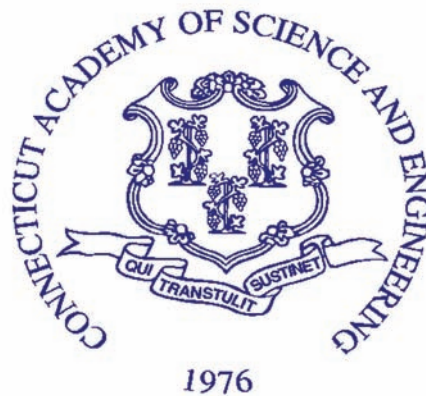


PREPARING FOR THE HYDROGEN ECONOMY: TRANSPORTATION

JUNE, 2006

A REPORT BY

THE CONNECTICUT
ACADEMY OF SCIENCE
AND ENGINEERING



FOR

THE CONNECTICUT DEPARTMENT OF
TRANSPORTATION

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A REPORT BY

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ORIGIN OF INQUIRY: CONNECTICUT DEPARTMENT OF
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This study was initiated at the request of the Connecticut Department of Transportation on May 25, 2005. The project was conducted by an Academy Study Committee with the support of Joseph M. King, Jr., Project Study Manager, and Kelvin Hecht, Study Consultant. The content of this report lies within the province of the Academy's Transportation Systems Technical Board. The report has been reviewed by Academy Members A. George Foyt, PhD, and Lee S. Langston, PhD, Chairman of the Academy's Energy Production, Use and Conservation Technical Board. Martha Sherman, the Academy's Managing Editor, edited the report. The report is hereby released with the approval of the Academy Council.

Richard H. Strauss
Executive Director

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Connecticut Department of Transportation or the Federal Highway Administration. The report does not constitute a standard, specification, or regulation.

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16. Abstract Hydrogen fueled vehicles are proposed as an approach to improve energy security, and to reduce emissions of controlled pollutants and green house gases. Most current or projected fuel cell powered vehicles require hydrogen fuel while the current infrastructure provides a well defined system for petroleum based fueling. The transition to a system based on institutionalizing hydrogen as a readily available fuel is yet to be developed. Some states, such as California, are currently engaged in establishing such systems. Connecticut currently has not developed either a strategy or plan to address this issue. The objective of this study was to provide a literature-based best practices review of the current state of knowledge regarding transitioning to and planning for a hydrogen-based transportation fueling system within the US or other countries to identify issues/barriers relevant to developing a hydrogen-based transportation fueling system in Connecticut.			
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EXECUTIVE SUMMARY

STATEMENT OF INQUIRY

Background

Hydrogen-fueled vehicles have been proposed as one approach to reducing both dependence on imported energy and emissions of controlled pollutants and greenhouse gases. Development of hydrogen-fueled vehicles and, in particular, hydrogen-fueled vehicles with fuel cell power plants, began in the 1990s and received increased emphasis with the president's State of the Union address in 2003, which proposed a \$1.2 billion effort to develop hydrogen-fueled vehicles and infrastructure.

Study Description

This study was conducted for the Connecticut Department of Transportation (ConnDOT) by the Connecticut Academy of Science and Engineering.

The objective of the study is to provide a literature-based, best practices review of the current state of knowledge regarding transitioning to and planning for a hydrogen-based transportation fueling system in the United States or other countries. Specifically, the aim is to identify issues/barriers relevant to developing a hydrogen-based transportation fueling system in Connecticut, taking into consideration safety, methods for delivery of hydrogen to fueling stations (such as shipping or on-site reforming from natural gas) and timelines for implementation. The study identifies issues relevant both to fleet operations and the general public's use, as well as policy options for the state of Connecticut to address hydrogen-fueled transportation issues amenable to state action.

SUMMARY OF FINDINGS

Hydrogen

Hydrogen is the most abundant element in the universe. It burns cleanly, with low emissions and water as the primary product and, when used in combination with a fuel cell, it produces power at very high efficiency.

On Earth, hydrogen is found primarily combined with oxygen in water or with carbon in hydrocarbon fuels such as natural gas or petroleum. Consequently, energy input is required to produce pure hydrogen. This makes hydrogen, like electricity, an energy carrier rather than an energy source. Also, like electricity, a wide variety of energy sources can be used to produce hydrogen, making it possible to derive hydrogen from indigenous sources and reducing dependence on energy imports. Where hydrocarbon energy sources are used to produce hydrogen, greenhouse gases will be produced and must be captured and sequestered to avoid releasing these gases to the atmosphere. Also, like electricity, hydrogen is expensive to transport and store in terms of energy losses and capital requirements.

The net result of hydrogen's advantages and disadvantages is that it promises to be a good energy carrier for transportation applications just as electricity is a good energy carrier for stationary applications.

While hydrogen is at an early stage of development for transportation, it is currently produced in large quantities for industrial use and is distributed broadly across the United States and the world. US production is the energy equivalent of about 5% of the nation's current gasoline energy consumption, so hydrogen production is already at a meaningful level with respect to transportation demand.

Hydrogen Transportation Development Effort

The 2003 State of the Union message proposed a \$1.2 billion national effort to develop hydrogen-fueled transportation. The president stated that "...With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."

The US Departments of Energy (DOE) and Transportation (US DOT) have established comprehensive programs with detailed plans to develop all aspects of the vehicle and infrastructure technology to make hydrogen-fueled transportation feasible technically and economically. These aspects include generation of hydrogen from conventional and renewable sources, hydrogen transportation and storage, utilization of hydrogen in vehicles with fuel cells or internal combustion engines, and safety standards and codes covering all areas. Laboratory development and testing of components and systems are supplemented by rigorous testing of vehicles and infrastructure. National government-funded efforts are also underway in other countries, notably in Europe and Japan, and there are significant, privately funded efforts in auto, energy, fuel cell, and infrastructure companies who would be involved with hydrogen-fueled transportation.

Many states have programs to facilitate development of hydrogen-fueled transportation. Eleven have comprehensive plans in the form of hydrogen roadmaps. Connecticut ranks high in terms of the number of professionals involved in hydrogen and fuel cell development. Connecticut companies are leaders in stationary fuel cell and transportation fuel cell development as well as in electrolysis systems. The state has a robust demonstration and commercialization activity in support of stationary fuel cell applications. Initial hydrogen-fueled transit bus demonstrations are planned, but there is little state-initiated effort directed at hydrogen-fueled transportation.

The technical and business challenges of hydrogen-fueled transportation are significant, and dates for commercialization are uncertain. In the United States, periodic, comprehensive and objective reviews of the plans and status of the federal programs are made on a regular basis by a committee of the National Research Council. The summary of the first of these reviews includes the following:

- "This is a broad, very challenging research effort to assist in the development of high-risk technologies that will enable the vision of a clean and sustainable transportation energy future.

- Research goals have been established for 2010 and 2015 that, if attained, promise to overcome the multiple high-risk barriers to achieving that vision.
- The committee believes that research in support of this vision is justified by the potentially enormous beneficial impact for the nation.
- Funding levels and the consequent research results during the next few years should allow future reviews to make a more firmly based assessment.”

Commercialization Schedule

Consistent with a high-risk technology activity, there is considerable uncertainty regarding projected schedules for commercialization of hydrogen-fueled transportation. The earliest projections are for limited production of a dual-fuel hydrogen/gasoline version of the BMW Seven Series vehicle in 2008 and limited serial production of a Honda hydrogen fuel cell vehicle in 2010. Toyota and GM project production between 2010 and 2020 if technical targets are met. The most pessimistic statements on schedule are by a former DOE assistant secretary, Joseph Romm, who stated in January 2006 that he was more pessimistic, indicating that hydrogen-fueled cars would not emerge “until 2040 *at best* and may well prove to be a dead end.” Development plans prepared by DOE, US DOT, the European Union and several vehicle and energy companies indicate the following schedule is planned and possible:

- Research and development activities through 2015 to establish the basis for a decision to commercialize automobiles. Limited serial production may begin by 2010 for both internal combustion engine and fuel cell fleet vehicles fueled with hydrogen.
- Initial deployment in fleet vehicles, probably with significant government incentives, during the second decade of the twenty-first century. Transit buses may be the initial application. US DOT goals are to have 10% of transit bus purchases in 2015 be hydrogen-fueled models. Hydrogen generation may be produced by electrolysis or steam reforming at fueling stations, supplemented with shipments of gaseous or liquid hydrogen from central plants.
- Advancements in hydrogen storage and fuel cell technologies will reduce costs, weight and size such that hydrogen-fueled vehicles will have improved performance and economics by the third decade of the twentieth century. This will result in broader application to commercial vehicles and private automobiles and a gradual reduction of government incentives.
- Mature deployment will follow by mid-century with renewable sources of hydrogen and hydrogen fuel cells dominating vehicle power. Hydrogen distribution networks may evolve as demand increases.

A number of alternative approaches for improving energy security and pollution emissions associated with transportation are at more advanced stages of development. These include hybrid vehicles, clean diesel vehicles, and alternative fuels such as natural gas, ethanol and biodiesel. Lessons learned from experience with these technologies will benefit deployment of hydrogen-fueled vehicles. In particular, natural gas vehicles have pioneered use of gaseous

fuels in transportation. Hybrid vehicles are providing operators, maintenance personnel, and first responders with experience with high voltage electrical systems and electric drives, both of which are shared with fuel cell vehicles. While applicable experience will ease deployment of hydrogen fuel cell vehicles, improvements to energy security and emissions with alternative technologies will make commercialization of hydrogen-fueled vehicles more challenging.

Connecticut Investment Requirements

Converting to a hydrogen-fueled transportation system would involve significant capital investments for Connecticut. Connecticut has 21,000 miles of streets and highways used by nearly 3 million vehicles. Many of these vehicles are in over 800 fleets with more than 25 vehicles each. These fleets, and particularly the state fleets, are prime candidates for early deployment of hydrogen-fueled transportation. Nearly 1,500 fueling stations are located in Connecticut. Seventy of these are state owned for state vehicle use, and 23 are at service plazas on I-95 and the Merritt and Wilbur Cross parkways.

Issues/Barriers/Concerns

To identify issues associated with introduction of hydrogen-fueled transportation to Connecticut, literature searches and interviews were conducted with parties that

- were interested in safety and insurance;
- had experience with other alternative fuels;
- were involved with development of hydrogen-fueled transportation; and
- were associated with state planning and industry associations.

There were no fundamental barriers to the introduction of hydrogen-fueled transportation in the state identified. However, there are state actions which will be required to permit use of hydrogen-fueled transportation in Connecticut.

Concerns *related to vehicles* and their performance include

- fuel storage volume and range limitations;
- operation in temperature extremes;
- vehicle performance – acceleration and speed;
- vehicle durability and reliability; and
- cost.

Range limitations have been problematical for both electric vehicles and compressed natural gas (CNG) vehicles. At the beginning of the intensive effort to develop hydrogen-fueled transportation, fuel cells could not start rapidly in below-freezing temperatures. Electric vehicles and some CNG vehicles have had poor performance. The current cost of hydrogen fuel cell vehicles is high, as is the cost of the limited volume vehicles being demonstrated. Durability and reliability are particular concerns with transit bus applications.

Concerns *related to infrastructure* include

- cost, energy losses, and emissions associated with generation and transportation of hydrogen;
- increased land requirements for fueling stations;
- unfamiliar dispensing apparatus and procedures; and
- availability of fueling stations.

Almost all hydrogen used in the United States is generated utilizing steam methane reforming, which has energy losses and capital cost, and releases greenhouse gases. While development efforts are directed at improving or eliminating these factors for production from natural gas (primarily methane) and alternative methods, development is at an early stage. Currently, most hydrogen produced is consumed on-site or delivered “over the fence” to a contiguous customer; only a small percentage is distributed broadly by compressed gas tube trailer, liquefied hydrogen tank trucks, or by a limited pipeline system. Compressing or liquefying hydrogen for storage or transport is energy- and capital-intensive. Alternative methods in the form of metal hydrides, chemical hydrides, metal-organic compounds, and nano-scale approaches are at a very early stage of development. Hydrogen will be dispensed using equipment and techniques similar to those for CNG. While these techniques present no problems for CNG for fleet operations with professional operators and on-site fueling facilities, they have created customer acceptance issues for some operators who are either personal users or fleet users with only occasional use of the vehicles. Availability of fueling stations is a significant problem, even for some fleet operations with on-site fueling stations.

Primary concerns *in the safety area* are

- public concern with safety and development of national and industry standards for all aspects of hydrogen-fueled transportation;
- incorporation of appropriate national and industry standards into state and local codes and regulations;
- identification of applicable codes and standards for state and local jurisdictions so that permitting and design can begin with a comprehensive understanding of requirements;
- first responder training; and
- ability to obtain liability insurance.

While hydrogen has been used safely in industrial settings for decades and studies show that, if properly handled, it is safe for commercial and personal use, lack of public awareness and experience raises concern for safety. National, industry, and international standards, covering all aspects of hydrogen infrastructure and its use in vehicles, are being developed, but many are not complete and, when issued, they will require adoption in state and local codes and regulations before permitting officials will use them. Because broad use of hydrogen is new, few permitting officials are fully aware of all requirements; this leads to a slow and laborious permitting process with the high probability that additional requirements will be identified late

in the design and construction process, which will cause delays and additional expense. There is also concern with ability to obtain liability insurance because of a lack of experience with risk associated with hydrogen use.

Concerns related to *business and market development* include the following:

- Long-term investment in research and demonstration causes delays in investment return.
- Meeting technical and economic objectives for hydrogen-fueled transportation remains a difficult challenge with uncertain results.
- Alternative technologies may provide benefits similar to hydrogen-fueled transportation before hydrogen transportation is deployed.
- All aspects of hydrogen transportation will have high cost during the initial deployment period.
- Success in bringing hydrogen-fueled transportation to fruition requires positive decisions and good execution by many independent organizations, including government, vehicle manufacturers, infrastructure equipment manufacturers, energy firms, and industrial gas firms.

The combination of business and market development concerns increases investment risk; however, auto, major oil, infrastructure, industrial gas, and fuel cell companies are investing heavily in hydrogen-fueled transportation. Substantial government support during research, development, demonstration, and the market development period is critical to maintaining private investment. Public-private partnerships may be needed to ensure an effective approach to deployment.

