and vehicle hydrogen refueling would be used – for example, at universities or utility companies. This approach may provide a greater return on the initial infrastructure investment.

Several respondents said that the development of stationary and transportation markets has increased the attention paid to the question of hydrogen sources. The U.S. Department of Energy has begun to fund exploration of clean coal, nuclear, and ethanol as potential hydrogen sources. Meanwhile, development of better hydrogen generation appliances, such as small-scale natural gas reformers and electrolysis devices, has benefited multiple markets.

If different fuel cell technologies are employed for different applications, will there be any shared economies-of-scale between markets? Some respondents suggested that early fuel cell markets will help advance manufacturing techniques. One fuel cell manufacturer noted that manufacturing lessons learned from one market would be applicable to others. Two fuel cell manufacturers questioned whether volume production of one application would reduce costs for other fuel cell types.

As most respondents think fuel cells will first be introduced in the small portable applications market, there is a sense that putting fuel cells in the hands of consumers will help increase familiarity with this new technology and pave the way for consumer acceptance of later applications. One respondent noted that familiarizing mechanics and technicians with fuel cells would be an important benefit of early fuel cell deployment.

Attention to fuel cells resulting from development of early markets could spur investment in other fuel cell types. As one respondent noted, "*having the same name could help raise investment; however, this could have a reverse effect*" in that, should an early fuel cell market attract negative attention, it could turn investors off of other fuel cell applications.

Military Applications

The United States military provides a unique opportunity to deploy fuel cell technology due to its unique purchasing habits because the military, more so than other markets, is more likely to value non-economic factors above simple cost considerations. Stated another way, it is the customer most likely to be willing to absorb an initial cost premium if the product satisfies their tactical requirements.

While there appears to be a consensus among the respondents that there exists a potential market opportunity in the military arena, it is not entirely clear where that market will evolve. The scaleable nature of fuel cell technology allows for the consideration of a multitude of military applications. These perceived military applications fall into three general categories; micro-applications, auxiliary power units, and vehicle propulsion. While each category offers its own opportunities, there exist several technical and policy impediments that will have to be overcome.

Micro-applications comprise any number of small-scale portable devices generally powered by disposable or rechargeable batteries. These portable devices provide an opportunity for fuel cells to be used as a replacement for battery power in the field. One fuel cell manufacturer estimated that the U.S. military uses in excess of 2,400 different types of batteries for small-scale portable power needs including computing, telecommunications, monitoring devices, and sensors. By replacing the traditional battery power source with small-scale fuel cells the U.S. military stands to benefit in several ways. Fuel cells offer a longer life cycle than do batteries, thereby increasing the field operating time of the unit being powered, and they could free the military from the burden of transporting a plethora of battery types into the field of operations. While most respondents generally regarded PEM as the fuel cell of choice for most military applications, direct methanol fuel cells were often cited as the most viable option for micro-applications.

Auxiliary power applications include larger devices that would generally be powered by the use of a diesel generator in the field, or devices used to provide vehicles with onboard electrical power. Fuel cells could be particularly beneficial in this area because they possess some rather attractive attributes. Fuel cells emit a relatively low heat signature and they operate much more quietly than ICEs. This makes them quite attractive when one considers stealth of operation. Additionally, they may reduce the amount of diesel required in the field thereby ameliorating a key logistical issue for the military.

Finally, vehicular transportation provides a third opportunity for fuel cell implementation, though this application seems to pose greater difficulty than the previous two. While most generally agree that there may be possible uses for fuel cells as a replacement for the ICE in lightweight and civilian vehicles (provided that there is a resolution to the fuel question) durability remains an issue. Given the shock and vibration that off-road and combat vehicles are subject to, it seems unlikely that fuel cells will prove to be a viable alternative to the ICE for combat vehicles in the near-term.

Several respondents noted that fuel cells provide a substantial benefit aboard very large vehicles and in large naval vessels. That is, they allow for the dispersion of the vessels' power source throughout the ship which may provide a tactical advantage in terms of power generation when facing attack by rendering the vessel less subject to a total loss of power if struck by a single piece of ordnance.

Ultimately, the same questions exist for the military that exists in other civilian markets. What type of fuel cell should be used? If the answer is PEM, how does one get hydrogen, where is the fuel processed, and how is it to be transported to where it is needed? On-site reformation was identified as the common response yet many respondents identified the military's single fuel doctrine as a key hurdle to on site reformation.

The logistical challenge of getting fuel where it is needed is a daunting one for the military. To reduce this logistical challenge the military has opted to use a single fuel source that offers a good balance of weight, volume, ease-of-use and energy density. They have identified JP-8 – a kerosene-based jet fuel -- as their fuel of choice. However, JP-8 can have sulfur content as high as 3000 ppm and is generally considered too dirty to be reformed for use in PEM fuel cells.

One respondent pointed out that fuel cells might have only limited application in field operations because the armed forces are presently tied to the existing fuel infrastructure. Thus, there exists a need to develop a high quality, sulfur-tolerant fuel reformer in order to implement a fuel cell solution. However, smaller portable systems (below 1kW) allow for the use of specialty pre-packaged fuels, essentially avoiding the on-site reformation issue altogether.

Developmental Drivers in the Transportation Fuel Cell Market

Debating the future of fuel cell research and infrastructure development amounts to no more than an academic exercise if one fails to consider the key issues that drive what is in truth a rather dramatic societal change. It is regarding this subject, the factors driving fuel cell development, that we have seen a significant change regarding the respondents' opinions. While the three key issues cited in our original report, criteria air pollutants, global warming, and oil availability, continue to drive the United States towards a hydrogen economy, a new presidential administration as well as the events of September 2001 have conspired to propel the issue of energy security to the fore.

The events of September 11, 2001 have inspired the current U.S. Administration to devote resources to the investigation of alternative technologies that appear to hold some promise for weaning the U.S. from its foreign oil dependency by allowing it to become more self-sufficient in terms of providing its energy needs. The Bush Administration has, through various programs at the U.S. Departments of Energy, Transportation and Defense, chosen to focus a significant amount of attention on fuel cells and hydrogen as the energy source of the future. As one energy producer stated, *"President Bush has decided that this will be his legacy."* Whether or not this is true, it is undeniable that current U.S. policy has had a tremendous impact on fuel cell development, both in terms of funding and public awareness. At the same time, several of our respondents agree that more should be done. One environmental group expressed concern that the current Administration's efforts may in fact detract from a greater goal of reduced emissions.

> *"…There is some thought that President Bush is focusing on hydrogen as a "holy grail" that is coming, so there is no need to do anything about auto emission and fuel economy in the near-term."*

Clearly environmental concerns remain a key element in the push to develop fuel cell technology. One fuel cell manufacturer explained that pollution is still the big driver, especially at the local level. Climate change, though possibly a more significant issue at the government level, is less of a driver at the community level because climate change *"…still seems distant to most people."*

In addition to the afore-mentioned, efforts of the world's automobile manufacturers were described as both a driver and a liability to the advancement of fuel cell technology. One expert explained:

> *"The automakers are the choke point for fuel cells; if they don't want it, it won't happen. They don't have any reason right now to transfer from their current technology to fuel cells…the power resides with the auto-manufacturers, and the auto manufacturers have settled, for a variety of reasons, on hybrids."*

However, some have argued that a growing sense of competition among automakers has stimulated development by inspiring them to develop programs so that they don't get left behind. One environmentalist explained:

"…a sense of competition among auto manufacturers has been a contributor. Company A doesn't want to see company B eat their lunch. The international gap is not a technological one, it is a business and marketing gap. Honda and Toyota could have 100,000 vehicles on the road before the U.S. automakers place their first."