Suggestions for State Action

Many of the concerns noted above can be addressed only by the federal government, vehicle manufacturers, and infrastructure companies. The federal government's efforts are quite comprehensive and address all appropriate issues. Significant progress is being made toward very specific technology targets. Each of the federal demonstration projects involves all the business entities whose contributions are critical to success, so concerns related to the participation of other parties who are required for success can be reduced or eliminated. While these efforts carry the majority of the burden for developing hydrogen-fueled transportation, participation at the state and local level is also a requirement for success. While state and local participation in the early stages of research has been limited, now that the effort involves significant demonstration activity, state participation is required to take advantage of the demonstration experience, and actions are required now to avoid having elements under state and local control delay deployment of this beneficial technology.

Connecticut has already taken several actions, including the following:

- Industry development and demonstration activities
- Higher education activities
- Established the Connecticut Hydrogen and Fuel Cell Coalition
- Related support from Connecticut Clean Energy Fund and Connecticut Innovations, Inc.
- Planned demonstrations of hydrogen-fueled transit buses
- Enacted legislation requiring formation of a fuel cell and hydrogen cluster and a comprehensive plan for fuel cell and hydrogen economic development

A number of Connecticut companies are leaders in the technologies associated with hydrogen-fueled transportation and several are participating in programs of the federal government, other national governments and other states to develop hydrogen-fueled transportation. Connecticut higher education is also involved, most notably the Connecticut Global Fuel Cell Center at the University of Connecticut. An industry group with a number of members from Connecticut industry, law firms, education, and government has been formed to support hydrogen and fuel cell development. The Connecticut Clean Energy Fund has a robust program in support of stationary fuel cells and Connecticut Innovations has invested in some of the companies in this area. A recent announcement of state support for distributed generation is another example of an action supporting alternative energy and stationary fuel cells. Hydrogen-fueled bus activities are planned by CTTransit and the New Haven Transit District. State planning associated with hydrogen-fueled transportation has, thus far, been minimal and there have been no specific state-sponsored activities on hydrogen-fueled transportation. However, in 2006 legislation was enacted requiring the Department of Economic and Community Development to establish a Hydrogen and Fuel Cell Cluster and a comprehensive plan for hydrogen and fuel cell economic development. A progress report is to be provided to the General Assembly in January 2007 and the plan is to be completed by January 2008.

Going forward, Connecticut policy makers can choose among several action options. Two are suggested here.

- Option 1: A *monitoring* program which positions Connecticut for hydrogen-fueled transportation after deployment in other states
- Option 2: A *promotional* program which positions Connecticut to be among the states with earliest deployment of hydrogen-fueled transportation

Tasks in the monitoring program option would include:

- Task 1: Monitoring progress in hydrogen-fueled transportation
- Task 2: Establishing a proactive codes and regulation environment
- Task 3: Anticipating hydrogen-fueled transportation in infrastructure design and construction
- Task 4: Developing a comprehensive Connecticut or regional plan

The promotional program option would include the above tasks, conducted more intensively, as well as the following tasks:

- Task 5: Funding demonstration programs
- Task 6: Public outreach
- Task 7: Establishing partnerships

In the promotional program, it is suggested that a regional approach be considered for Connecticut's efforts.

Selection of the appropriate option could be the result of the following assessments:

- Economic impact
- Hydrogen program progress
- Results with alternative fuels and technologies
- Deployment evidence

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1. INTRODUCTION

BACKGROUND

This study follows somewhat related studies by CASE on alternative transit bus technologies, demonstration of hybrid diesel-electric buses and fuel cells (Reference 1.1; Reference 1.2; Reference 1.3).

Since completion of the first and third reports identified above, technology and demonstrations of hydrogen fuel cell vehicles and the associated fuel infrastructure have advanced dramatically, with more than 40 buses and more than 100 automobiles on the road and over 100 hydrogen fueling stations in place globally. Major development and demonstration activities by the United States, other national governments, and other state governments are underway and virtually all the world's auto companies, several bus companies, many energy companies and many fuel cell, electrolysis and industrial gas companies are participating. If successful, these efforts will result in early hydrogen-fueled vehicles on the road within the second decade of the twenty-first century, making this an appropriate time to assess the steps Connecticut should consider to prepare for hydrogen-fueled transportation.

SCOPE OF INQUIRY

This study was conducted for the Connecticut Department of Transportation (ConnDOT) by the Connecticut Academy of Science and Engineering (CASE).

The objective of the study is to provide a literature-based, best practices review of the current state of knowledge regarding transitioning to and planning for a hydrogen-based transportation fueling system in the United States or other countries. Specifically, the aim is to identify issues/barriers relevant to developing a hydrogen-based transportation fueling system in Connecticut, taking into consideration safety, methods for delivery of hydrogen to fueling stations (such as shipping or on-site reforming from natural gas) and timelines for implementation. Additionally, the study will identify issues relevant both to fleet operations and the general public's use, as well as suggestions for action by Connecticut in regard to resolution of the issues amenable to state action.

APPROACH

The study approach involved the following:

- Review of literature and websites to assess the technical issues and status of hydrogen infrastructure and hydrogen vehicle technology.
- Discussions with individuals who have interest and experience in and responsibility for: safety, codes and insurance; alternative-fueled vehicles; fleet operations; development and demonstration of fuel cells and hydrogen infrastructure hardware; state government efforts in transportation, energy and environment. These discussions identified issues or barriers associated with deployment of hydrogen-fueled transportation in Connecticut. The discussions were supplemented with published information on the same topics.

- A review of programs on hydrogen-fueled transportation sponsored by US government agencies, other countries, other states and Connecticut.
- Preparation of a description of the current Connecticut transportation infrastructure.
- Preparation of suggested actions for Connecticut which supplement other programs relative to the issues of hydrogen-fueled transportation specific to Connecticut.

The balance of the report is provided in the following chapters:

- Chapter 2: Elements of Hydrogen-Fueled Transportation System: Approaches and Status
- Chapter 3: Status and Experiences with Other Non-Traditional Transportation Fuels
- Chapter 4: Scope of Hydrogen Fuel Requirements in Connecticut and Current Experience with Hydrogen in Connecticut
- Chapter 5: Concerns of Interested Parties
- Chapter 6: Summary of Findings and Concluding Remarks

In addition, the report contains:

- Glossary
- References, Notes and Acknowledgements
- Appendix A: Hydrogen Characteristics
- Appendix B: Standards Organizations
- Appendix C: Status of National, International, and Industry Codes and Standards for Hydrogen-Fueled Transportation
- Appendix D: Experience with Non-Traditional Transportation Fuels and Technologies
- Appendix E: Interested Parties

2. ELEMENTS OF A HYDROGEN-FUELED TRANSPORTATION SYSTEM: APPROACHES AND STATUS

2.1 INFRASTRUCTURE ELEMENTS

Hydrogen is the most abundant element in the world. However, on Earth, it is found only chemically combined with oxygen in water and with carbon and other elements in hydrocarbons such as coal, petroleum and natural gas. It is combined with carbon, oxygen and other elements in renewable fuels such as methanol or ethanol. The most attractive hydrogen utilization device, the fuel cell power plant, operates best on pure hydrogen. Chemical, electrochemical, photochemical, biological or thermochemical processes are used to convert the hydrogen-containing compounds into pure hydrogen. Pertinent hydrogen properties are provided in Appendix A.

Hydrogen can be thought of as an energy carrier (Reference 2.1) like electricity. The energy carrier is generated from the raw source (water, hydrocarbons, renewable fuel) either at a central point or at distributed locations. At the dispensing site where vehicle hydrogen supply is replenished, hydrogen compression, storage, and dispensing equipment will be required. For distributed generation of hydrogen, the dispensing site will also require conversion equipment.

Like electricity, hydrogen generation, transportation, and storage involve significant capital cost and energy losses. Like electricity, hydrogen is safe if properly handled. Like electricity, it is clean and unobtrusive at the point of use. Very importantly, from the viewpoint of reducing imported energy, hydrogen can be derived from diverse sources including conventional and renewable sources. Many of these sources are indigenous to the United States and some are available in Connecticut.

Hydrogen is a significant portion of the industrial gas industry which, in 2003, employed over 10,000 employees and had revenues of \$6.5 billion (Reference 2.2.) Globally, there are 45 billion kilograms of hydrogen produced annually, with the US producing 9 billion kilograms (Reference 2.3). The US production is equivalent to about 5% of current US consumption of gasoline so, while small in comparison, the hydrogen production is already at a meaningful level with regard to demand of hydrogen-fueled vehicles. Much of the hydrogen is produced and consumed in ammonia and petrochemical plants; the balance is shipped to a wide range of industries for use in their products. Hydrogen is shipped and stored at customer sites in either gaseous or liquid form, with liquid hydrogen being the choice when distances between the production site and the customer are longer or when customers require larger quantities of hydrogen. Praxair, a Connecticut company, is one of the leading suppliers of hydrogen.

Gaseous hydrogen is transported in tube trailers and in pipelines. Estimates of hydrogen pipeline length in the United States range between 720 and 1,000 kilometers, with pipeline length in Europe estimated at about 1,500 kilometers (References 2.4 and 2.5). The US pipeline system serves over 50 customers in Alabama, California, Florida, Indiana, Iowa, Louisiana, Michigan, and Texas (2.4 and 2.5). Major industrial gas companies (Air Liquide, Air Products, and Praxair) are involved with ownership and operation of these pipelines. The oldest existing

system is located in Germany's Ruhr area. It is 210 kilometers long and has been in use for 50 years without any accidents. The longest hydrogen pipeline is 400 kilometers and runs between France and Belgium (Reference 2.7).

The long-term and extensive operation of hydrogen infrastructures throughout the world provides valuable input to the effort to expand codes and standards from their current base in industrial use for transportation fuel applications.

The DOE Hydrogen Program is focused on achieving a delivered hydrogen cost of \$2 to \$3 per gallon of gasoline energy equivalent (delivered, untaxed, 2005 dollars) by 2015, which is the goal date for industry commercialization decisions for hydrogen-fueled transportation (Reference 2.1).

Current cost of hydrogen delivered to industrial customers is high. A Shell estimate puts delivered cost of hydrogen in 100 kilogram quantities at \$15 per kilogram, which is equal to \$15 per gallon of gasoline equivalent based on energy content. When the hydrogen is used for a fuel cell, the increased efficiency effectively doubles the range of the vehicle such that the cost of 1 kilogram of hydrogen is roughly equivalent to the cost of 2 gallons of gasoline as seen by the end consumer. Shell also estimates the cost of hydrogen leaving the gate of a central generation plant to be only \$1 per kilogram, which illustrates the high cost of hydrogen transportation. (Reference 2.11). Praxair has provided other estimates for hydrogen cost which are shown in Table 2.1 (Reference 2.8). Purchases of hydrogen for fuel cell research and demonstration activities by United Technologies fall within these cost ranges (Reference 2.9). These data show that delivered hydrogen is many times the cost of hydrogen at the point

Cost basis* (Assumes \$7 per million BTU natural gas cost)	Cost (\$ per 1,000 cubic feet)	Gasoline equivalent cost (\$ per gallon)**
At point of generation from steam methane reforming		
100 million standard cubic feet per day	3.5 to 4	1.5 to 1.7
50 million standard cubic feet per day	4 to 4.5	1.7 to 1.9
10 million standard cubic feet per day	4.5 to 5	1.9 to 2.1
<u>Delivered</u>		
Liquid hydrogen	10 to 20	4.2 to 8.5
Tube trailer hydrogen	25 to 50	10.6 to 21.1
Cylinder hydrogen	Over 50	Over 21.1

*Cost delivered to a fueling station; storage and dispensing costs at the fueling station are not included.

**Gasoline equivalent is based on equivalent energy content. Since fuel cell vehicles can be double or more the efficiency of internal combustion engine vehicles, an equivalent amount of hydrogen energy will yield double the miles.

Table 2.1. Current Hydrogen Costs as a Function of Generation Plant Size and Delivery Method from Praxair

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of generation, and the influence of hydrogen generation volume and delivery method on cost. Note that the delivered costs are costs of fuel delivered to the station; additional costs would be incurred for compression, storage and dispensing at the station.

The elements of the hydrogen-fueled transportation system, depicted in Table 2.2, include generation, distribution, storage, and utilization. Each portion of the table indicates the current methods as well as advanced options under development. For the current methods, the most frequent approach is listed first and for the advanced methods, the first listings are for the techniques which are most advanced.

	Generation	Distribution	Storage	Utilization
Current methods				
	Steam methane reforming; electrolysis	Tube trailer; liquid trailer; cylinder; pipeline	Compressed gas; liquid	In plant use for petrochemicals and chemicals; over-the-fence sale to other company; distributed to industrial companies
Advanced methods				
	Sequestration; thermochemical from nuclear heat; photolytic; algae growth	Local generation and delivery networks	Metal hydrides; chemical and petrochemical hydrides; high surface area absorbents; nano-scale water bubbles	Hydrogen internal combustion engines; fuel cells

Table 2.2. Current and Advanced Approaches to Elements of Hydrogen Economy

2.2 GENERATION SOURCES AND PROCESSES

2.2.1 Commercial Generation of Hydrogen

Hydrogen can be generated from a wide range of sources using different processes. Table 2.3 (based on Reference 2.3) lists the range of commercial sources with their processes, identifies the consumable requirements other than the primary energy source, and defines their contribution to global hydrogen supply. In the United States, steam methane reforming of natural gas provides 95% of the hydrogen.

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Source	Process	Other consumables	Portion of global hydrogen production (Ref 3.1)	Portion of US hydrogen production*
Natural gas	Steam methane reforming	Water, Air	48%	95%
Petroleum products	Partial oxidation	Air	30%	
Coal	Gasification	Water, Air	18%	
Electricity	Electrolysis	Water	4%	

* Reference 2.10

Table 2.3. Global Hydrogen Generation Sources and Processes

Hydrogen is currently used in ammonia production, petroleum refining, metal processing, glassmaking, and other applications. The amounts are significant in relation to potential future demand for hydrogen as a transportation fuel. For example, the energy equivalent of present day US hydrogen production is about 8 billion gallons of gasoline, which is 5% of vehicle gasoline consumption. However, Shell estimates that 94 % of global hydrogen is consumed within the plant where it is generated (an oil refinery for example) and another 5.4% is sold “over-the-fence” to contiguous customers (Reference 2.11). This leaves only 0.5% of the global hydrogen production which is delivered by truck or pipeline to industrial customers.