An automaker further commented:

"There has been a lot of development resulting from the very competitive nature of the business. [We] do not want to lose technology leadership. No one wants to come in second."

Our interviewees explain that over the past three years, while the 'traditional' drivers remain influential, political issues and intra-industry competition have focused greater attention on fuel cell development to good effect. A fuel cell manufacturer summarized with the following:

" Energy security went to the front after September 11th. Now everyone is aligned politically. This is very good. We should see more money going into hydrogen storage, and research and development. Then, the government should become an early purchaser. Competition among governments will drive this…states and regions are competing to become fuel cell clusters. I think that countries will compete in the same way."

When Will Fuel Cells Capture Significant Market Share?

Prior to our discussion it seems necessary to define the term 'significant' which turned out to be so vague and relative a term that it was initially difficult to elicit a meaningful answer from our respondents during the interview process. Settling upon a definition proved more difficult than we anticipated because what may seem to be a significant number of units to a small fuel cell developer may hardly be enough to justify market entry to a large energy supplier.

Through repeated conversation we ultimately settled on the following definition: when discussing the adoption of a new technology one can assume that 'significant market penetration' occurs at some point between 10% and 20% of annual U.S. vehicle sales. The general opinion of the respondents was that the 10% level seems to allow for the momentum of the technology to propel itself forward exponentially. Or as one researcher put it:

> *"There isn't really much of a time-line difference between 10% and 20% market penetration. Once you hit 10%, the market will pick up quickly. It is non-linear in development."*

With a definition of significance in hand we can turn our attention to the respondents' opinions. It should come as no surprise that, of those who were willing to attempt to specify a timeframe, estimates varied wildly. Estimates for significant market penetration for both passenger and transit vehicles fell within a range that spanned from the years 2010 to 2040 with 75% of the estimates falling in the decade bounded by 2010 and 2020.

Despite this variance among the predictions there are some generalizations that can be made regarding points of agreement among the respondents. We can, from the responses received, infer two things. First, all of the respondents except for one believe that fuel cell technology will evolve to the point where it does eventually capture a significant share of the U.S. automobile and transit markets. Second, that level of market penetration is not likely to occur before the end of the present decade.

Additionally, a majority of respondents cited a belief that transit fleets would adopt fuel cell technology some five years before the passenger market. There were three reasons generally given for this opinion.

First, transit operations have a tendency towards early adoption as a result of their centralized fueling and maintenance facilities, which would allow them to more easily resolve the hydrogen infrastructure issue.

Second, diesel transit buses generally operate in densely populated areas which should create some obvious benefits for transit applications because running in a congested area creates a greater incentive for zero emission vehicles.

Third, competition from other governments will create an incentive to accelerate the adoption of fuel cell technology by transit operators. For example, one auto manufacturer pointed out that China has established as a goal the operation of fuel cell buses at the 2008 Olympic Games in Beijing. This does not necessarily create a direct incentive for the average transit operator to accelerate his plans but, it does provide a motivation for policy makers to either enact legislation that is designed to create an incentive for fuel cell adoption, or to increase funding for research and demonstration initiatives.

Regarding the passenger vehicle market several respondents observed that the introduction of fuel cells to the market is likely follow the same path that has been followed by hybrid technology to date. Here is the process as predicted by one fuel cell manufacturer:

> *"Passenger vehicles will happen in three phases. We are in the first phase now with the launch of pre-production vehicles numbering in the hundreds. We will test for a few years and learn more about the technology and how to improve it. Assuming this is successful, we will move to phase two, which is the next generation of fuel cells in fleets. There you will see fuel cell vehicles numbering from the low hundreds to the thousands. Phase three… will be in the tens of thousands of vehicles."*

The respondents believe that the timing of market penetration for both passenger vehicles and transit fleets will be affected by a variety a factors including: gasoline and diesel prices; technical issues such as durability and fuel cell life expectancy; the level of government incentives and investment; the evolution of codes and standards related to hydrogen; and the development of hydrogen infrastructure. All of these issues will be discussed in further detail in subsequent sections.

So, how have the respondents' views changed over the years since Future Wheels was first published? Given the responses thus far, it may come as no surprise that their opinions regarding the timing of market penetration have become more conservative. As a result of a perceived slow down in addressing the influencing factors listed above, at least half of our respondents indicated that their time estimates had slipped by a few years; the most pessimistic said that they now viewed commercialization over the next 20-30 years less likely than it appeared three years ago. Other respondents indicated that their opinions had not changed. The most optimistic were the auto manufacturers themselves with one stating:

> *"There have been a lot of leaps in technology…[fuel cell vehicles] have moved from R & D to vehicle development."*

Long-Term Prospects for Transportation Applications

It might seem a given that the prospects are good for long-term commercial success of fuel cells for transportation. Automobile manufacturers are making huge investments in fuel cell development, fuel cell manufacturers are moving their products from the laboratory to demonstration and even early consumer use, and governments around the world are committing public resources to ensure fuel cell development. Nevertheless, many respondents noted that, at this point, the whole transportation fuel cell effort is still highly speculative. Estimated target dates for significant market penetration for all vehicle applications have moved further out relative to where they were three years ago, and are frequently estimated as being no closer than a decade away. When discussing what may or may not happen in a decade and beyond, the conversation is inherently somewhat speculative.

Since the target dates for commercial introductions have slipped, we asked respondents for their view on the commercial viability of fuel cell vehicles, to see if there were any major concerns, any major show-stoppers on the horizon. We asked about five categories of fuel cell vehicles: passenger, transit buses, medium-duty, other heavy-duty, and off-road. Generally, the outlook is still positive for automotive and transit vehicles, but some respondents were more pessimistic. The outlook for the heavy-duty and off-road vehicles was more negative.

Passenger Vehicles

The view here was mixed, with most respondents rating the prospects as good or very good, but with others believing it is more speculative and uncertain. Not surprisingly, the automakers and fuel cell companies were optimistic about the potential for long-term commercial success. They noted that the internal combustion engine would be around for a long time yet, but in the very long term, fuel cells would take over the market. Several respondents who were bullish on the passenger market cited the car companies' large financial investment as evidence of fuel cells' commercial viability.

Cost seemed to be a big factor in how the passenger market was rated. One respondent asserted that "*they will take the whole passenger market when the price hits the 10s of dollars/kW*." Others who were more uncertain about the passenger market said that cost was the major barrier to be overcome. They expressed doubt that passenger vehicles could achieve the cost reductions necessary to meet the passenger market's pricing targets. For others, however, the durability issue was pre-eminent, reflecting the debate over how the fuel cell markets will develop. Some respondents said that fuel cells would show success in the passenger vehicle market before the transit market because the passenger market demands a 5,000-hour operational life whereas the requirements for the transit market are significantly greater.

The long-term nature of fuel cell commercialization is enough to convince one respondent that the whole enterprise is highly speculative. According to this view, it will take at least 20 years to address the technological issues for fuel cell vehicles – especially for development of hydrogen storage technologies:

> *"So many other factors will have arisen during this timeframe that it is impossible to predict anything. We could see battery electric technology becoming competitive in that time. Or you could have greater electrification of the transportation system. Other radical possibilities are equally as likely as fuel cells."*

A few respondents noted that the success of hybrid-electrics make the outlook for fuel cells less certain. Hybrids are extending the life of ICEs, taking away some of the efficiency advantages that fuel cells offer over conventional ICEs. Others noted that the delay of the California Air Resources Board's ZEV requirements had slowed progress in fuel cell development.

Transit Vehicles

The views on transit were generally positive. Many thought that it would achieve commercial success before the passenger market because cost is less of an issue. The cost of the fuel cells is amortized over many years, and the vehicles have revenue-generating capabilities. Also, environmental drivers are more important in the transit market, which will push interest in fuel cells. One respondent noted that this could be a strong driver for developing countries to deploy fuel cell transit vehicles. Countries looking to bypass the gas/diesel infrastructure could move straight to hydrogen for commercial fleets. Some respondents were less optimistic about transit buses, seeing them only as an interim demonstration platform because of the durability requirements. Others felt that fuel cell production would not be justified for the transit market alone; in this case, development of a transit fuel cell market is dependent on successful development of the passenger vehicle market.

Medium-Duty Vehicles

Because there is less attention being paid to medium-duty applications, respondents seemed less certain about the viability of fuel cells in this market. Several did say that fuel cells would be a good option for medium-duty service vehicles. One environmental advocate noted that General Motors is demonstrating a fuel cell FEDEX truck in Japan, which this respondent felt was a good application. Others mentioned that urban delivery vehicles offer an incentive to switch to a more environmentally friendly technology because they operate in congested areas that frequently struggle to maintain compliance with federal air quality standards, and because they operate on low-mileage fixed routes and return to a central depot at night. As one consultant noted, for commercial delivery companies like UPS and FEDEX, "*they can make a business case here that the business will benefit from being perceived as environmentally friendly.*"

Heavy-Duty Vehicles

The prospects for heavy-duty trucks are poor, at least for fuel cells as the primary propulsion device. The drive cycle for long-haul trucks is ideal for the incumbent technology, the diesel engine. Heavy-duty trucks travel very long distances at steady highway speeds. Diesel engines are already extremely efficient in this mode, so there is no incentive to switch to fuel cells. This was the consensus view of most respondents. Some also noted that it will be impossible to switch to fuel cells for cross-country driving without a widespread hydrogen infrastructure. The amount of fuel required to operate a heavy-duty truck on long haul trips would also be a barrier. When compared to diesel tanks, the required hydrogen storage tanks would be much bigger in both volume and weight.

The potential for fuel cells in the truck market is as APUs. It was noted that fuel cell APUs have good potential for military applications, and that the military is already exploring this option. For commercial trucks, some thought that fuel cell APUs could replace the current practice of idling the trucks while the driver is sitting at the truck stop. This issue has attracted the attention of environmentalists and government regulators, who see this as a good opportunity for reducing the environmental impact of heavy-duty trucks. However, other respondents expressed skepticism that fuel cell APUs would be used for this purpose. They asserted that truck stop electrification is a simpler, cheaper way to address this problem.

Off-Road Vehicles

Opinions regarding the off-road vehicle market were mixed. Many did not have strong opinions about this market, but no one suggested that fuel cells would be viable for heavy-duty off-road vehicles like back hoes. The problem for fuel cells is the durability and ruggedness required for these applications. Diesel engines have an advantage here because they are reliable, robust, and long-lived, and they offer superior low-end torque.

A few respondents said that fuel cells could be applicable for small off-road applications, where you might only need a 25 – 30 kW fuel cell. Suggested applications included airport ground service vehicles and golf course equipment, which generally have centralized maintenance facilities and fixed service routes.

Definition of Fuel Cell Types

A fuel cell consists of two electrodes separated by an electrolyte. Fuel cells are typically classified according to the type of electrolyte used. As the U.S. Department of Energy's website notes, it is the electrolyte that "determines the kind of chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors."[1] These factors, in turn, determine the applications for which each fuel cell is best suited.

Proton exchange membrane fuel cells (PEM) use a solid polymer electrolyte (they are also known as "solid polymer fuel cells") which must be hydrated to allow the hydrogen ions to move in it. They operate at low temperatures (around 50ºC or 120ºF), which means they can start up quickly. PEM fuel cells use a noble-metal catalyst and a proprietary membrane. The most commonly used catalyst is platinum, which is sensitive to carbon monoxide at low-temperature operation. PEM is the leading fuel cell technology in development for transportation applications.

- ***Direct methanol fuel cells (DMFC)***: DMFCs are a type of PEM fuel cell that use methanol directly as the source for hydrogen, eliminating the need for a fuel reformer or hydrogen and making the fuel cell system very compact. They operate on a solution of water and methanol, with operating temperatures in the same range as PEM, about 50ºC (120ºF). To date, efficiencies for DMFCs are low, with output levels up to 5 kW; at this level, they are primarily suitable for micro-applications.

- ***Regenerative PEM-based fuel cells***: PEM fuel cells can be designed to run in reverse, acting as an electrolyser. When operating in reverse, the fuel cell uses electricity to separate water into oxygen and hydrogen fuel, which can then be run back through the fuel cell to generate power. This feature makes the regenerative fuel cell ideal for coupling with solar and wind electricity generation.

Alkaline fuel cells (AFC) are one of the most developed of the fuel cell types. The Apollo and space shuttle programs used AFCs because of their very high efficiency. The space shuttle fuel cells are operated with an aqueous potassium hydroxide (KOH) electrolyte at a temperature of around 100ºC (212ºF). AFCs have a low tolerance for all carbon bearing gases, which requires use of extremely pure hydrogen and oxygen supplies.

Phosphoric acid fuel cells (PAFC), which utilize widely available phosphoric acid as the electrolyte, are the most commercially developed fuel cell. Their operating temperature is around 200ºC (392ºF), which does not give them instant startup capability, but does make them more tolerant of carbon monoxide. PAFCs have been used in commercial operations, where they have demonstrated good durability and reliability.

Solid oxide fuel cells (SOFC) use a ceramic electrolyte and operate at very high temperatures, around 1000ºC (1830ºF). The high temperature means SOFCs can internally reform hydrocarbons, such as natural gas, without the need for a separate reforming unit; however, they do not have instant startup capability, as the fuel cell requires a lengthy warm-up period. The high temperature environment puts more stress on the system components, reducing system durability. SOFCs are often considered for cogeneration applications that can capture and utilize the system's waste heat, improving the overall system efficiency.

Molten carbonate fuel cells (MCFC) use a high temperature carbonate mixture for the electrolyte and operate at about 650ºC (1200ºF). High temperature operation means that MFCSs can internally reform hydrocarbons, but also results in a lengthy startup delay as the fuel cell warms up. The carbonate mixture causes corrosion problems, reducing durability. Like SOFCs, MCFCs are considered for cogeneration applications that capture and utilize the system's waste heat, increasing the fuel cell system efficiency.

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Fuel Cell Technology

Fuel Cell Types for Transportation

The debate regarding two issues seems to have subsided since the original publication of *Future Wheels*. First, whereas there was a significant amount of debate surrounding the optimal fuel cell type for transportation, the experts that we spoke with in 2003 were, for the most part, unanimous that the choice would be PEM (using hydrogen), and that the choice of fuel cell would be unaffected by the placement of the reformer.

Second, a consensus seems to have been reached regarding another issue that was hotly debate only a few years ago, onboard reformation. This time around, the majority of our respondents believe that reformation will take place off-board.