Steam methane reforming of natural gas (which is primarily methane) is the most prevalent method for generating hydrogen because it uses a relatively inexpensive energy source and the lowest cost and highest efficiency conversion process. The process heats methane and steam over a nickel-based catalyst at 1,200° to 1,400° F. to form hydrogen and carbon monoxide, i.e., $\text{CH}_4 + \text{H}_2\text{O} + \text{Heat} \Rightarrow 3 \text{H}_2 + \text{CO}$. The stream is combined with additional steam and passed over a low temperature catalyst (400° to 500° F.) to form additional hydrogen, carbon dioxide and heat in a process known as water gas shift, i.e., $\text{H}_2\text{O} + \text{CO} \Rightarrow \text{H}_2 + \text{CO}_2 + \text{Heat}$. A pressure swing absorption or membrane separation process is then used to separate the hydrogen from carbon dioxide. Most of the hydrogen produced using steam methane reforming is produced at large, central plants for use in petroleum refining or production of ammonia. Hydrogen used for these purposes is generated at the site where it is used. A small amount of hydrogen is transported to a mix of industrial customers. A small amount of steam methane reforming is accomplished at smaller plants located at the site where a customer uses the hydrogen for food processing, metal working, glass manufacturing, and other industrial uses. Praxair, a Connecticut company, uses this technique to produce merchant hydrogen, i.e., hydrogen for commercial sale.

Partial oxidation of petroleum is used to produce hydrogen for use in refinery processes which upgrade the natural petroleum constituents to yield greater quantities of gasoline or to reduce sulfur in the refinery products. Partial oxidation combines fuel and air in a high temperature process where the amount of air is too small to permit complete combustion. The result is a synthesis gas mixture of carbon monoxide and hydrogen. If higher purity hydrogen is needed, the water gas shift process can be applied to produce additional hydrogen and carbon dioxide and then the carbon dioxide can be removed through pressure swing absorption or membrane processes.

Coal gasification is essentially the partial oxidation process applied to coal. Water and air are combined with coal in a number of different approaches including moving bed or slagging gasification, fluid bed gasification, or entrained flow gasification. The size of the coal and the method of contacting the air, water, and coal differ among these processes. All the processes produce a synthesis gas which could be fed to a water gas shift process to increase yield followed by purification.

Electrolysis is a very familiar approach to generating hydrogen because it is usually covered in junior high science classes. Electricity is passed through electrodes in water, liberating hydrogen and oxygen at the positive and negative electrodes. The process is used in industrial or laboratory applications where small amounts of hydrogen are required and in applications (submarines and spacecraft) to generate oxygen where electric energy is available, space is limited, and high reliability and low weight are required. Several Connecticut companies produce electrolysis equipment. Proton Energy Systems, a division of Distributed Energy Systems Corporation, produces equipment for industrial applications and is applying them to vehicle filling station demonstrations. Treadwell, Incorporated and the Hamilton Sundstrand Division of United Technologies Corporation produce electrolysis systems for submarines and spacecraft, and Avalence Corporation is developing electrolysis systems as well.

2.2.2 Carbon Dioxide Sequestration

One-third of US carbon dioxide emissions are associated with transportation (Reference 2.12) and reduction of greenhouse gas emissions is often given as justification for hydrogen fuel development. Unfortunately, hydrogen production from hydrocarbons (natural gas, petroleum, coal) produces carbon dioxide as a by-product. While use of electricity in the electrolysis process doesn't produce carbon dioxide directly, 71% of the electricity in the United States is produced with hydrocarbon fuels (Reference 2.13). Consequently, in order for use of hydrogen fuel to reduce greenhouse gases and any associated global warming issues, carbon dioxide associated with its production must be sequestered without release to the atmosphere or eliminated from the atmosphere after release. While current sequestration is limited and primarily associated with enhanced oil recovery, the potential capacity for storing carbon dioxide in geologic or deep ocean locations is several orders of magnitude greater than annual carbon emissions of 6.2 gigatons (Reference 2.12).

The DOE established a Carbon Sequestration Program within the Office of Fossil Energy in 1997 and a basic research program in the Office of Science in 1999. Much of the effort is managed by the National Energy Technology Laboratory (NETL). DOE proposed a FY 2006 budget of \$67.2 million for these efforts, an increase of nearly 50% over the FY 2005 budget (Reference 2.14). DOE efforts are directed toward proof of feasibility and demonstration of storage integrity. Objectives include a reduction of sequestration cost from the current \$100 to \$300 per ton of carbon emissions avoided to a level of \$10 or less per ton by 2015 (Reference 2.7).

Approaches associated with carbon dioxide sequestration at the point of hydrogen generation include geologic sequestration in oil and gas reservoirs and in unmineable coal seams where the carbon dioxide can contribute to enhanced recovery of these fuels. Other geologic possibilities include storage in deep saline formations or direct injection into deep ocean areas. A limitation of these approaches is the requirement for hydrogen generation to be located conveniently to the geologic sink for the carbon dioxide. Consequently, hydrogen may have to be transported

long distances to the point of use. Alternatively, the carbon dioxide could be transported from hydrogen generation systems to the geologic or ocean sink. DOE is currently engaged in a demonstration involving transportation of carbon dioxide from a coal gasification plant in Beulah, North Dakota, via a 320-mile pipeline to an oilfield in Saskatchewan, Canada. Other efforts include a British Petroleum activity in the Aberdeen area of Scotland to generate hydrogen from natural gas, separate the carbon dioxide, and inject it into an oil field in the North Sea (Reference 2.15).

Decentralized generation of hydrogen from natural gas at the point of use or dispensation offers a method to substitute lower-cost transportation of natural gas in the existing infrastructure for high-cost transportation of hydrogen. The point source methods for sequestration discussed above are not amenable to distributed hydrogen generation (although consideration could be given to transporting the by-product carbon dioxide from the distributed points of generation to the sequestration location). Consequently, DOE carbon management efforts include enhancing the natural processes such as photosynthesis which remove or store carbon in land and water ecosystems. DOE is also working on novel systems, including chemical pathways such as magnesium carbonate, in which “the entire global emissions of carbon in 1990 could be contained in a space covering 100 square kilometers to a depth of 150 meters” (Reference 2.16).

2.2.3 Advanced Hydrogen Generation Approaches

Advanced hydrogen generation processes include high-temperature electrolysis and high-pressure electrolysis. DOE is working to develop these processes using heat from advanced high-temperature nuclear reactors or solar energy at Oak Ridge National Laboratory and Idaho National Laboratory (Reference 2.17).

Efforts are also underway to develop aqueous phase reforming and to enhance conventional steam methane reforming by abstracting carbon dioxide from the reaction products as it is formed, thereby increasing yield and reaction rate.

A number of advanced approaches to generate hydrogen on a sustainable basis with no net addition to carbon dioxide emissions are under investigation through efforts of the DOE and others. Most of these approaches, noted briefly below, are in a very early research stage, but they offer promise of a sustainable hydrogen fuel source.

The most highly developed of these approaches include solar and wind electricity generation with electricity input to electrolysis, and biological generation of ethanol with subsequent hydrogen generation by reformation processes. Solar and wind-driven generation of electricity are capital intensive and intermittent, and provide a product valuable in its own right for reduction of all emissions. Similarly, ethanol derived from grain or cellulose can be used directly as a transportation fuel to reduce emissions. Consequently, the benefit of these technologies might be reduced if they were to be diverted for hydrogen generation.

Other approaches generate hydrogen directly from sustainable sources. These include photochemical and photoelectrochemical water splitting and direct hydrogen generation from biomass such as switchgrass. Biological methods include producing hydrogen from pond scum or green algae (*Chlamydomonas Reinhardtii*); and a two-step process involving transformation of cellulose into glucose sugar, which is then converted to a glucose product and its by-product,

gluconic acid, which is then converted into hydrogen. Because of the low energy intensity and intermittent nature of solar radiation, and the low efficiencies of these processes, these approaches require significant land area.

Thermochemical hydrogen production utilizes high temperature process heat from gas-cooled nuclear reactors to decompose water into hydrogen and oxygen. These reactions do not involve carbon fuel and therefore do not contribute greenhouse gases. Several reactions can be used, including sulfur iodine (S-I) and hybrid sulfur (HyS) processes. In the S-I cycle, hydrogen is formed by decomposition of hydriodic acid at 400 ° C. to 500° C. Iodine is reacted with sulfur dioxide and water at 120° C. to produce hydrogen iodine plus sulfuric acid, and sulfur dioxide is regenerated by decomposing that acid at temperatures up to 900° C. Materials (including large quantities of iodine and sulfuric acid), separation and containment of three reactions in series, and oxygen and hydrogen management issues are research challenges to making this process practical. The HyS process uses the same high temperature process to decompose sulfuric acid to sulfur dioxide and oxygen. The only other step in this process is the oxidation of the sulfur dioxide to sulfur trioxide and sulfuric acid with the concurrent production of hydrogen using electrolysis. While the gas-cooled reactors to provide the process heat have been demonstrated in the United States and elsewhere, they are not in commercial use. Researchers at the French Atomic Energy Commission and the US Sandia National Laboratories and Savannah River National Laboratory are among those working in this hydrogen production arena worldwide. There are also active international programs to develop the high-temperature, gas-cooled reactor for process heat applications (Reference 2.17).

2.3 STORAGE

2.3.1 US Department of Energy Goals

Hydrogen energy density on the basis of weight is three times that of gasoline, and this attribute is among those which make it a fuel of choice for rocket upper stages. However, hydrogen energy density on the basis of volume is very low; liquid hydrogen, for example, has one-fourth the energy density of gasoline (Reference 2.18). This makes storage of sufficient hydrogen for acceptable, light-duty vehicle range (300 miles) one of the most significant challenges of the DOE Hydrogen Program (Reference 2.19). Low volumetric energy density is a problem in its own right, but also brings with it high tankage weight.

The current goals of the DOE hydrogen storage program are to develop onboard hydrogen systems which achieve a 300-mile vehicle range by 2015. Studies indicate this requires a specific energy density of 3.9 kWh/kg (9 weight percent hydrogen) and 2.7 kWh/liter. Cost goals are \$2 per kWh of energy stored (Reference 2.20). Intermediate goals have been established consistent with a 250-mile vehicle range in 2010. Detailed information on various forms of hydrogen storage, their development status, and DOE's program to develop them further is provided in Reference 2.18. DOE, as part of its hydrogen research activities, in 2003 issued a "Grand Challenge" for development of hydrogen storage systems, which resulted in establishment of Centers of Excellence on Metal Hydrides (Sandia National laboratories), Chemical Hydrogen Storage (Los Alamos National Laboratory and Pacific Northwest National Laboratory), and Carbon-Based Materials (National Renewable Energy Laboratory).

While the goals for hydrogen storage are set on the basis of storage in vehicles, the technology improvements for this storage requirement will also flow to storage in vehicle filling stations and to new transportation technologies.

2.3.2 Commercial Hydrogen Storage Techniques

Currently, hydrogen is stored commercially primarily as a compressed gas or a cryogenic liquid. Generally, liquid storage is associated with larger usage rates and longer transportation distances.

Commercially, hydrogen is stored as a high-pressure gas in tanks or cylinders at 2,000 psi. Advanced vehicle storage systems are based on carbon-reinforced tanks at 5,000 to 10,000 psi; 10,000 psi is generally considered to be the practical pressure limit. Compression energy consumption is 10 to 15% of the stored energy content. Other issues include refueling times, heat management, cost, and configuration. For example, tanks in a shape conforming to waste space available in a vehicle would permit longer range without compromising passenger or cargo capacity. High-pressure tanks are now certified worldwide, demonstrated in prototype vehicles, and available commercially. Currently, compressed gas storage is at one-third of the volume energy density and one-half of the weight energy density targets for 2015, with cost nearly ten times the 2015 target.

Liquid hydrogen storage is also in commercial use. Storage is at cryogenic temperatures below -250° C. (-418° F.). Liquefaction energy consumption is about 30% of the energy content stored, and boil-off of the stored hydrogen at a rate of 0.4% per day (Reference constitutes another energy and energy density penalty. Liquid storage has also been demonstrated in vehicles, although it is much less prevalent than gaseous storage because of the liquefaction energy and boil-off characteristics. Liquid storage is at 45% of the 2015 volume energy density target, 55% of the weight target, and cost is three times the 2015 target. An advanced hybrid tank concept combining gaseous and cryogenic storage is being studied to alleviate the current deficiencies of liquid storage, and there is a possibility that cost could be reduced with advanced design and high volume production. However, achieving DOE goals will probably require development of advanced hydrogen storage techniques.

2.3.3 Advanced Hydrogen Storage Techniques

Storage of hydrogen is of critical importance because it affects three aspects of hydrogen-fueled transportation: distribution of hydrogen, fueling stations, and vehicles. In all three of these, the weight, volume and cost of hydrogen storage are important factors. A number of advanced storage technologies are being investigated, including reversible metal hydrides, chemical hydride materials, carbon materials, and high surface area sorbents.

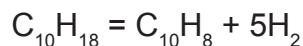
Metal hydride storage based on iron-titanium hydrides is used commercially in limited, small power-level, and small production-volume applications. Because it doesn't require high pressure or low temperature containment, hydride storage can be in complex shapes which take advantage of unused space in a vehicle. One property of metal hydrides is that they require heating to release the hydrogen; from a safety viewpoint, this is an advantage, but polymer exchange membrane (PEM) fuel cell waste heat temperatures are marginally able to supply this heat, so there may be an efficiency penalty. Heat is given off in the "charging" stage and heat

management must be considered in the system design. Other issues requiring development include slow charge and discharge rates, durability, and cost. Simple metal hydrides don't have the energy density required, so current research is directed at more complex hydrides such as alanates (sodium/aluminum/hydrogen compounds) and lithium amides. Some of this research is being conducted at United Technologies Research Center in East Hartford. Currently, projected weight and volume energy densities are only 25% of the 2015 goals and cost is eight times the goal.