Simply stated, the overwhelming majority of respondents believe that PEM is the technology best positioned today to overcome the technical hurdles to mass adoption by the transportation industry. The decision regarding PEM is not influenced by the issue of on- versus off-board reformation. As one auto manufacturer stated:

> *"It's PEM…the others aren't viable for reasons of cost, durability, and operating temperature."*

While other existing fuel cell types were discussed there appeared an overall belief that it is doubtful that any new fuel cell technologies would be established that could supplant PEM as the type to be used in the coming decades. One researcher stated,

> *"It is unlikely that there will be a newly developed fuel cell type. The development period is simply too long…if fuel cells work at all, it will be PEM."*

Some of the key reasons cited for PEM include its low operating temperature, and shorter warm-up and start-up times. PEM was also cited as offering the greatest potential for the kind of cost reductions that will allow the technology to evolve into a viable choice for consumers.

Other possible technologies that were mentioned include direct methanol, solid oxide, molten-carbonate, and alkaline. Direct methanol was observed to be better suited for small portable devices and battery replacement. Respondents explained that some of the automakers seem to have cooled on direct methanol technology for reasons of cost and power density. One expert offered that the development of a methanol infrastructure seemed less likely than it did three years ago due to the toxicity concerns surrounding the fuel. Solid oxide was offered as a possibility for passenger and transit vehicles; however, this technology has technical properties (high operating temperatures and long warm-up time) that make it better suited for stationary applications than transportation. Molten carbonate was described as being viable for trains and ships. Alkaline fuel cells offer high efficiency that makes them suitable for aerospace applications. Many respondents were quick to qualify their answers by explaining that all of these technologies will continue to be tested and that a significant technological advance in any one of them could tip the scales in that technology's favor. However, PEM seems to be the likely candidate, and, if there is to be a break through with another technology, it will have to happen quickly because once the industry dedicates itself to a particular technology it will be difficult to change course.

Cost Barriers to Successful Commercialization

When asked to address the possible cost barriers to the development of a commercially viable fuel cell stack for transportation the respondents discussed a variety of issues that need to be resolved in order for a commercially viable fuel cell vehicle to be offered to market. As the interviews proceeded certain common observations began to emerge. These observations tend to fall into one of two categories: costs involving the fuel cell stack itself, and costs that are not specific to the stack but are related to the development of the vehicle. We will take up the discussion of cost issues related to the fuel cell stack first.

There were five key observations regarding stack related cost barriers: 1) the number of parts used in the stack; 2) the cost of the catalyst; 3) the cost of the membranes; 4) automation of assembly; and, 5) supply chain development.

The number of parts refers to the raw quantity of parts that are assembled to create the fuel cell stack including the plates and other required components. Three of our respondents stated that this creates a significant issue in terms of the cost of the completed stack. If one considers that each individual part carries with it all the costs of its individual design, manufacture, delivery and integration it should become clear that by simply reducing the sheer number of parts assembled to create the final product there exists a potential for significant savings which is in turn reflected in the cost of the final product. They further noted that, if the developmental process followed by other advanced transportation technologies is any kind of indicator, this issue should resolve itself through continued research and development efforts as manufacturing and technological advances allow for efficiencies in component design and assemblage. One fuel provider noted:

> *"All that other equipment…pumps, air and water management, etc., is balance of plant stuff. The U.S. DOE is focusing a lot of attention on balance of plant stuff."*

That the cost of the catalyst used in the manufacture of fuel cell stacks is most often mentioned as the key cost issue facing fuel cell manufacturers today should come as no surprise to anyone familiar with the technology. The most commonly used catalytic material used in PEM today is platinum, which also happens to be one of the more expensive elements available. The goal here is to either reduce the cost of the platinum, reduce the quantity of platinum used in manufacture, or remove platinum from the process altogether. Despite the fact that platinum prices have fallen over the past decade it seems unlikely that the market will adjust such that the cost of platinum will decline so far as to make it cost effective for transportation applications. Therefore, we are left to pursue the two latter options. Our respondents do concur that the reduction, or ideally elimination, of platinum as a catalyst is a matter of research and funding. Several respondents noted that the hybridization of fuel cell vehicles would allow for the use of smaller fuel cells, which in turn implies a lesser amount of platinum onboard each vehicle. Additional platinum savings may also be pursued through low catalyst loading technologies and platinum recovery plans.

The respondents believe that the last three stack related cost issues -- the cost of the membranes, automation of assembly, supply chain development -- would likely be addressed, either directly or indirectly, through economies of scale. However, they believe that a "chicken and egg issue" exists. That is, suppliers won't invest in more cost efficient mass production technologies until they see some volume; however, there won't be any volume until costs come down. The same argument can be made when discussing the need for competition among suppliers of components and membranes as a prerequisite to cost reduction. That is, new competitors aren't likely to enter the market until they see enough demand to generate a profit.

Aside from stack related issues, there were also three key observations that were not specific to the stack but related to the general operation of fuel cell vehicles. These include hydrogen storage, the usable life of the fuel cell, and the required investment in hydrogen infrastructure.

The technical issues surrounding onboard hydrogen storage are treated in greater detail later in this report. What is recognized here is that regardless of the technology used to store hydrogen onboard the vehicle, the respondents believe that to offer a commercially viable passenger vehicle, that vehicle must be capable of storing enough fuel to permit it a range of at least 300 miles. Most of our respondents believe that the cost of doing so is presently prohibitive, and further time and research will be required before a cost efficient means of hydrogen storage is available. It is important to note that this was not a point of unanimous agreement among the interviewees. Two indicated that they believed that storage was not an issue because current storage technologies will permit the required 300-mile range if one addresses the issue from the point of view of vehicle development. In other words, build a more efficient vehicle and storage is no longer an issue. One independent researcher offered the following:

> *"There is no hydrogen storage issue…the biggest barrier is that too much attention is being paid to stack cost instead of vehicle physics and the development of fuel efficient platforms."*

The lifespan of the fuel cell was identified by some respondents as an issue that is also resolvable through further investment in research. The idea here is clear. If a fuel cell has an operational life expectancy of only 1000 hours (approximately 20,000 miles), then the vehicle becomes too expensive to operate on a per mile basis when compared with an ICE vehicle that can provide its owner with at least 100,000 miles of operation when properly maintained.

Infrastructure, while also treated in a later section, was discussed as a cost issue because the source and extent of investment will impact the cost of operation for the vehicle owner, either through the cost of fuel or in the cost of the vehicle itself.

The key observation here lies not only in the stated cost barriers but also, in the respondents' opinion that these issues can and will be addressed through continued development efforts. Finally, we should note that some respondents did make clear that, given the developmental status of the technology, the costs associated with the technology are not necessarily out of line with where they should be. In the words of one fuel cell developer:

> *"Everyone is fixated on how much a fuel cell vehicle costs today. For example, a fuel cell vehicle today reportedly costs millions of dollars. But, a hand-built prototype ICE vehicle also costs millions. As the fuel cell industry ramps up, costs will come down."*

Remaining Technological Challenges

In the beginning of this report we reviewed the major changes in fuel cell technology and hydrogen infrastructure development since the first *Future Wheels* report three years ago. Given that, since then, fuel cell manufacturers and vehicle OEMs have developed the next generation of their fuel cell technologies, put the fuel cells in various vehicle platforms, begun demonstrations, and continued fuel cell R&D with an eye toward volume manufacturing capability, what technical challenges remain before fuel cells can be successfully commercialized? Based on lessons learned thus far and improvements made over the past few years as a result of this intense development focus, there is greater clarity surrounding the remaining technological challenges to full-scale commercialization of fuel cell technology. (It should be noted that several respondents abstained from responding because they were not close enough to the fuel cell manufacturing side of the industry.) On the hydrogen infrastructure side, recent demonstration programs offer insight into key issues; these issues will be discussed in a later section.

Respondents cited three major challenges: cost, durability and reliability. These were sometimes cited as show-stoppers, should fuel cells fail to meet targets for these attributes. They are also intertwined, as work on the fuel cell stack to increase its lifetime will impact its cost per kW. As a result, they are receiving the most attention from government in terms of R&D and demonstration funding. Other engineering issues such as freezing temperature operation, heat rejection, and impurities tolerance were cited as outstanding, but most respondents saw these as on the pathway to successful resolution.

Finding a resolution to these issues will require time, money, and testing. Most respondents noted that the next year or two will bring clarity to the question of whether these issues can be resolved. Fuel cell companies are putting their new fuel cell technology – already significantly advanced over three years ago – into field trials. These demonstrations will highlight problems, allow fuel cell manufactures and vehicle OEMs to try various possible solutions, and, it is hoped, make the pathway to resolution clear.

Cost Challenges

Although cost is not precisely a “technical” barrier, it is clearly related to development of the technology. Most respondents cited cost as a key barrier that, if not resolved, would prevent commercial success in the passenger vehicle and transit bus markets. (Cost issues are discussed at length in the previous section.)

Durability

As previously noted, the passenger vehicle market requires a fuel cell that can operate for 5,000 hours before failure occurs. The transit bus market requires at least a 10,000-hour operational life. However, according to one respondent with experience in fuel cell development, most fuel cell stacks currently fail after only 1,000-2,000 hours. Although another fuel cell manufacturing company indicated that the technology is rapidly advancing toward the 5,000-hour mark, there remains work to be done if the technology is to meet the commercial durability requirements for both the passenger and transit vehicle markets.

As one fuel cell manufacturer noted, it is critical to reduce the mean time between failures for the fuel cell system. According to this manufacturer, the failure rate largely results from balance-of-plant issues. Efforts to reduce the complexity of the system will help to reduce failure rates. In addition, more field trials will help to pinpoint the problem areas, and fuel cell manufacturers will have to work closely with suppliers to help them design components appropriately.

General Stack Issues

Beyond the basic stack life challenge, respondents mentioned a host of technical challenges relating to the stack, including freezing, platinum reduction, and tolerance of CO and other contaminants:

Platinum reduction: This is really a cost issue, but the burden is on the engineering side to reduce the amount of platinum loading required for the catalyst. Platinum is one of the most costly components of the fuel cell system.

Sub-freezing temperature operation: Right now, if a fuel cell car were to be left outside during freezing temperatures, the fuel cell would turn to a block of ice. This raises two concerns. First is how to start the vehicle in a timeframe acceptable to the average driver if the fuel cell is frozen. Second is how to avoid degradation of the stack as it repeatedly goes through freeze/thaw cycles. Fuel cell manufacturers and automakers are working to address these problems, which they noted is essentially an engineering and packaging issue.

Tolerance of contaminants: Fuel cell manufacturers are working on the problem of poisoning of the fuel cell by contaminants in the hydrogen and in the air mixed with the hydrogen. Right now, PEM fuel cells require very pure hydrogen, as the platinum catalyst is rendered ineffectual if contaminated by carbon monoxide or sulfur. When these impurities are present, they react with the platinum and stop their catalytic reaction. Respondents seemed to feel that this problem was in the process of being successfully addressed. If this issue is not addressed, it will be a significant cost burden, as the hydrogen will have to be purified to a very high degree.

Balance of Plant Issues

Several respondents note that there needs to be continued engineering and testing of the ancillary components in the fuel cell system. Key issues to be addressed include heat and water management and the overall system packaging. Again, this is important in addressing the major overarching issues of cost, durability and reliability.

Start Up Time

Three years ago, this was a frequently noted problem. For the most part, respondents either felt that this issue has already been addressed or were confident that it is in the process of being resolved successfully. One reason for this issue's resolution can be attributed to the rejection of onboard reformation. Getting a gasoline reformer to start up in a consumer-acceptable time was a major problem for onboard reformation systems, so removing this option removes the problem.

Power Density

Work is ongoing to increase the efficiency of the fuel cell system. One respondent noted that fuel cells need a good step improvement in the power efficiency of the fuel cell, in order to reduce the amount of hydrogen storage required to get an acceptable range. Conversely, if there is a major breakthrough in hydrogen storage, or in the overall vehicle efficiency, this would make the fuel cell system efficiency less of a concern (although the cost of hydrogen would still provide a strong incentive to increase fuel efficiency). Many respondents cited hydrogen storage as a major barrier to successful commercialization of the fuel cell vehicles.

Hydrogen ICEs, Hybridization, and Fuel Cells

The Hydrogen ICE

The respondents were divided over the issue of direct-drive hydrogen ICE vehicles. Roughly 65% of those who answered the question believed that there would be marketing, to some extent, of hydrogen ICE vehicles while the remainder said either that we will not see a substantial introduction of ICEs, or that they were undecided.

Those who indicate that there will not be a market for hydrogen ICE vehicles believe that there doesn't seem to be any rationale for a market to develop. As one hydrogen supplier simply stated:

> *"There will be no hydrogen-powered ICEs. Why would you? If one has the infrastructure, use fuel cells. They are more efficient than an ICE and superior to hybrids. There is simply no advantage to hydrogen ICEs."*

Another respondent pointed out that the current U.S. Administration seems "lukewarm" towards them. Several respondents did offer possible reasons why hydrogen ICEs would be introduced. The introduction of hydrogen ICE vehicles may accelerate the development of hydrogen infrastructure. This was clearly the most common argument for the eventual introduction of hydrogen ICEs. The general argument claimed that if it may take a decade to offer fuel cell vehicles to consumers in any kind of quantity, hydrogen ICEs may be an intermediate step. The hydrogen ICE vehicle could provide a near-term solution for oil dependency while stimulating the development of hydrogen infrastructure that would in turn stimulate the adoption of more efficient fuel cell vehicles in the future. Thus, despite certain inefficiencies we may see an introduction of hydrogen ICEs. In discussing the situation one auto manufacturer said the following:

> *"Hydrogen ICEs will probably happen…however, using hydrogen with ICEs does not make sense from an efficiency point of view. You are taking the fuel with the worst well to tank efficiency and combining it with least efficient propulsion technology."*

Among those who believe that there will be an introduction of hydrogen ICEs there was a fair amount of disagreement regarding the extent of the potential market for such vehicles. There was, however, widespread agreement that such vehicles would only serve as an intermediate step towards fuel cell transportation because the auto manufacturers' interest is in the value proposition created by the increased efficiency and decreased emissions offered by fuel cell technology. Additionally, fuel cells allow for the use of the automotive power plant as a plug-in auxiliary generator during engine down time, noted by several respondents as a benefit that ICEs do not offer.

Finally two interviewees did point out that we are likely to see hydrogen ICE vehicles to some extent simply because at least one auto manufacturer (BMW, who did not respond to our requests for an interview) is presently developing a hydrogen ICE program.

Hybrid Technology and Fuel Cells

There seems to be a general consensus that fuel cell vehicles are likely to be hybridized. There were three key reasons offered by the respondents.

Hybridization will allow for the use of smaller fuel cells while possibly extending their operational life. This is a significant point when one considers the cost issues discussed in previous sections. The use of a smaller fuel cell implies a lesser amount of expensive catalyst carried by each vehicle, reducing per vehicle cost. At the same time, hybridization reduces the demand put upon the fuel cell when the vehicle is accelerating and at other peak demand times. This may result in an increase in the usable life of the fuel cell, which significantly affects the operational cost of the vehicle as well.