A Prius hybrid using advanced metal hydride storage from ECD Ovonic is being demonstrated with a range of nearly 200 miles from a tank volume of 33 liters or 8.6 gallons, equal to the standard Prius gasoline tank. Ovonic is conducting research to bring the range to DOE's 300-mile goal. Another research goal is to decrease the fill time from the current 8 minutes to 5 minutes (Reference 2.22).

Chemical hydrogen storage includes reaction of compounds such as sodium borohydride, magnesium hydride, or light metals with water or steam to produce hydrogen and another compound. These systems require water, which makes them subject to freezing, and produce a by-product which must be removed and recycled outside the vehicle. Millennium Cell is the company best known for developing and demonstrating this technology; their current focus is on portable power for military applications (Reference 2.23).

Another form of chemical hydrogen storage involves hydrogenation and dehydrogenation of hydrocarbons. For example, according to the DOE's electrical efficiency and renewable energy website, "the decalin-to-naphthalene reaction can release 7.3 weight percent hydrogen at 210° C. via the reaction:



A platinum-based or noble metal supported catalyst is required to enhance the kinetics of hydrogen evolution." Other examples of chemical storage couples are being investigated by DOE. Like the other form of chemical storage, however, the by-product fluid must be removed from the vehicle and regenerated elsewhere. Energy is required during regeneration. In DOE program progress reports for 2004, Air Products reported a liquid phase material which shows 5 to 7 weight percent hydrogen and a volume density of greater than 0.05 kilograms/liter. Efforts to reduce the required dehydrogenation temperature are underway involving this and other promising materials (Reference 2.24).

Chemical storage methods currently are at around 40% of the 2015 energy density goals while cost is four times goal. Like metal hydrides, these approaches have configuration flexibility that makes better use of complex available spaces in vehicles.

Carbon-based materials such as carbon nanotubes, aerogels, and nanofibers are hydrogen storage candidates. These are in very early research stages with performance well below DOE targets, while manufacturing and reproducibility questions exist. Recently, however, the Stanford Linear Accelerator Center announced that they estimated the hydrogen storage potential for single walled carbon nanotubes to be up to 7.5 weight percent (Reference 2.25).

High surface area sorbents are also being pursued, including microporous metal-organic frameworks clathrates and polymers. The University of Connecticut is working on lithium nitride as part of this activity. These concepts are at a very early research stage.

Nano-scale water bubbles. A press release on March 10, 2006 described application for a patent on a device that creates nanometer-scale water bubbles filled with hydrogen (Reference 2.26). There is little information on this approach and details and status are unknown. However, it illustrates application of different physical principles to the hydrogen storage problem.

2.4 DISTRIBUTION AND DISPENSING

2.4.1 *Hydrogen Distribution Approaches*

The low volumetric energy density of hydrogen poses problems for distribution in the same way it poses problems for storage. Low volumetric energy density leads to larger capital investment, storage and transport energy losses, and costs to transport a given amount of energy. For example, a compressed gas tube trailer can transport only 300 kilograms of hydrogen; consequently, 15 compressed gas tube trailers would be required to transport the energy equivalent of one gasoline tank truck (Reference 2.3). A liquid hydrogen tanker with 8,000 gallons capacity would transport 2,200 kilograms of hydrogen, which reduces the number of trucks for one gasoline truck equivalent to two; while this is much less than for compressed gas, it still results in much more expensive transportation costs. Both trucking approaches to distribution also involve energy loss and emissions from the trucks themselves.

Since gaseous hydrogen has only 30% of the energy density of natural gas, pipeline systems for hydrogen are also more costly in terms of energy consumption, capital investment, and overall transport cost. Reference 2.4 calculates that a pipeline which transports a given quantity of natural gas will reduce its energy-carrying capacity by 20% to 25% if used to transport hydrogen. Gas compression energy will be increased by a factor of three or more. Hydrogen is currently transported by pipeline. These pipelines are high-pressure pipeline systems, but are for very specialized applications; they have very small diameters and use expensive steels (Reference 2.27).

The US hydrogen program is developing the materials and standards for safe, lower-cost hydrogen pipelines (Reference 2.28).

Conventionally, hydrogen is transported in CNG tube trailers over shorter (100 to 200 miles) distances and by liquid tanker trailers, railcars, or barges over longer distances. Where significant concentrated demand is present, hydrogen is transported in pipelines.

The advanced storage methods discussed in Section 2.3.3 have application to transportation as well if they can be developed to have superior economics to current methods.

Another approach to transportation is to transport natural gas by pipeline (a high percentage of gasoline filling stations are located near natural gas pipelines) and convert it to hydrogen through steam methane reformers located at fueling stations, or ultimately at the point where vehicles are garaged. A similar alternative is to transport electricity by wire to electrolysis units located at fueling stations or at the point where vehicles are garaged. These methods have the advantage of a well-developed infrastructure, but the disadvantage of loss of economy of scale in the conversion equipment compared to central conversion systems. Honda and Plug Power are experimenting with a home energy station in which natural gas is converted to electricity, heat,

and hydrogen, which is then dispensed to a hydrogen-fueled vehicle (Reference 2.29). Home fueling of CNG has been demonstrated and electric vehicles are charged where they are stored.

2.4.2 Hydrogen Filling Stations

A hydrogen filling station has several components: compression, storage, dispensing, and, possibly, generation via on-site conversion of hydrogen from water, natural gas or chemical hydrides. The footprint (land requirements) of the station is strongly influenced by separation distances required by current standards, which set minimum separation distances for the station components, as well as by storage space requirements and, in some cases, the space required for conversion equipment. In Connecticut, land availability, particularly along major transportation corridors, is quite limited; consequently, reduction of separation distances is very important.

California has a significant and growing infrastructure of hydrogen filling stations. Sixteen are in operation and 15 more are planned. Eleven of the 16 operating stations are for fleet vehicles, while five are for public use. All of the 15 planned stations are for public use. These stations use a variety of storage technologies: compressed gas, liquid, and combination liquid and gas. A number of the stations have electrolysis units, a smaller number have natural gas reformers, and one has a combination of reforming and electrolysis. Wind and solar-powered electrolysis systems are included in the mix. These stations have capacity for at most 20 cars per day, which is sufficient for the 95 hydrogen-fueled vehicles currently in California (the average gasoline station in the United States serves 350 cars per day (Reference 2.30)). Station design, equipment manufacture, and station operation are performed by energy, electrolysis, industrial gas, auto and fuel cell companies, transit companies, government agencies, and academic institutions (Reference 2.31).

Dispensing of gaseous hydrogen is similar to dispensing of CNG. The California filling station designs and others build on CNG technology. Dispensing of liquid hydrogen is similar to dispensing of liquefied natural gas (LNG) and refueling stations for LNG-fueled trucks have been operating for some time. Dispensing of liquid hydrogen is being developed by BMW and others. A February 2005 report describes a prototype dispenser suitable for hydrogen, CNG, and a natural gas-hydrogen mixture (Reference 2.32). That report describes the controls, safety features, and operation of the dispenser. Fill rates should be consistent with the 3 to 5 minutes it takes to fill a gasoline-fueled automobile.

There are currently 169,000 gasoline filling stations in the United States (Reference 2.33). Experience with diesel-fueled autos shows acceptable availability requires that 10% to 20% or more of these stations have the alternative fuel – diesel or hydrogen. The cost of adding hydrogen fuel capability to 30% to 50% of the gasoline stations has been estimated at one half trillion dollars (Reference 2.3). The investment would occur over at least one to two decades. While this investment requirement is challenging, it is not inconsistent with the investment capacity of the major energy companies. Capital and exploration expenditures of the major petroleum companies in 2003 were in excess of \$600 billion (Reference 2.33).

2.5 UTILIZATION OF HYDROGEN

Commercially, hydrogen is used in ammonia production, petrochemicals, food processing, methanol production, chemical and metallurgical industries and electrical generator cooling.

Aerospace applications include spacecraft propulsion and spacecraft electric power.

Fuel cell power plants currently deployed for stationary electrical power purposes convert natural gas within the power plant to hydrogen, which is then used in the fuel cell stack itself. Fuel cell application for standby electrical power is under development; this application uses pure hydrogen from pressurized tanks.

Connecticut companies – UTC Power Division of United Technologies and FuelCell Energy, with at least 250 units installed – in addition to Fuji Electric of Japan account for virtually all the world’s installations of commercial and demonstration stationary fuel cell power plants at power levels of 25 kW or more. A company in the Albany, New York area, Plug Power, accounts for a major portion of smaller fuel cell power plants which are in the demonstration stage (Reference 2.34).

Central station power plants involving a coal gasifier, hydrogen separation from carbon dioxide, sequestration of the carbon dioxide and hydrogen-fueled combined-cycle are under development. The primary objective is reduction of greenhouse gas emissions and increased generation efficiency.

Use of hydrogen in transportation is under development, with most of the effort devoted to use in fuel cell power plants, although there is a smaller effort for use of hydrogen in internal combustion engines. UTC Power Division of United Technologies provides the fuel cell power plants used in BMW, Hyundai, and Nissan automobiles and also provides power plants for transit buses operating in California and Europe.

Currently there are many hydrogen-fueled fuel cell vehicle demonstrations in the United States, Europe, Japan, and Korea. The vehicles include automobiles of various types, transit buses, and delivery trucks. In the United States, California has the largest fuel cell vehicle population. These demonstrations are described further in Section 2.7.

2.6 NATIONAL, INTERNATIONAL AND INDUSTRY CODES AND STANDARDS

2.6.1 Introduction

A survey was conducted of national, industry, and international codes and standards activities that address safety issues associated with the generation, storage, transport, and use of hydrogen as a fuel in an over-the-road transportation application.

National standards – those accredited by the American National Standards Institute – are developed as a consensus of those directly and materially affected by the standard, such as a balanced committee comprising manufacturer, user, regulatory and insurance interests. Industry standards are generally developed by the organization’s members. Both types of standards are referenced in federal, state, and local regulations. An international standard would generally first have to be adopted as a US standard before it would be referenced by federal, state, or local regulations.

A short description of all codes and standards organizations active in this area, along with their contact information, is provided in Appendix B, and the status of codes and standards and first responder training associated with hydrogen-fueled transportation at the national level is provided in Appendix C. Updates regarding the status of these codes and standards are available at a website supported by the US Department of Energy National Renewable Energy Laboratory (NREL) (Reference 2.35).

The national and international codes and standards activity is largely a volunteer effort of the standards organizations, standards committee participants and their organizations. The DOE and US DOT provide coordination assistance and sponsor research associated with specific technical issues related to codes and standards. The effort is comprehensive and deals with all aspects of the hydrogen infrastructure and use of hydrogen as a fuel. The information in Appendix C is organized as follows:

- Hydrogen infrastructure issues including:
 - On-site hydrogen generation
 - Hydrogen storage
 - Hydrogen piping
 - Hydrogen pipelines
 - Over-the-road transport of hydrogen
 - First responders
- Use of hydrogen as a fuel including:
 - Vehicle design
 - Service station design
 - Hydrogen dispensing
 - Garages
 - Tunnels
 - First responders
- Government Oversight

Codes and Standards activity in Connecticut is discussed in Chapter 5, Section 5.4.

2.7 EFFORTS BY FEDERAL GOVERNMENT, OTHER STATES, AND OTHER COUNTRIES

Connecticut's efforts in the field of hydrogen-fueled transportation must be coordinated with the existing, large efforts by the federal government, other states, and other countries in order to avoid duplication, to complement these efforts, and to execute those tasks required to prepare

for the hydrogen economy which are specific to the state of Connecticut. The efforts of the entities outside Connecticut are discussed below.

2.7.1 US Federal Government Efforts

US efforts in the field of hydrogen-fueled transportation began with the Partnership for New Generation of Vehicles (PNGV). This effort began in 1993 as a partnership between auto makers and the federal government to develop technology for mid-size vehicles with 80 mile-per-gallon fuel economy without sacrificing performance, size, cost, emissions, or safety. The PNGV plan involved selection of the most promising technologies by 1997, concept prototypes available in 2000, and a production prototype by 2004. The program budget, shared equally by the government and the auto companies, was a billion dollars or more. Fuel cells were among the technologies considered and demonstration power plants were operated, but diesel hybrids were selected as the propulsion technology in 1997 and concept prototypes were built in 2000. The National Research Council (the study arm of the National Academies – see www.nationalacademies.org/nrc.) conducted annual peer reviews of the PNGV program. The PNGV program may have generated interest in hybrid vehicles in Japan and in fuel cell vehicles by Daimler Chrysler and Ballard (Reference 2.36). The PNGV program had a narrow focus on diesel hybrids which led to its demise in 2002 (Reference 2.37).

The federal effort regarding the development of fuel cell vehicles was continued under the FreedomCAR Program, which was announced as a joint effort between DOE and the US Council for Automotive Research (USCAR) in January 2002. This effort received significant impetus in the January 28, 2003 State of the Union speech by President Bush, who said, “A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car – producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free.” The 2005 and 2006 State of the Union speeches also contained references to hydrogen-fueled transportation.

The budget for the FreedomCar and Freedom Fuel programs was proposed as \$1.7 billion dollars over a five-year period in January 2003 (Reference 2.38) and annual budgets have been roughly consistent with that figure since 2003.

The federal program in hydrogen-fueled transportation involves the DOE in research and development and demonstration in light-duty vehicles (automobiles) and the US DOT in heavy-duty vehicles (transit buses, trains, trucks, etc).

2.7.1.2 US Department of Energy Program

The DOE prepared a hydrogen roadmap in 2002 which outlines the goals, strategic issues, barriers, and key activities associated with hydrogen-fueled transportation. (Reference 2.39). DOE then prepared a Hydrogen Posture Plan reflecting the activities of all DOE offices, including: Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy and Science (Reference 2.40). The Posture Plan envisions the following phases of transition to a hydrogen economy:

PREPARING FOR THE HYDROGEN ECONOMY: TRANSPORTATION
ELEMENTS OF A HYDROGEN-FUELED TRANSPORTATION SYSTEM:
APPROACHES AND STATUS

- Research and development through 2015
- Transition to the marketplace from 2010 to roughly 2025
- Infrastructure investment phase from 2015 through 2035
- Fully developed market and infrastructure phase from 2025 through 2045 and beyond

Early phases of commercialization will utilize current hydrogen production techniques, but later phases are anticipated to utilize techniques that minimize use of fossil fuels and emissions of greenhouse gases with hydrogen production from clean coal technologies, photolytic water splitting, biological processes, and nuclear thermochemical water splitting. Similarly, hydrogen storage will advance from compressed gases and liquid hydrogen at the start of commercialization to solid state approaches by 2045. It is also possible that localized and long-distance hydrogen pipelines will supplant hydrogen transport by gaseous or liquid tank trucks and distributed generation of hydrogen by 2045. DOE activities will include efforts directed at hydrogen production, delivery, and storage, conversion in fuel cells and internal combustion engines, application demonstrations, a Codes and Standards and Safety activity, and public education.

For the Energy Efficiency and Renewable Energy office of DOE, the roadmap was followed by development of a draft plan in June 2003 which was posted for public comment and reviewed by a panel of the National Research Council (Reference 2.41). Following incorporation of the review, a final plan was published (Reference 2.42). The plan addresses activity in all aspects of the hydrogen infrastructure and hydrogen vehicles during the Research and Development Phase of the Posture Plan. Three phases of Research and Development have been established: Phase 1, Technical Feasibility from 2000 through 2004; Phase 2, Controlled Plant Test and Evaluation between 2004 and 2010; and Phase 3, Commercial Readiness Demonstrations from 2010 through 2015. These pave the way for commercialization after 2015. Goals have been established for each of the individual aspects of the plan (for example, hydrogen production, transportation and storage, fuel cells) and goals consistent with the individual aspects have been expressed in the goals for the demonstration automobiles in 2010 and 2015 shown in Table 2.4

	At end of Phase 2, Controlled Fleet Test and Evaluation, 2010	At end of Phase 3, Commercialization Readiness Demonstrations, 2015
Vehicle range (miles)	250	300+
Fuel cell durability (hours)	2,000	5,000
Delivered hydrogen cost, (untaxed in 2005 dollars per gallon of gasoline equivalent) (\$/gge)*		2 to 3*
Refueling	Safe and convenient refueling by trained drivers	Safe and convenient refueling by trained drivers

* Revised goal published in DOE press release July 14, 2005. The goal is independent of the production and delivery pathway

Table 2.4. DOE Hydrogen Program Goals

DOE has also issued a draft Manufacturing Roadmap (Reference 2.43).

A biennial review of progress toward these goals is conducted by an independent party – the National Research Council.

Vehicle demonstrations to validate achievement of the interim goals are now underway, with four teams of vehicle manufacturers and major oil companies producing vehicles and installing fueling stations. The teams include

- DaimlerChrysler/ British Petroleum
- Ford/British Petroleum
- General Motors/Shell
- Hyundai/Chevron

Each of these teams will deliver and operate a fleet of about 30 vehicles and operate a number of fueling stations. Most of these will be located in California and some will be located in Michigan for cold weather demonstration. The vehicles will be delivered between 2005 through 2007 and technology improvements will be added as they become available. As part of the demonstration programs, the participants are training first responders and conducting public outreach activity to inform the public about hydrogen-fueled transportation.

Other organizations, including Hydradix and SunLine Services Group, Inc., Air Products and Chemicals Inc. and the Gas Technology Institute, are also demonstrating hydrogen fueling stations. The activity also includes efforts in renewable hydrogen production systems and power parks. These are sites where electricity and hydrogen are both produced, for example, from renewables or alternatively, in a concept being developed by FuelCell Energy, where co-production of hydrogen and electricity from a hydrocarbon fuel is done (see Chapter 5, Section 5.3). The hydrogen can be stored and later used as a vehicle fuel or converted back to electricity in a fuel cell during periods of peak demand.

2.7.1.2 US Department of Transportation Program

The US DOT program focuses on medium- and heavy-duty vehicle development. Transit buses represent an attractive early deployment opportunity because they involve centrally fueled and maintained fleets with professionals involved in all fueling, operation, and maintenance. Size and weight constraints are less severe than for light-duty vehicles, federal support for purchases is routine, and transit buses operate in congested areas where hydrogen fuel benefits are maximized and receive broad public exposure. The hydrogen and fuel cell bus goal is to have 10% of new US bus purchases be fuel cell buses by 2015. (Reference 2.44.)

The US DOT published its hydrogen plan in October 2005 (Reference 2.45). This plan identifies four primary activities:

- Safety Codes, Standards and Regulation
- Infrastructure Development and Deployment
- Safety Education, Outreach and Training
- Medium- and Heavy-duty Vehicle Development, Demonstration and Deployment

The plan refers to “industry-targeted commercial integration of hydrogen vehicles by 2010 ... the DOE commercialization target of 2015 and ... transition from demonstration to deployment in the 2015 to 2020 time frame.”

Early testing of methanol-fueled fuel cell transit buses was conducted at Georgetown University, and early hydrogen-fueled buses were tested at Chicago Transit. Current demonstrations include hydrogen-fueled internal combustion engine buses as well as hydrogen-fueled fuel cell buses with improved technology fuel cell power plants.

The latest bus demonstration of three heavy-duty transit buses was dedicated at ATransit in Oakland, California, on March 13, 2006. The dedication included a fueling station by Chevron, which is capable of fueling three buses and ten hydrogen-fueled automobiles per day. The heavy-duty transit bus is built by Van Hool bus, system integration is by ISE, and the fuel cell is manufactured by UTC Fuel Cells. (Reference 2.46). An additional bus of identical design is being operated by SunLine transit in Palm Springs, California (Reference 2.47).

2.7.1.3 National Organizations

Several organizations are associated with fuel cells and hydrogen at the national level. The National Hydrogen Association (NHA) (Reference 2.48) has over 100 members, including major industry, small business, government, and university organizations. Its objectives are the following:

- Assist in information transfer among research, industrial, and government programs
- Provide a national focal point for hydrogen interest that can assist state and federal government organizations and private industry in developing hydrogen initiatives in emerging technologies
- Develop public and government education programs that provide information about the potential for hydrogen as an energy carrier and for hydrogen technologies
- Develop approaches to specific projects that can serve as innovative models for production, storage, and use of hydrogen

The NHA holds an annual meeting which provides information on the current status of hydrogen research, development and demonstration efforts for US and international organizations.

The US Fuel Cell Council (Reference 2.49) is an industry organization with 120 members “dedicated to fostering the commercialization of fuel cells in the United States.” It has the following working groups:

- Codes & Standards
- Education & Marketing
- Government Affairs
- Materials & Components

- Portable Power
- Power Generation
- Sustainability
- Transportation

Fuel Cells 2000 (Reference 2.50) “is an activity of the Breakthrough Technologies Institute (BTI), a non-profit [501(c)(3)] educational organization formed to promote the development and early commercialization of fuel cells and related pollution-free, efficient energy generation, storage and utilization technologies and fuels.” Its activity includes the following:

- “Prepare and disseminate written materials on the benefits and near-term availability of the family of fuel cell technologies.
- Conduct informational briefings and meetings to provide policy makers, selected science, environmental and energy reporters, and others a detailed look at the technology, its promise, and related policy choices.
- Conduct educational conferences, prepare and distribute educational materials, and develop model policy statements for fuel cells.
- Maintain a website so that internet users around the world will have access to a wealth of information about fuel cell technology.
- Maintain a library of literature on fuel cell development projects around the world.”

Fuel Cells 2000 has a number of useful reports on global fuel cell activity on its website. Contributors receive a newsletter and other benefits.

2.7.2 Activities in Other States

Many states have hydrogen and fuel cell activity. A comprehensive review of state and regional activities and pending legislation is provided in a publication by BTI and available at www.fuelcells.org (Reference 2.51). This report states that there are activities in 47 states and the District of Columbia. One indication of a state’s activity in hydrogen is the existence of a hydrogen plan or roadmap. Eleven states have hydrogen roadmaps that were analyzed by the Appalachian State Energy Center: California, Florida, Illinois, Minnesota, New Jersey, New Mexico, New York, Ohio, South Carolina, Texas, and West Virginia. These roadmaps are described in Reference 2.52. Several states have hydrogen activity of particular interest:

- California and New York are large states with high levels of pollution and have strong industry, government, or coalition activities underway.
- Ohio and Michigan are states where auto industry employment is very important and where participation in hydrogen vehicle manufacturing is an important economic issue.

Activities in these four states and proposals for multi-state activities are described below.

2.7.2.1 CALIFORNIA

California's activities are significant. They include the California Fuel Cell Partnership, the Hydrogen Highway, and activities at a number of universities. This existing activity has resulted in the majority of demonstration hydrogen vehicles (both automobiles and buses) being located in California. The impetus for these activities comes from California's long-standing air pollution problems and their historic leadership in environmental regulation. Action in California is supported by auto companies and others in part because of the size of its automobile market and in part because of the reputation of its population as being receptive to innovative new products.

The California Fuel Cell Partnership (Reference 2.53) involves 31 companies and government agencies who have joined to "promote fuel cell vehicle commercialization." Several Connecticut companies (Praxair, Proton Energy Systems, and UTC Power) are members of the Partnership. Organization members have placed 120 fuel cell automobiles in demonstration programs and are currently demonstrating seven fuel cell buses. These demonstration activities include US government programs described above. The Partnership has a goal of demonstrating 300 fuel cell vehicles by the end of 2007. The Partnership has located a number of fuel cell vehicles and a hydrogen fueling station at its Sacramento headquarters, provides first-responder training, studies of fuel cell vehicle issues, and has toured 54 California cities in its public outreach activity.

The California Hydrogen Highway (Reference 2.54) is sponsored by the state of California. It was initiated by Executive Order S-7-04 on April 20, 2004 and has the goal of establishing a hydrogen filling station every 20 miles on major California highways, a total of 150 to 200 stations. Sixteen stations are in operation with 15 more planned. Some of these stations have been constructed as part of the DOE and US DOT demonstration programs described above. The stations use a variety of hydrogen supply technologies, including electrolysis and steam methane reforming systems to generate hydrogen on site.

A number of universities in the California state system are involved with hydrogen energy. For example, the University of California, Davis conducts \$90 million in research in transportation, about half of which is conducted at The Institute of Transportation Studies. Environmental vehicle technologies, including fuel cells and hydrogen, are one of the three primary focus areas of the institute. Other California colleges and universities with courses and/or research involved with fuel cells include: California Institute of Technology; Humboldt State; San Diego Miramar College; University of California, Berkeley; The National Fuel Cell Research Center at University of California, Irvine; and University of California, Riverside.

2.7.2.2 NEW YORK

New York is a state with a large population and the capability to provide extensive funding for research and development. It ranks with Connecticut in terms of the number of fuel cell researchers in the United States, with General Motors fuel cell research being conducted at Honeoye Falls near Rochester; Delphi conducting research at Henrietta, also near Rochester; Plug Power fuel cell company located in Latham, near Albany; MTI Micro Fuel Cells Inc., a subsidiary of Mechanical Technology Inc., in Albany; and GE Corporate Research and Development in Schenectady. While Praxair is headquartered in Connecticut, much of its

hydrogen activity is located in New York. A recent article estimates that there are nearly 800 researchers in the Rochester area alone (Reference 2.55).

New York has an extensive energy research program conducted by the New York State Energy Research and Development Administration (NYSERDA), which was established in 1975 by the New York State Legislature. The NYSERDA budget is about \$200 million per year. A small amount of this budget is devoted to hydrogen-fueled vehicles, which involves testing of an internal combustion engine hydrogen vehicle operating near Buffalo and a Honda fuel cell vehicle fueled by a home refueling system provided by Plug Power. NYSERDA is also working on a Hydrogen Transportation Corridor along the New York Interstate System in conjunction with Shell Hydrogen.

The New York Hydrogen Roadmap (Reference 2.56) envisions a demonstration phase through 2010 followed by deployment in cities, clusters and corridors, with state vehicles among the first users during the period 2010 through 2015 followed by expansion to statewide hydrogen networks in the 2015 to 2020 time period.

2.7.2.3 OHIO

Ohio's interest in fuel cells arises because of its heavy employment in the auto industry and university involvement in fuel cells.

The Ohio Fuel Cell Coalition (Reference 2.57) is "a united group of industry, academic, and government leaders working collectively to strengthen Ohio's fuel cell industry and to accelerate the transformation of the industry to global leadership in fuel cell technology and applications." The coalition has nearly 80 members. It sponsors an annual fuel cell symposium.

Ohio support of fuel cell and hydrogen research is provided through the Third Frontier Project (Reference 2.58), which is "the state's largest-ever commitment to expanding Ohio's high-tech research capabilities and promoting innovation and company formation that will create high-paying jobs for generations to come. The 10-year, \$1.6 billion initiative [is] designed to

- build world-class research capacity;
- support early-stage capital formation and the development of new products; and
- finance advanced manufacturing technologies to help existing industries become more productive."

Ohio expects to leverage the state funds with support from federal and other sources.

The fuel cell portion of this effort is "a \$103 million program that aims to spur job creation in Ohio while positioning the state as a national leader in the growing fuel cell industry" (Reference 2.59). Ohio has a number of colleges and universities involved with fuel cells, including Case Western Reserve University, Ohio State, Stark State Technical College, and the University of Cincinnati.

A recent announcement in March 2006 by the Dana Corporation, an auto industry supplier located in Ohio, regarding successful tests of a proprietary hydrogen generation approach, is one example indicating that Ohio is having success in meeting the objectives stated above.

2.7.2.4 MICHIGAN

Like Ohio, Michigan's interest in fuel cells stems from the automobile industry. Michigan ranks first in the nation in automobile research and development, with 60,000 professionals and \$10.3 billion annually in expenditures. Michigan ranked second overall in R&D expenditures (Reference 2.60).