Hybridization ameliorates the onboard hydrogen storage issue resulting in greater range for any given storage capacity and reducing per mile overall hydrogen consumption.

Finally, hybridization allows for the vehicle to benefit from regenerative braking technology by allowing the vehicle to capture and store for later use energy that would otherwise be lost through vehicle braking.

Fuel Cells vs. the Pairing of a Hydrogen ICE With a Hybrid-Electric Drivetrain

While a small majority of respondents believe that hydrogen ICEs will be offered in the future, a large majority of respondents believe that pure fuel cell vehicles are a superior alternative to the pairing of a hydrogen ICE with a hybrid electric drivetrain.

Hydrogen ICEs, though clean relative to gasoline ICEs, tend to produce a significant amount of NO_x. Fuel cells offer a zero-emission alternative to hybridized hydrogen ICEs while also offering gains in efficiency. One fuel cell developer summarized the discussion as follows:

> *"It's possible that we will see hybrid ICEs before mass market fuel cell vehicles. Ford is exploring them as a bridge to build out the infrastructure. However, they will not be the ultimate replacement technology. Even though they are clean, they are not zero emission. You still have NO_x emissions. Fuel cells are better than a hybrid ICE because hybrid ICEs pair two different systems…which is more complex and costly."*

Fuelling the Fuel Cell Vehicle

Big Picture: What Are the Major Challenges Regarding Infrastructure Development?

When discussing any new vehicle technology, inevitably the phrase “chicken and egg” will come up. The big question when a new vehicle type is introduced that will not necessarily utilize the existing refueling infrastructure is, how does one fund an entirely new infrastructure? Consumers will not buy a vehicle that cannot be conveniently fueled, but the massive investment required to install new refueling stations or to “retrofit” existing stations may not come when there is no vehicle market to attract that investment and promise an adequate rate of return.

Most respondents noted that this is a major barrier to developing the fuel cell market. A few were more optimistic, asserting that this problem is overstated and likely will not prove difficult to overcome. There were a variety of proposed approaches to resolving the chicken and egg dilemma:

- Develop a backbone: Many respondents urged government support for developing early refueling stations. As one fuel cell manufacturer put it, government could fund the “backbone” of a hydrogen infrastructure, funding installation of regional hydrogen refueling centers. Private funding would then step in to develop the local fueling stations connected to that backbone.

- Hydrogen supply centers: Develop early hydrogen supply centers in connection with demonstrations of both transportation and stationary fuel cells. These could be places like universities or office buildings. This approach would spread the investment costs over the two fuel cell applications.

- Keep doing what we’re doing: Some said that this problem is being overstated. As one fuel cell manufacturer noted, hydrogen infrastructure is already being implemented “as needed" in order to supply hydrogen for existing demonstrations. As the fuel cell vehicle market continues to develop, it will likely happen in commercial fleets, with necessary infrastructure being put in place. By the time the technology is ready for the private vehicle market, a limited number of hydrogen stations will already be in place that can meet the initial “early adopter” market.

- Think small: Another respondent suggested that, early on, small-scale production from a mix of electrolysis and on-site reformation could build the infrastructure with relatively small investments over time: *"You could have a station that would refuel 50 vehicles at a cost of about $150,000 station. This is a financial exercise more than a technical one."*

Fuel Choice and Development of Hydrogen Sources

Currently, most hydrogen is produced from natural gas. Many respondents said it is necessary to cultivate other sources, with an eye toward keeping down the cost of the hydrogen and the well-to-wheels environmental impact. The U.S. Department of Energy is devoting resources to developing hydrogen production from clean coal, nuclear and ethanol, in order to expand the range of cost-effective options beyond natural gas. Many respondents stressed the need to develop renewable hydrogen sources, to draw the greatest environmental benefit out of the fuel cell transformation.

A New Paradigm

The hydrogen refueling infrastructure need not be modeled after the existing vehicle fueling station network. Hydrogen is more conducive to a distributed generation scenario, with small hydrogen generation devices being deployed at the retail station level. These devices could generate hydrogen from the most appropriate local source of hydrogen, whether that be natural gas, clean coal, biomass, renewable electricity, or other sources. Some respondents noted that, if the major energy companies do not step in with the required investment, electrolysis companies or other small hydrogen appliance companies could step in.

Another aspect to fuel cell refueling, according to some respondents, is that it will require cooperation between the vehicle OEMs and the fuel provider. Right now, said one respondent, the automotive world is "balkanized", with car companies viewing vehicle development as entirely separate from refueling, and vice versa on the part of the energy companies. With fuel cells, these parties will have to cooperate in order to develop communications protocols between the cars and the refuelers.

Codes and Standards

A majority of respondents cited the development of appropriate codes and standards as critical to the successful deployment of a hydrogen infrastructure. Siting, zoning, handling and other codes and standards issues need to be addressed if hydrogen infrastructure is not to be impeded. Respondents stressed that hydrogen safety standards need to be developed at a national level, and, ultimately, an international level. Right now, everything is very localized, with individual fire marshals making decisions for each proposed station. One automaker stressed that hydrogen now needs to be looked at as a consumer product and regulated appropriately:

> *"For example, some of the issues to be addressed are the fact that hydrogen is an odorless gas, it doesn't give off light when it burns etc. Right now, it is regulated as an industrial chemical, not as a consumer product."*

Putting hydrogen into contact with millions of consumers, instead of a small number of highly trained industrial professionals, will entail a new set of safety concerns.

The setting of safety standards is not only needed to ensure that hydrogen can be handled safely by consumers, it can also reduce infrastructure costs by ensuring that infrastructure developers don't incur needless expense by excessively overbuilding in the name of safety. For example, the California Fuel Cell Partnership implemented very expensive safety measures, offering duplicate and triplicate safety back-ups, as a form of insurance against accidents in this early demonstration phase. While this makes sense early in the development of fuel cells, it will also give the industry a chance to analyze which measures are necessary and which may be duplicative, helping to reduce costs in future infrastructure deployments.

Education and Public Awareness

Respondents stressed the importance of educating the public about hydrogen. In spite of the greater attention paid to fuel cells, too many people still associate hydrogen with two things: the Hindenberg disaster and the nuclear bomb. Educating facility operators at early fleet deployments will be critical to ensuring that these initial deployments are successful. Then, in order to ensure that the automotive market can be successful, a broader education effort will be needed. One respondent cautioned against undertaking public education efforts given the still-speculative nature of the technology, warning that such efforts could be counterproductive if they raise expectations that are not met and confuse the public about other clean transportation choices that are closer at hand.

Onboard Reformation vs. Off-Board Hydrogen Production

Our experts have indicated that their opinions about fuel processing have evolved since the original publication of *Future Wheels*. There has been a consolidation in their collective belief that the majority of hydrogen generation will take place off-board the vehicle. They offer several reasons.

The most common reason offered to support off-board production centered on the cost to the consumer. Installing a reformer onboard a vehicle constitutes the addition of another complete component system to the vehicle. This increases the manufacturing and maintenance complexity of the vehicle while also increasing the cost borne by the operator. It would be more efficient in terms of both cost and complexity to install a stationary reformer at a refueling site where the fixed cost of reformation could be distributed among multiple users. Additionally, off-board production allows for CO_2 sequestration. Some respondents also cited existing technical challenges to onboard reformation including start-up, stability, and vehicle space limitations.