The state of Michigan formed a non-profit corporation, NextEnergy, to address alternative energy solutions for electricity generation and transportation (Reference 2.61). NextEnergy is located within TechTown, a 501(c)3 organization with an alternative energy zone providing tax benefits in the Wayne State University Research and Technology Park. The NextEnergy slogan is "economic security through energy diversity." NextEnergy initiatives include an industry working group focused on advancing the use of hydrogen fuel in Michigan. Their efforts include codes and standards, one of the locations for the DOE Hydrogen Fleet Demonstration and Validation Program, educational awareness programs for first responders and local officials, and promotion of hydrogen infrastructure. Participants include automotive original equipment manufacturers (OEMs), energy companies, and government entities as well as others with a stake in the Michigan hydrogen infrastructure.

In addition to the efforts noted above, Michigan is home to the federal Environmental Protection Agency's (EPA) National Vehicle and Fuel Emissions Laboratory, which is testing a DaimlerChrysler Sprinter Van powered by a hydrogen fuel cell and operated by UPS under an EPA program. This includes a hydrogen fueling station located at the laboratory (Reference 2.62). Michigan has seven hydrogen fueling stations operating or planned.

Success of Michigan's economic development efforts is illustrated by a recent announcement by Ovonic Hydrogen Systems LLC, a subsidiary of Energy Conversion Devices Inc. (Reference 2.63). The company has modified a Prius hybrid vehicle to operate its internal combustion engine on hydrogen using a proprietary metal hydride storage system from Ovonic which provides twice the hydrogen storage capacity of a 10,000 psig compressed gas tank of the same size. One vehicle is being tested at the Ovonic headquarters in Rochester Hill, Michigan, and another is being tested as part of a five-year, \$7 million, multi-vehicle, hydrogen-hybrid demonstration funded by and located at the South Coast Air Quality Management District Headquarters in Diamond Bar, California.

2.7.2.5 MULTI-STATE ACTIVITIES

Two multi-state initiatives are being promoted; each involves a hydrogen highway, one in the East (Reference 2.64) and one in the Midwest (Reference 2.65).

2.7.3 Activities in other Countries

Hydrogen-fueled transportation is being developed worldwide. Canada, Europe, and Japan are areas of particular interest. The International Partnership for the Hydrogen Economy has 17 member companies who coordinate efforts to accelerate the development of hydrogen energy (Reference 2.66).

2.7.3.1 CANADA

Canada is home to Ballard, which has the leading vehicle experience in the fuel cell industry. Currently, Ballard fuel cell power plants are in over 130 vehicles and they are working with eight vehicle manufacturers (Reference 2.67). DaimlerChrysler and Ford were early investors in Ballard. Canada is also home to Hydrogenics, located in Ontario, which manufactures fuel cell power plants for transportation and stationary applications and electrolysis systems (Reference 2.68).

The Canadian Fuel Cell Industry Association is Fuel Cells Canada (Reference 2.69). Additional information on Canadian fuel cell companies and projects is available on their website. Information on Canadian Hydrogen Projects is provided in Reference 2.70.

2.7.3.2 EUROPE

The European Union (EU) is currently engaged in the five-year, Sixth Framework Programme in fuel cells and hydrogen with 30 projects funded at a total EU contribution of just over 100 million Euros. As part of this European Union program, a hydrogen roadmap progress report was issued in February 2006. The progress report, which contains considerable analysis of key issues, can be found at the HyWays website (Reference 2.71). The largest bus demonstration project in the world involves 33 DaimlerChrysler fuel cell buses in 11 cities in Europe, Iceland and Australia. The effort is carried out under the name Clean Urban Transport Europe (CUTE) and provides hydrogen from central locations (52%) or local generation (48%) by steam methane reforming or electrolysis (Reference 2.72)

In addition to the EU efforts, the German Transport Minister recently announced an investment of 500 million Euros over the next 10 years toward developing hydrogen-powered vehicles. The Mayor of London has announced a £ 22 million green energy package proposal for 2006/2007 that includes introduction of 70 fuel cell buses to London by 2010. These announcements were provided on the Fuel Cell Europe website (Reference 2.73), which also lists its members, including many European companies.

DaimlerChrysler is the leading company worldwide in terms of hydrogen fuel cell vehicle fleet experience, having operated over 100 vehicles. This includes 33 fuel cell buses, three Sprinter delivery vans operated by UPS in Europe and Asia, and 60 automobiles operating worldwide.

2.7.3.3 JAPAN

Japan has robust hydrogen activity, with all the major car and bus companies involved with hydrogen vehicle demonstrations. In some cases, i.e., Honda, both internal combustion engine vehicles and fuel cell vehicles are being pursued. The Japan Hydrogen and Fuel Cell Project (Reference 2.74), which involves over 20 companies, has resulted in creation of a dozen hydrogen fueling stations in Japan during its first phase, which ends this year. A second five-year phase of the project will begin next year (Reference 2.75).

Japan appears to be the first country with a hydrogen fuel cell train. Test runs of the train are scheduled to begin in July 2006, with testing in passenger service scheduled for 2007 (Reference 2.76).

2.8 PROJECTED COMMERCIALIZATION SCHEDULES

Projected dates for hydrogen-fueled vehicles vary widely. Among the earliest projections is one by BMW, which plans to begin serial production of a few hundred Seven Series BMW vehicles with dual-fuel gasoline/hydrogen internal combustion engines beginning in 2010 (Reference 2.77). Longer projections include those by Joseph Romm, a former Principal Deputy Assistant Secretary and Acting Assistant Secretary of the DOE's Office of Energy Efficiency and Renewable Energy. In 2004, Romm predicted that hydrogen may become a significant vehicle fuel in the second half of the twenty-first century (Reference 2.78). In January 2006, Romm was more pessimistic, indicating that hydrogen-fueled cars would not emerge "until 2040 *at best* and may well prove to be a dead end" (Reference 2.79). These widely varying milestones for hydrogen-fueled transportation indicate the degree of uncertainty associated with overcoming difficult technical challenges. However, comments by the National Research Council recognize the effort is "an extremely challenging program..." which "is justified by the potentially enormous beneficial impact for the nation..." (Reference 2.41).

Given the significant technical challenges, Connecticut's efforts to prepare for hydrogen-fueled transportation should proceed based on careful review of progress in the United States as well as worldwide efforts to develop the elements of hydrogen-fueled transportation vehicles and infrastructure. The review should also concentrate on projected dates for key commercialization events, which are provided on the following page in Table 2.5.

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APPROACHES AND STATUS

Activity/Event	Projected schedule	Detail
Research and demonstration Phase		
DOE for autos (1)	Through 2015	Includes two demonstration phases
Interim goals DOE (1)	2010	
DOT for buses (2)	Through 2015	
Final goals and readiness for commercialization (1)	2015	Technology projected to meet commercialization targets
Commercialization phase		
Market transition (3)	2010 through 2025	Initial commercialization in fleet vehicles, initially government fleets, based on early storage techniques and hydrocarbon sources of hydrogen
Fuel cell transit buses reach 10% of purchases (5)	2015	
Market transition (4)	2013 to 2016	
Market and infrastructure expansion (3)	2015 through 2035	Technology improvements, growth beyond fleet vehicles
Broad application (4)	2015 Begins by 2020	
Mature market (3)	2025 through 2045	Hydrogen from sustainable sources, mature market for private vehicles
Dominant (4)	2030 to 2040	

1. Reference 2.42
2. Reference 2.35
3. Reference 2.40
4. Reference 2.80 (Note that the dates provided are assumptions.)
5. Reference 2.44

Table 2.5. Government Schedule Objectives

The table shows a gradual introduction to the market beginning in 2015 for light-duty vehicles. It is possible that medium- and heavy-duty vehicles such as delivery vans and transit buses will have earlier introductions. For example, US DOT has set a goal to have 10% of transit bus purchases in 2015 be hydrogen-fueled models (Reference 2.44). Early commercialization will probably involve current hydrogen production and storage methods and be based primarily on hydrocarbon fuels. Longer-term storage techniques with smaller volume and lower weight will be introduced and sustainable sources of hydrogen will grow to dominate. The EU program assumptions generally agree with those from DOE and US DOT.

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Commercialization schedule goals and projections by vehicle and infrastructure companies are provided in Table 2.6.

Company	Projected Commercialization Dates	Detail
BMW	2008 to 2010	Dual-fuel internal combustion engine vehicle in Seven Series BMW
DaimlerChrysler (2)	2012 Commercialization 2020 Cost and lifetime comparable to conventional propulsion systems	
GM (3)	2010	
Honda (4)	2010	
Shell (1)	2015 to 2025 market penetration for autos 2040 market dominance	5 to 19 million fuel cell cars on road by 2020 50% of new purchases are fuel cell cars with 150 million fuel cell vehicles on the road

1. Reference 2.11
2. Reference 2.81
3. Reference 2.82
4. Reference 2.83

Table 2.6. Projected Commercialization Dates by Vehicle Manufacturers and Hydrogen Infrastructure Companies

Table 2.6 provides projections by industry sources of vehicle introduction dates. In many cases, the companies will not project these dates until they are relatively near because of the uncertainties associated with the technology. The consensus date for commercialization of fuel cell automobiles at the National Hydrogen Association Meeting was 2020 (Reference 2.84). The first introduction of hydrogen-fueled vehicles may occur in internal combustion engine automobiles like the BMW Seven Series vehicle noted in Table 2B. There was discussion of the use of hydrogen in internal combustion engine vehicles at the recent National Hydrogen Association annual meeting (Reference 2.85). The advantage of this approach is that it permits earlier introduction of hydrogen fuel benefits, while awaiting development of fuel cell technology.

3. STATUS AND EXPERIENCE WITH OTHER NON-TRADITIONAL TRANSPORTATION FUELS

Fueling vehicles with hydrogen is only one approach to reducing dependence on petroleum imports and pollution. Other approaches involving use of other fuels are at a more advanced stage, and the history of use of these fuels provides important background as well as technology for hydrogen-fueled vehicles. While the background may accelerate hydrogen-fueled vehicle deployment, success with these alternative approaches could provide some of the same benefits associated with hydrogen-fueled vehicles, thus providing strong competition for hydrogen-fueled vehicles and potentially delaying their deployment.

The alternative fuels which are in early stages of deployment include natural gas, ethanol and biodiesel. Because natural gas is stored and dispensed primarily in the form of a compressed, lighter-than-air gas, natural gas vehicle experience provides significant benefit to deployment of hydrogen-fueled vehicles. This experience also provides an operational basis for identifying and resolving issues associated with hydrogen-fueled vehicles.

The alternative technology of interest is hybrid vehicles. These vehicles are pioneering control, electric drive, and high-voltage safety issues, which will also be faced by hydrogen-fueled fuel cell vehicles. This experience will facilitate deployment of hydrogen-fueled fuel cell vehicles.

Appendix D provides more information on these alternative fuels and technologies. Key issues identified by experience with other fuels and technologies are included in Chapter 5.

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CURRENT EXPERIENCE WITH HYDROGEN IN CONNECTICUT

4. SCOPE OF HYDROGEN FUEL REQUIREMENTS IN CONNECTICUT AND CURRENT EXPERIENCE WITH HYDROGEN IN CONNECTICUT

4.1 CURRENT CONNECTICUT TRANSPORTATION SYSTEM

Transportation in Connecticut involves vehicles, roadways, and refueling stations. Understanding the magnitude of the current transportation system is important in considering hydrogen-fueled transportation. Following are summaries of key information on vehicles, highways, and refueling stations in Connecticut.

4.1.1 Vehicles

Table 4.1 shows statistics on Connecticut vehicles. With nearly 3 million vehicles and over 2 million automobiles, Connecticut represents 1.3% and 1.5%, respectively, of the US total for these categories.

While the number of independently owned and operated vehicles makes up the vast majority of vehicles, fleets are important applications for initial deployment of new technology vehicles – particularly with a technology such as hydrogen fuel, which requires significant infrastructure investment. The infrastructure barrier is reduced significantly for vehicles operated within a short range of a central refueling facility. Because many fleet vehicles don't travel far each day, a shorter range than for over-the-road, point-to-point operation is acceptable. This eases problems with high-volume storage associated with fuels like CNG or hydrogen. State-owned fleets are particularly attractive because they are very large and because they are susceptible to government policies to encourage technologies associated with social benefits.

The Department of Administrative Services (DAS) owns 4200 light-duty vehicles, which include 3,000 automobiles and 1,200 vans and light trucks. The vehicles turn over every six years, so a new technology will diffuse rapidly through the fleet (Reference 4.1). These vehicles are purchased by the DAS, and operated by individual departments who are responsible for fuel costs (Reference 4.2).

ConnDOT has significant influence over the buses operated by CTTransit as well as buses operated by the other transit districts. CTTransit is owned by ConnDOT and operated under contracts with four different operating companies. ConnDOT provides significant funding for the other transit fleets (Reference 4.3). The large transit buses have a twelve-year life expectancy, so diffusion of a new technology is slower than for the light-duty vehicles.

ConnDOT also has influence over vans in the Easy Street fleet, which is one form of ride-sharing practiced in Connecticut. ConnDOT advances money for purchase of the vehicles, which then is paid back from fares paid by the riders (Reference 4.3).

Municipal and private fleets also represent a significant early opportunity for new vehicle technology. Based on statistics provided by the Connecticut Department of Revenue Services

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(DRS), there are over 81,000 vehicles in fleets of over 25 vehicles each. There are 858 fleets, excluding leased vehicles registered to auto and truck dealerships. Over 10% of these fleets exceed 100 vehicles. The larger fleets are associated with package delivery services, school buses, utilities (electric, gas, telephone, water, cable TV, fuel oil, propane), ambulance services, companies providing services to homeowners, wholesalers, taxis, rental car outlets, refuse collection, construction, and municipal fleets. The DRS data could be analyzed further when marketing of hydrogen-fueled vehicles begins.

Measure	Statistic	Data Source
Total vehicles		
Total vehicle registrations	2, 964,000	US Highway Administration, Highway Statistics, 2003
Automobiles	2, 041,000	US Highway Administration, Highway Statistics, 2003
Motorcycles	63,000	US Highway Administration, Highway Statistics, 2003
State-owned or influenced vehicles		
State light-duty vehicle fleet (purchased by Department of Administrative Services)	3,000 automobiles 1,200 Vans or Buses	Connecticut Climate Change Action Plan 2005, Transportation and Land Use Sector.
Buses		
CTTransit	480 full size (30, 35, 40 foot), 169 smaller buses and vans	Mike Sanders, ConnDOT
Other CT transit districts	167 full size buses, 298 smaller buses and vans	Mike Sanders, ConnDOT
Ride Share vehicles (Easy Street)	330 Vans	Mike Sanders, ConnDOT
Municipal and private Fleets		
Number of fleets with more than 25 vehicles	858	Department of Motor Vehicles. Data Provided to R. Strauss, CASE
Number of fleets with 100 or more vehicles	91	Department of Motor Vehicles, Data Provided to R. Strauss, CASE

Table 4.1. Connecticut Vehicle Statistics

4.1.2 Vehicle Traffic Within the State and Crossing State Borders

Vehicle traffic in Connecticut is monitored regularly at many locations along each state-maintained highway (Reference 4.4). Traffic in both directions of travel is monitored.

The hydrogen infrastructure in Connecticut will have to accommodate vehicles operated within the state as well as vehicles traversing Connecticut from other states. Nearly 700,000 vehicles cross Connecticut’s borders each day, with 52% of these vehicles traveling on Interstates 84, 91 and 95. Traffic surveys in 2004 determined the percentage of these vehicles which are traversing the state between New York, Massachusetts, and Rhode Island (Reference 4.5). Since these interstate highways probably account for most of the traffic traveling through Connecticut, estimates based on vehicles traversing at these points are believed to be a reasonable estimate of the total number of vehicles traversing the state. That means that most of the traffic crossing the borders at other locations involves vehicles going from one state to the other and then returning to the original state for commuting or shopping purposes.

Table 4.2 shows total traffic flow at the borders on these roads and the percentage of vehicles traversing the state at each crossing point. The estimated number of vehicles traversing the state of Connecticut is about 86,000 cars per day. While other crossing points – particularly Route 15 at the Greenwich border, which has total traffic flow of 48,100 cars per day – may account for some additional vehicles traversing the state, the five points listed in Table 4.2 probably account for most of the traffic crossing Connecticut between New York, Massachusetts, and Rhode Island.

Location	Daily traffic flow* (number of vehicles)	Percentage of vehicles traversing Connecticut**	Number of vehicles traversing Connecticut***
I-84 in Danbury	72,100	27	9,750
I-84 in Union	50,900	40	10,200
I-91 in Enfield	73,900	10	3,700
I-95 in Greenwich	127,200	16	10,200
I-95 in Stonington	40,000	45	9,000
Total	364,100	24	42,850

* Reference 4.4

** Reference 4.5

***Assumes that each vehicle is counted twice in these data, once as they enter and again as they leave so that the number of vehicles traversing the state is half of the number implied by the percentage in the column to the left (Reference 4.6).

Table 4.2. Traffic Flow on Major Highways at Connecticut Borders

4.1.3 Highways

Connecticut has 21,089 miles of streets and highways. The interstate system and other parkways and expressways account for 582 miles of this total, with local streets accounting for about two-thirds of the total. The balance is collector and arterial roadways. The Interstate 91, 95, and 84 corridors are the most important of these for alternative-fueled vehicles because they represent links in what could be an alternative- fuel transportation corridor spanning many states.

4.1.4 Fueling Stations

Summary statistics on fueling stations in Connecticut are provided in Table 4.3. A total of 1,429 stations is indicated by tax receipts monitored by DRS. About 1,000 of these stations are public access stations and the balance are fueling locations serving a private vehicle fleet. Monthly

gasoline station volumes range from 20,000 gallons to 300,000 gallons at stations located on major highways or at major highway exits (Discussion with Michael Fox, president of the Gasoline and Automotive Dealers of America, on December 30, 2005).

Station characteristics	Number of stations	Information source
Retail stations	Approximately 1,000	GASDA (www.gasda.org)
Limited access fleet stations	Approximately 400 to 500	GASDA
Total stations in CT	1,429	Department of Revenue Services
Stations owned by ConnDOT	70 (5 with alternative fuel)	Janice Snyder, ConnDOT
CNG stations	11	Alternative Fuels Data Center, National Renewable Energy Laboratory
Service plazas on Merritt, I-95	23	Dan Smachetti, ConnDOT
Rest areas	8	Dan Smachetti, ConnDOT

Table 4.3. Connecticut Fueling Stations

ConnDOT operates 70 fueling stations for use by state-owned vehicles. Vehicles assigned to various state departments and agencies use these stations and the department or agency is billed for the fuel dispensed.

Connecticut has 23 service plazas with both fuel and food available located along the Merritt Parkway and I-95. The contracts for operation of these stations will expire in 2008, and a study is now underway to determine the needs for upgrading these service plazas. That study includes consideration of alternative fuels. A Request for Proposal will be issued in 2007 to begin this process (Discussion with Daniel Smachetti, ConnDOT, on January 19, 2006). A website for information on the study of requirements, etc. is available (Reference 4.7). In addition to these service plazas, Connecticut has eight official rest areas along major highways which do not have fuel service available. These areas, however, are owned by the state and could present opportunities for alternative fuel service in the future.

4.2 POTENTIAL HYDROGEN DEMAND ASSOCIATED WITH CONNECTICUT TRANSPORTATION

In order to assess the potential demand for hydrogen in Connecticut based on conversion of current petroleum product volume to potential for hydrogen fuel volume, several figures are provided in Table 4.4. Information on experimental hydrogen filling stations and commercial transportation of hydrogen is provided in Table 4.5. The tables are discussed below.

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Indicator	Petroleum product volume (gal/month)	Hydrogen energy equivalent (kg/month)	Equivalent hydrogen demand (kg/month)*	Reference
Total state consumption of gasoline	117 Million	117 million	58 million	www.eia.doe.gov October 2005 data
Large gasoline stations	300,000	300,000	150,000	Michael Fox, GASDA
Small gasoline stations	30,000	20,000	10,000	Michael Fox, GASDA
100 vehicle package delivery fleet diesel consumption	15,000	15,000	7500	Calculated from diesel data from Reference 4.8
Single fuel dispenser at high volume station	37,500	37,500	18,750	Assume 4 islands with 2 dispensers (two sided) per island

* Assumes hydrogen fuel cell efficiency double that of petroleum fueled vehicle

Table 4.4. Petroleum Product Volumes and Hydrogen Volume Equivalents

In Table 4.4, the term “Hydrogen energy equivalent” means the amount of hydrogen which has the same energy equivalent as the petroleum product quantities shown. Hydrogen-fueled vehicles using fuel cells are expected to double the efficiency of petroleum-fueled vehicles, so the hydrogen demand will be only half the demand if efficiency was the same; accordingly, the “Equivalent Hydrogen Demand” is only half the demand which would be incurred if the efficiencies were the same.

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Indicator	Unit of measure	Quantity	Reference
Experimental refueling station in California serving 40-foot buses and a fleet of automobiles	Kilograms per month	4,500	AC Transit website: www.actransit.org Hydrogen generated by steam methane reforming
Experimental refueling station in California serving one 30-foot bus and automobiles	Kilograms per month	720	AC Transit website: www.actransit.org Hydrogen generated by electrolysis
Liquid hydrogen tank truck (10,000 gallons)	Kilograms	2,500	Reference 4.9
Hydrogen tube trailer capacity (100,000 standard cubic feet)	Kilograms	250	Reference 4.9
Hydrogen tank capacity for Ford Focus hydrogen vehicle	Kilograms	4	2005 progress report for DOE Hydrogen Program by Ford Motor Company at www.hydrogen.energy.gov
Cylinder (400 standard cubic feet)	Kilograms	1	Reference 4.9

Table 4.5. Hydrogen Quantities for Experimental Refueling Stations and Transportation

The information in Tables 4.4 and 4.5 is presented to provide a context for discussion of hydrogen-fueled transportation. Certainly, no one expects hydrogen fuel to replace gasoline in any significant sense in the near future, but the total gasoline consumption in Connecticut provides a starting point for calculating the hydrogen demand if and when hydrogen-fueled vehicles begin to replace a portion of Connecticut’s three million vehicles. In the same sense, for the foreseeable future, a public access service station may not have more than one or two fuel dispensers with hydrogen fuel.

Table 4.4 shows that a single dispenser at a high volume station would dispense 37,000 gallons of gasoline per month and if that dispenser served an equivalent number of hydrogen fuel cell automobiles, it would dispense 18,750 kg of hydrogen per month. Current high-volume gasoline stations have two dispenser units per island with vehicles able to fuel from either side of the dispenser. Since current dispensers provide multiple grades of gasoline (they are referred to as multi-product dispensers, or MPDs) taking one dispenser for a single alternative fuel would have an impact on queuing time, so it’s likely the hydrogen dispenser would be located on a separate island.

Table 4.5 indicates both conventional (tube trailer, liquid hydrogen tanker, and cylinder) methods of transporting hydrogen to a customer site as well as the hydrogen volume dispensed by two of the hydrogen refueling stations in California. For a particular station, one could envision initial quantities of hydrogen being supplied from delivery of multiple individual hydrogen cylinders and, as the volume demand grows, the station supply could transition to tube trailer, then liquid hydrogen supply or on-site generation of hydrogen from electricity

by electrolysis, then on-site generation of hydrogen from natural gas with steam methane reforming. One of the vehicles in the DOE technology validation program (the Ford Focus) achieves a 250-mile range with a 4 kilogram hydrogen tank (DOE's ultimate goal is a 250-mile range by 2010 and a 300-mile range by 2015). DOE's interim goal for hydrogen vehicle refueling time is 5 minutes with an ultimate goal of 3 minutes.

4.3 HYDROGEN INFRASTRUCTURE IN CONNECTICUT

Connecticut has no hydrogen production facilities. The closest hydrogen production facilities are by-product hydrogen production facilities in western New York, liquid hydrogen production facilities in southern Quebec, and gaseous production facilities in Pennsylvania and New Jersey. A satellite terminal is located on the Connecticut-Massachusetts border near Interstate 91 (Reference 4.10).

Hydrogen is delivered to research and industrial users in Connecticut in cylinders, tube trailers, and liquefied hydrogen trailers. Storage on customer sites is in either gaseous or liquid form.

Currently, Connecticut consumes 0.5 to 1.5 million standard cubic feet per day (Reference 4.11). This is equivalent to between 1,200 and 3,600 kilograms per day, which corresponds to about 0.1% of the roughly 2 million kilograms per day demand associated with converting Connecticut transportation to hydrogen (see Table 4.4).

5. CONCERNS OF INTERESTED PARTIES

5.1 IDENTIFICATION OF INTERESTED PARTIES

For the purposes of this study, interested parties include organizations or persons who could either positively or negatively influence the development and deployment of hydrogen-fueled transportation in Connecticut. They also include those with related experience that may be helpful in understanding the issues and approaches from related technologies, which could then be applied to hydrogen-fueled transportation. The interested parties fall into several categories.

Interested parties in the safety category include government officials associated with codes, first responders, and insurance carriers. It is assumed that these officials would mirror the concerns of the general public.

Interested parties with relevant information from experience with other alternative fuels currently in use, with vehicle fleets, fueling stations, or with efforts by other states in alternative fuels, provide insight based on their experience. For example, parties with experience with natural gas as a transportation fuel have a particularly useful perspective because this fuel, which is a gas at ambient conditions, has similar issues to those of hydrogen.

Parties who participate in current commercial hydrogen activities or with development of hydrogen-fueled transportation have a good understanding of hydrogen and its use and the issues arising with hydrogen.

Other interested parties include those who have understanding of Connecticut state initiatives associated with transportation, energy, alternative fuels, and hydrogen. These parties were contacted to determine current activities and plans which may relate to hydrogen-fueled transportation in Connecticut.

Parties in all categories were contacted to gain their input in order to define the critical issues associated with hydrogen-fueled transportation. Most of the contacts were by telephone, but some personal visits and some reports on related initiatives were used. Appendix E provides a list, by category of interest, of the individuals contacted in the course of this study. Appendix E also indicates the particular issues identified in Section 5.2, which were noted by each party.

5.2 INTERESTED PARTY CONCERNS AND ASSESSMENT

Concerns expressed by the interested parties can be categorized as concerns about vehicles, infrastructure, codes, standards and safety, and business and market development.

5.2.1 *Vehicle Concerns*

Hydrogen-fueled vehicles could utilize either internal combustion engines or fuel cells, and development and demonstration with both types of motive power are underway. The internal

combustion engine vehicles, at least initially, will have lower cost than the fuel cell vehicles, and there are unlikely to be any operational issues. However, internal combustion engine vehicles will be less efficient, thereby accentuating concerns associated with fuel storage and range.

Vehicle concerns included the following:

- Fuel storage volume and range limitations
- Operation in temperature extremes
- Vehicle performance – acceleration and speed
- Vehicle durability and reliability
- Cost

FUEL STORAGE VOLUME AND RANGE LIMITATIONS

Parties expressed concern about the interrelated issues of fuel storage volume and range. Small automobiles with CNG fuel have very limited trunk space and cannot be used effectively in cases where trunk space is essential. For example, the Department of Child and Family Services often has to transport clients and their belongings to a new residence and this is made very difficult with most of the trunk occupied by a compressed gas tank. The other manifestation of the low energy density of gaseous fuels on a volume basis is that range will be limited if the vehicle cannot provide reasonable storage volume. While this doesn't appear to be a problem for transit buses, it has presented a problem with natural gas-fueled delivery vehicles operated by UPS. Routes in Hartford are fairly compact and flat, but routes in the Waterbury area are longer and have more hills. UPS experienced problems with trucks running out of fuel in the Waterbury area. Hydrogen has an even lower volume-energy-density than CNG, so this problem will be even more critical.

To eliminate concerns with hydrogen storage volume and range, development efforts funded by DOE and OEMs are working to establish improvements to many different forms of hydrogen storage, with measurable objectives established for completion in 2010 and 2015. Demonstration that the objectives have been met will be achieved through component-level and vehicle testing. Current status is below these objectives and closing the gap between this status and satisfactory values is challenging. Failure to meet the objectives may limit application to large vehicles with low range requirements, such as transit buses, until the DOE goals are met.

OPERATION IN TEMPERATURE EXTREMES

Fuel cell power plants for vehicles contain water spread throughout the power plant and operate at fairly low temperature. Water presents a problem during cold weather storage and operation. Low temperature operation means that radiators capable of rejecting heat at higher ambient temperatures and higher altitudes will have to be sized larger than those in current vehicles.