An additional argument supporting off-board hydrogen generation involved the efficient use of reformation capacity. Regarding this issue, one interviewee explained:

> *"…onboard reformers need to be big enough to meet the vehicle's peak requirement periods, such as is observed during acceleration. This means that during most of its duty cycle the reformer is only called upon to operate at a fraction of its capacity…if the reformer is off board it could service multiple vehicles instead of just one for the same investment."*

Although off-board production was cited by almost 70% of the respondents as the most likely hydrogen fueling option, several experts indicated that they expected to see experimentation, most likely based on locale, with various on and off-board technologies. Over time, they explained, the most suitable methods and fuels would emerge as the dominant choices. One fuel cell developer indicated that, for example, onboard reformation may make sense for long-haul trucking applications and heavy vehicles with longer duty cycles where hydrogen storage capacity could become problematic.

Two of our respondents did indicate that they believe onboard reformation to be the ultimate goal, noting that, while the cost of onboard reformation is roughly the same as hydrogen storage, the reformer uses less vehicle space. Finally, as one hydrogen company explained:

"The jury is out…it could go either way. It is important to note the convenience of refueling experienced by the consumer must be at least as good as it is today."

Centralized vs. Distributed Generation

For those who believe that hydrogen production will take place off-board there was general agreement that it would initially take place at local refueling stations simply because a sufficient hydrogen infrastructure system has not yet evolved. Things became somewhat less clear when they were asked to consider the future of hydrogen generation. If hydrogen is initially generated locally, would the industry evolve toward a centralized model? While some indicated that the decision would be one based on locale, there were two key reasons that this was generally considered unlikely.

First, distributed generation avoids the "chicken or the egg problem," associated with hydrogen infrastructure by avoiding the need for large-scale capital investment. It is far simpler, as well as economically less onerous, to install individual reformers at localized refueling sites on an as needed basis than it would be to develop a nationwide hydrogen distribution network. Second, after some number of miles there exists a point where it becomes economically inefficient for fuel companies to transport hydrogen. This, however, is closely related to hydrogen storage technology and leaves open the possibility for technical advances in hydrogen storage that would allow for hydrogen to be more efficiently stored and in turn transported. One fuel cell developer explained:

"Where? It can be a mix depending on the region. Some areas with hydrogen pipelines can do it centrally. For others, reformation at the refueling station with natural gas or methanol makes sense. For the foreseeable future it will be a mix. Beyond 25 years, when the hydrogen economy kicks in and there has been greater investment in hydrogen infrastructure, the efficiency offered by central production may make that more attractive."

Onboard Hydrogen Storage: What Are the Key Issues?

As one respondent noted, *"the major challenge to hydrogen storage is hydrogen storage."* Compressed hydrogen continues to be the primary near-term viable technology. Existing hydrogen tanks use 3,600 psi compression, and, as of now, this only provides a typical passenger car with a 125-150 mile range. The average gas car has a range of 300 miles between fill ups, and the industry agrees that this goal must be met if fuel cell cars are to be commercially viable. The question is, can this problem be resolved?

Opinions were decidedly mixed, and concern about hydrogen storage is one of the greatest potential barriers to successful fuel cell vehicle commercialization. Some saw this as the most likely show-stopper to the whole fuel cell development effort. Others felt that advances in compressed hydrogen storage would be sufficient to address this issue. The likelihood that advanced storage technologies would emerge that could be commercially viable was not rated very positively by most respondents. And a few respondents felt that the focus on storage is the wrong way to approach this problem.

Compressed Hydrogen Storage

In tackling the hydrogen storage problem, there are trade-offs among range, volume, weight and cost. The range issue is clear – the goal is to reach a 300-mile range; anything less that will not be acceptable. If compressed hydrogen tanks are to be the storage method, it will be necessary either to increase volume or to increase storage pressure, compressing more hydrogen into a smaller volume. Currently available commercial hydrogen storage tanks allow for compression to 3,600 psi, while 5,000 psi tanks have been developed and deployed in early demonstrations of fuel cell vehicles. This increases range, but not to the 300-mile goal. Consequently, some automakers are testing 10,000 psi tanks. Mention of 10,000 psi tanks on private automobiles provoked a strong response from respondents. Many are emphatic that this level of compression will never be safe for widespread consumer use. A few respondents noted that increasing compression is not a linear effect: increasing to 10,000 psi from 5,000 only produces about a 25% increase in storage capacity while increasing the amount of energy used for compression. The time required for refueling also increases when compressing to 10,000 psi, and this could be a drawback for consumers accustomed to quick fill ups at the gas station. A government representative also noted that the weight of the tank increases, as the higher pressure requires stronger tank reinforcement. Nevertheless, several respondents expressed confidence that 10,000 psi could be made to work; any breakthrough developments currently being made behind the scenes could change the outlook for this technology.

Storage vs. Vehicle Efficiency

A small number of respondents said that the hydrogen storage problem is a red herring. They believe this issue can be resolved if approached from the right angle. They stressed the need to increase overall vehicle efficiency, which would reduce the amount of hydrogen needed to reach the target 300-mile range. Right now, fuel cells are being integrated into vehicles designed for internal combustion engine systems. If the fuel cell vehicle were to be redesigned from the ground up, there would be ways to address the spacing issue, rather than forcing the hydrogen tanks into space designed for mechanical propulsion systems and gas tanks. One fuel cell manufacturer said appropriate vehicle design would allow SUVs to achieve 300-mile range with a 5,000 psi tank; smaller cars would only require a 3,600 psi tank. Another respondent stressed the need for a vehicle redesign that would include lightweight composite materials in place of the existing steel body cars. These respondents were more optimistic about the prospects of developing a commercially viable fuel cell vehicle even without a major breakthrough in hydrogen storage technology.

Advanced Hydrogen Storage Options

Three years ago, *Future Wheels* reported on expert opinion regarding such advanced technologies as metal hydrides, chemical hydrides, and carbon nanotubes. These were all in the early stages of development relative to compressed hydrogen storage, but they garnered interest as potential breakthroughs that could change the hydrogen storage picture. Three years later, they don’t seem any closer to becoming the breakthrough that some had hoped for. Overall, respondents said that they hadn’t seen evidence of any of these options proving themselves to be likely viable options in the near future.

Metal hydrides: Metal hydrides are good for achieving volumetric density. Weight was the problem most often cited with this technology. Most respondents commented that the high weight-to-hydrogen ratio made this storage technology inappropriate for vehicle applications. Some said it might make more sense for stationary fuel cells where weight is not a concern.

Chemical hydrides: Again, respondents had not seen any breakthroughs suggesting that this technology is becoming more viable. One problem cited is the issue of recyclability.

Carbon nanotubes: Most respondents noted that carbon nanotubes, while intriguing, are, as one respondent put it, "*still in the sci-fi realm.*" Some questioned whether initial positive laboratory results were replicable. Others felt they could have potential, but they are so far from moving out of the laboratory that is it not possible to make an intelligent estimation of their potential.

Potential Hydrogen Sources

When asked to cite the most promising sources of hydrogen for fuel cells in the transportation industry our experts mentioned a variety of possible scenarios including nuclear, ethanol, methanol, electrolysis and gasoline. However, two distinct trends emerged from within their collective responses. Nearly 70% of those who responded identified an eventual move towards renewable sources as the most likely scenario. At the same time, 80% of those who anticipated a move towards renewables also indicated that natural gas would be the fuel of choice in the short run. One energy supplier asserted that, while early demonstrations might use renewable hydrogen sources:

> *"…As the fuel cell market ramps up over the next 20 years, hydrogen must be reformed from fossil fuels. In the early stage of fuel cell development, it doesn't make sense to combine the most expensive fuel source with the most expensive propulsion technology."*

The majority of respondents indicated little if any change in their opinions regarding this question over the past two years.

Despite the strong show of support for natural gas as the near-term fuel of choice for hydrogen, several concerns were raised about its long-term viability. Market price instability was cited as an impediment to stable fueling costs. Should there be a jump in the spot price of natural gas, as did occur a few years ago in the Northeastern United States, then the per mile cost of vehicle operation could rise substantially raising the specter of a cost ripple effect that could impact the economy at multiple levels.

The long-term supply of natural gas was also called into question by one auto manufacturer who suggested that it is not clear that there exists a store of natural gas sufficient to meet the hydrogen production needs of the United States as it evolves toward a true hydrogen economy. At the very least, the increased demands placed on the natural gas supply by large-scale hydrogen reformation would necessitate increased drilling, which may or may not be feasible.

Others noted that in discussing fuels for hydrogen generation one must evaluate the issues that are driving the policy forward. If one is to consider national security as a driver, then it does not seem clear that reliance upon natural gas will offer a long-term solution. In the end, they argue, reliance upon natural gas constitutes no more than a shift from one form of dependence to another. If the energy shift is driven by environmental concerns, then the shift occurs from one fossil fuel to another with a questionable net benefit.

All of these arguments lead to the conclusion that, ultimately, hydrogen will be produced using water-electrolysis from renewable sources of electricity. In discussing the likely renewable sources the respondents offered a rather substantial list that includes hydropower, wind, solar, and biomass. But, is using renewably generated electricity to produce hydrogen for transportation the most efficient use of that resource? One expert offered the following viewpoint on the wisdom of using renewable sources for hydrogen:

> *"The government should focus on how to make hydrogen without CO_2…Any renewably generated electricity should first be used to offset less clean electricity generation. It doesn't make sense to generate hydrogen from it because that will reduce the gain had by generating electricity from a renewable source."*

Two respondents indicated that nuclear power is a potential hydrogen source if one is strictly concerned with emissions. However, others expressed concern regarding the use of nuclear power. One automaker said:

> *"I don't think that they have thought this [nuclear] through. If you look at the lifecycle energy assessment it doesn't look good. So much energy goes into building a nuclear plant that they spend the first 20 years in an energy deficit."*

It seems logical, as pointed out by some, that the choice of a hydrogen energy source would ultimately be an economic decision based upon local appropriateness. In some areas it may make sense to use wind, in others hydro may make more sense. Where natural gas or coal is inexpensive and abundant then the choice will be made appropriately. It's the economics of local regions will determine the ultimate fuel source.

The Role of Government in Fuel Cell Market Development

Should Governments Help? If So, How?

Having explored the progress made in developing transportation fuel cells and accompanying infrastructure, and highlighted the many remaining challenges to creating a successful long-term transportation fuel cell market, we thought we'd give our interview subjects a chance to propose ways the government may help in this endeavor. Or tell us whether government has any useful role at all. No one suggested that government does not have a part to play, but views on the best way to support the fuel cell market were varied.

- **Fund basic R&D, vehicle demonstrations**: Respondents stressed the need for major funding of basic fuel cell R&D, to help industry address the big remaining challenges of cost, durability and reliability. They also said government funding for demonstrations will be needed to help advance the technology through real-world experience in field trials. One respondent noted that it is important to have coherent programs; this respondent expressed concern that funding in the U.S. is being awarded to individual pet projects, and that this may not give the greatest "*bang for the buck*". One respondent felt that, until all fundamental technology barriers were cleared, the government role should be restricted to basic R&D, and that demonstrations are premature.

- **Developing hydrogen infrastructure:** Related to the above suggestion is government support for development of an initial hydrogen infrastructure. This is already happening to some extent through government-supported demonstrations. The European bus program requires that a hydrogen station be developed in each of the ten cities that will deploy fuel cell buses. The California Fuel Cell Partnership – a collaboration among private entities and government agencies to investigate the pathway to fuel cell vehicle commercialization -- installed a major hydrogen fueling station at its headquarters. Many respondents felt that a bigger effort is needed here. They suggested the government fund hydrogen supply centers, which could serve as initial building blocks for early fuel cell vehicle deployment and would support continued investment by the private sector. However, some respondents thought that the infrastructure would develop on its own, in response to the vehicle introduction, and government should not focus funding here.

- **Developing hydrogen sources:** The government needs to focus on developing hydrogen sources. Although the current hydrogen supply is adequate for initial market penetration, much more will be needed to support a significant capturing of the transportation market. Also, government support would help the drive to develop lower cost hydrogen generation capability, which will be crucial to building the market. Many respondents also said that government should support development of renewable sources, to ensure that the shift to fuel cell vehicles will reap the greatest best environmental benefit.

- **Policies to spur the market**: Respondents urged the government to develop "creative" policies to spur the market. Tax incentives for vehicle purchases and for refueling station installation were most were frequently mentioned. Another suggestion was making hydrogen fuel tax-free for 20 years.

- **Regulatory drivers:** Not surprisingly, regulatory drivers were more often suggested by environmental advocates, research organizations, or associations, not by the industries that would be regulated. Most of those who suggested regulatory drivers stressed they should be in combination with "carrot" policies such as funding of R&D or tax incentives. But they felt that both carrot and stick were needed to prod the fuel cell market forward. Suggested regulatory drivers were increasing federal fuel efficiency requirements, passing more stringent emissions standards, or regulating greenhouse gas emissions. It should be noted that, overall, regulatory drivers were not suggested as often as the other policy suggestions noted here.

- **Codes and standards:** There was near-general consensus that government must address codes and standards issue in order to ensure that these do not become barriers to fuel cell commercialization. Governments need to take the lead on this issue, working with established industry groups like the Society of Automotive Engineers and the U.S. Fuel Cell Council to set safety standards for hydrogen storage, vehicle refueling interface, siting of hydrogen tanks, garaging of fuel cell vehicles, and many others. These efforts are ongoing, but many respondents stressed that lack of attention to this could be a major roadblock to successful commercialization.

- **Early purchasing:** Many respondents, particularly the fuel cell manufacturers and auto companies, urged the government to become an early purchaser of fuel cell vehicles. They noted that government is the biggest vehicle purchaser in the U.S. and is not as price sensitive as the private sector.

- **Education:** Government should have a role in educating the public about hydrogen. Several respondents noted that public perceptions of hydrogen come from two negative associations, the Hindenberg disaster and the hydrogen bomb. If government is serious about developing a hydrogen-based transportation system, they should take the lead in educating the general public about fuel cells and hydrogen as a fuel. One respondent noted that there is a lot of talk about the importance of public education, but not much action. The respondent urged government to step up to the plate, as part of its overall effort to advance the fuel cell industry.

How Does the U.S. Compare With Europe, Canada and Asia In Promoting Fuel Cell Technology?

Respondents stressed the significance of President Bush's announcement that his administration would support funding for two major fuel cell vehicle and hydrogen infrastructure development programs, known as FreedomCAR and FreedomFuel. They felt that the U.S. government plays a critical role in moving this technology forward, even outside the U.S. As one company representative put it, "*The U.S. is little late to the game, but it is like an elephant: once it gets started, it can't be stopped.*" In fact, competition among governments could be beneficial to fuel cell advancement. Canada is striving to maintain its status as a center for fuel cell R&D. Europe is sponsoring the first major fuel cell bus demonstration program. Japan is providing major funding for their auto companies and is funding hydrogen station installation. The U.S. Department of Energy has just announced several solicitations for broad fuel cell vehicle demonstration and infrastructure deployment, and, within the U.S. itself, various states and regions are jockeying to position themselves as "fuel cell centers".