Operation in temperature extremes is associated with the mechanisms and operating temperature of fuel cell stacks. These concerns would not be shared by hydrogen-fueled internal combustion engines. At least two companies have reported that their fuel cell stacks can now be started and operated in sub-freezing temperatures. DOE demonstration efforts include vehicle operation in colder climates such as Michigan's and Connecticut's. Results of these tests will

show whether cold weather operating ability has been achieved. High-temperature operation capability requires radiator design to account for the low operating temperature of fuel cells compared to that of an internal combustion engine. This concern is mitigated by the higher efficiency of fuel cells. The net radiator size resulting from these positive and negative factors is established as part of the vehicle design and demonstration of the suitability of the radiator over a range of temperatures and altitudes. These concerns should be resolved definitively by the DOE vehicle test program.

VEHICLE PERFORMANCE – ACCELERATION AND SPEED

Performance in terms of acceleration and speed is a concern. This concern may be due to the fact that current alternative-fueled vehicles were adapted to use of these fuels rather than starting with these fuels as a design requirement.

Since the fuel cell power trains for demonstration vehicles are being designed “from the ground up,” they will be properly sized to meet vehicle performance objectives and vehicle performance of the DOE test fleets is expected to meet design specifications.

VEHICLE DURABILITY AND RELIABILITY

Transit bus and other intense-use fleet operations demand high reliability, because loss of service to customers who depend on a strict schedule is unacceptable and acquiring and maintaining reserve equipment to deal with breakdowns is a significant expense. Documenting a good reliability record prior to initial commercial service is expensive and time consuming. Transit buses, for example, have a 12-year design life and extended testing is required to relieve these concerns.

Vehicle durability will be demonstrated with operational demonstrations, laboratory tests, and analytical models. Durability requirements for automobiles are modest compared to those for vehicles such as transit buses. Achieving 200,000-mile durability for autos requires only 5,000 hours of fuel cell stack life. For transit buses, which operate many hours per day and which have a 12-year design life, cell stack durability must be over 40,000 hours. Since 40,000 hours is nearly five years, demonstrations will require years or validated accelerated life testing. A complicating factor is that, when a durability deficiency is discovered, the problem must be resolved and then testing resumed, starting at zero hours. To expedite durability demonstrations, laboratory tests of cells and stacks, along with durability modeling based on potential degradation mechanisms, are being performed. The combination of the laboratory testing, modeling and operational vehicle testing will provide confidence to overcome this concern. Obviously, the confidence will improve as vehicle time in service increases.

Prior experience with stationary fuel cells shows that reliability problems are primarily associated with ancillary components such as pumps, valves, and electronics (Reference 5.1). Reliability modeling of the complete power train, combined with operational test results and laboratory testing, will be used to demonstrate that reliability objectives have been met. Building confidence in reliability requires less time than building durability confidence because improved components can be retrofit to the demonstration vehicles and, within a relatively short time, the statistical confidence and customer confidence will reach satisfactory levels. It is important to have a sufficient number of vehicles in operation to establish the statistical confidence base, and it is also important to develop and substitute improved components so the reliability experience base grows.

COST

First cost is a concern with any new technology and prior experience with stationary fuel cells shows the concern is warranted. Even if savings in operating and maintenance cost over the life of the vehicle could compensate for higher first cost, capital budgets are constrained already and modification of capital budgets or accommodation of higher first cost because of balancing life cycle cost savings requires well-documented information based on real-life experience. For transit buses, which receive federal purchase support, legislation to accommodate a different balance between first cost and operating cost may provide acceptable economics for transit districts. Increased subsidies for the purchase of hydrogen-fueled buses, as compared to conventional transit buses, may be justified since hydrogen-fueled buses will reduce both pollution in urban areas and dependence on imported energy; in addition, hydrogen can be generated from hydrocarbons with sequestration of carbon dioxide, or from renewable sources.

Cost is probably the most difficult parameter to measure. Unlike the other product concerns for which an easily observable demonstration can be achieved, demonstrating cost at best involves sophisticated modeling and projection during early development stages. Costs of demonstration units are artificially high because development is an inevitable part of the design and manufacturing processes and total production is insignificant. Selling prices of early production vehicles are generally subsidized by manufacturers and actual costs are not publicly available. Translating component design, processing trial information, and business analysis into a sound estimate of cost in high-volume production is challenging, even for products with well established, commodity materials and long experience with the production processes. In addition, cost data in the development stage involve sensitive proprietary information. In the past, DOE has hired independent analysts to evaluate these development-stage data on stationary fuel cells, using non-disclosure agreements to protect proprietary information of developers. Unfortunately, since high production volumes of stationary fuel cells have not yet been achieved, these methods have not been validated. Both developers and DOE have the challenge of providing adequate supporting information on cost to establish purchaser confidence.

5.2.2 Infrastructure Concerns

Hydrogen infrastructure is a concern at least equal to concerns with vehicle issues. The following infrastructure concerns were identified:

- Generation of hydrogen
- Transportation of hydrogen
- Land requirements for fueling stations
- Unfamiliar dispensing apparatus and procedures
- Availability of fueling stations

GENERATION OF HYDROGEN

Generation of hydrogen from raw energy sources is expensive and has significant energy losses. The ability to produce hydrogen from raw energy sources without pollution or discharge of greenhouse gases is still in question. Current hydrogen generation capability is only a

small fraction of the capability required for meaningful transportation use and will involve a significant capital expenditure.

Conventional methods of hydrogen generation include steam methane reforming, partial oxidation of petroleum products, coal gasification and electrolysis. The environmental effects and costs of these methods are well established and it is likely that early deployment of hydrogen-fueled transportation will utilize these methods. Unfortunately, neither cost nor the environmental impact of current approaches is likely to be acceptable for more than limited deployment of hydrogen vehicles. Both methods as currently employed produce significant greenhouse gases, and steam methane reforming increases demand for natural gas, which is already in a supply situation requiring imports. Sequestration of carbon dioxide when production involves hydrocarbon resources can ease concerns with greenhouse gases, but this is a challenging technology in its own right and geology and geography limit the locations where it can be employed. Use of sustainable resources, such as solar or wind, to power electrolysis units or biomass to feed steam methane reformers is an inefficient use of these expensive resources. In the longer term, heat from nuclear reactions used with chemical processes or solar conversion through photochemical, photoelectrochemical or algae could provide low environmental impact hydrogen production methods, but these methods are still in the fundamental research stage and feasibility and cost are undetermined.

Current steam methane reforming production of hydrogen is primarily captive production integrated in petrochemical plants, and demand for merchant hydrogen for other uses is limited. Electrolysis systems are primarily used in laboratory situations or to meet small industrial demands. Increased demand for transportation fuel can lead to improvements to the costs and efficiencies of both processes. Unfortunately, the scale of current demonstration efforts is very small compared to the scale required for commercial plants with acceptable production cost. Gaining confidence in hydrogen generation cost may require establishing a concentration of vehicle demand in a limited geographic region in order to establish a commercial-level demand, which will provide confidence in the costs and environmental characteristics of improvements to these conventional methods. One major oil company is advocating a deployment approach which provides this vehicle concentration early in the deployment of commercial hydrogen-fueled vehicles (Reference 5.2).

Continued research in the longer-term methods involving nuclear heat, direct solar techniques, or algae will be required before these methods can be tested in meaningful operational service.

TRANSPORTATION OF HYDROGEN

Transportation of hydrogen fuel to the point where it is dispensed into a vehicle is currently very expensive. Delivered hydrogen is currently two to fifteen times as expensive as hydrogen at the point of generation (See Chapter 2, Section 2.1). Delivery of liquid hydrogen requires ten times as many truckloads to serve a fleet as gasoline does. Pipeline distribution requires significant demand.

High transportation costs may favor local generation of hydrogen through steam methane reforming or electrolysis. However, local generation of hydrogen may be more costly if higher equipment production volumes do not overcome the adverse effects of scale on cost. Local generation of hydrogen may make it difficult to sequester the carbon dioxide produced in steam methane reforming. Sequestration requires a geological formation appropriate to the purpose,

such as oil and gas reservoirs, unmineable coal seams, deep saline reservoirs, or deep ocean areas. It also requires large compressors, wells and pipes to inject the carbon dioxide, so scale effects on cost could be prohibitive. Since carbon dioxide volumes will be much less than those of hydrogen, it may be feasible to transport carbon dioxide from fueling stations to a central location for sequestration. DOE efforts are currently focused on large central sequestration plants.

Hydrogen transportation issues are associated with the same problems as storage of hydrogen on vehicles. The concepts for improved vehicle fuel storage will be applicable to hydrogen transportation by truck or rail, and when improved storage methods are available, they will be adopted for hydrogen transportation for current industrial uses, providing a meaningful demonstration of the characteristics of these methods. Development of a pipeline hydrogen transport infrastructure cannot be pursued until sufficient demand is imminent. Use of steam methane reformers or electrolysis units located at fueling stations can eliminate concerns with transportation. However, the cost of these approaches is likely to be high because there are only about 160,000 fueling stations in the United States. Producing equipment for these stations over a deployment period of 5 to 20 years does not constitute a high-volume market by vehicle production rate standards.

LAND REQUIREMENTS FOR FUELING STATIONS

Hydrogen fueling station equipment is large in comparison to that for gasoline fueling stations, particularly if on-site hydrogen generation is used. Locations of fueling stations are constrained by the amount of land available adjacent to roadways, and good locations are expensive, adding to the cost of hydrogen infrastructure.

Fueling equipment is also costly. It includes storage, compression and dispensing functions and may include generation of hydrogen through steam methane reforming or electrolysis. Production volumes for this equipment will be modest, as the total of nearly 160,000 fueling stations in the United States will be converted to hydrogen over a 10-20 year or longer period and the stations will be owned by many different parties. Consequently, production volumes will not be sufficient to achieve comparable economies to those for vehicles or energy equipment such as air conditioners or heating equipment.

While demonstration programs include fueling stations, they are not at commercial scale. Demonstration fueling stations are generally less than 150 kg of hydrogen per day, while fuel company parties believe 1,000 to 2,500 kg of hydrogen demand per day may be required for economic viability.

Hydrogen fueling stations will involve operating pressures considerably higher than those used for CNG vehicles. This raises concerns with equipment reliability and durability, especially during the early deployment period. Equipment utilization during demonstration activity is likely to be low, so the demonstration programs are not likely to identify and resolve all reliability and durability issues.

Like transportation, land requirements for hydrogen fueling stations are affected by the volume required for hydrogen storage and improvements for storage onboard vehicles will be applicable to the fueling station application. This land requirement issue could be alleviated to some degree by use of underground tanks. Another factor, however, is the large separation distances required by current codes and standards to minimize the possibility of fire and explosion. Also, there is a

lack of recognition in current codes and standards of the use of fiberglass and composite tanks for either CNG or hydrogen storage. As noted previously, DOE is addressing the storage technique question and a significant effort is underway to develop national and international standards for all aspects of the hydrogen infrastructure and hydrogen vehicles. Demonstration fueling stations have limited supply quantities but they provide testing of the codes and standards issues and can be used to demonstrate improved storage technologies.

UNFAMILIAR DISPENSING APPROACHES AND PROCEDURES

Nearly all hydrogen vehicle developers are basing their designs on gaseous hydrogen storage. Drivers are currently unfamiliar with dispensers for gaseous fuels and prefer conventional liquid fuel dispensers.

Hydrogen will be dispensed as a gas rather than as a liquid. This means consumers will have to familiarize themselves with different fueling apparatus and procedures and the involvement of high pressure is a concern for consumers. This has been an issue causing resistance to vehicles using CNG. Generally, with training and experience, these concerns are alleviated, e.g., European experience, and in fleet use where training and experience are provided, confidence grows rapidly and this concern is eliminated. Use of card keys to limit use to trained users can also address this concern. The DOE vehicle demonstration program provides this training and experience, although the limited quantity of vehicles and their initial use in fleet operations must be monitored and translated to a broader consumer acceptance. Some of the DOE demonstration sites have outreach programs to provide information, demonstration, and confidence to the general public.

AVAILABILITY OF FUELING STATIONS

Particularly in the early stages of deployment, hydrogen fueling stations will be much less available than gasoline stations. For private vehicle owners, this fact, combined with potentially shorter range of the initial vehicles, may create a hesitancy to purchase a hydrogen-fueled vehicle because trips of any length would involve careful planning. With fleet vehicles, searching for a filling station will interfere with productivity. An example from Connecticut state fleet experience with dual-fuel, CNG or gasoline vehicles is that drivers did not make the effort to access a CNG station and vehicles ran most of the time on gasoline.

The limited availability of fueling stations has impeded deployment of all alternative-fueled vehicles. It has concentrated their use in fleet vehicles which are used locally and which return to the same location at the end of each shift. It is likely that hydrogen-fueled vehicles will also be deployed initially in fleet use. Breaking out of the fleet use deployment to a broader commercial market will require public access to fueling stations. Some public access may be provided at fleet fueling locations, but this is not a business the fleet operations have an incentive to pursue.

The Lighthouse deployment approach advocated by Shell may be a mechanism for extending deployment limited to fleet application to broader public use. Establishment of hydrogen corridors similar to those developed for LNG may be another approach to deployment advancement. Using the Lighthouse deployment concept, initial deployment should concentrate vehicles and infrastructure in a limited number of locations, with growth beyond those concentrations postponed until conditions for acceptable economics are achieved. Growth could include local hydrogen supply networks to provide the best combination of the scale of centralized hydrogen generation and limited transportation costs.

5.2.3 Safety, Code and Insurance Concerns

Public perceptions of hydrogen safety and codes and standards permitting safe operation are key factors in successful deployment. The primary concerns in this area are

- public concern with safety;
- development of national, industry, and international standards for all aspects of hydrogen-fueled transportation;
- incorporation of appropriate national and industry standards into state and local codes and regulations;
- identification of applicable codes and standards for state and local jurisdictions so that permitting and design can begin with a comprehensive understanding of requirements;
- first responder training; and
- ability to obtain liability insurance.

PUBLIC CONCERN WITH SAFETY

Hydrogen has been used safely for many years in industrial settings. Technically, hydrogen has characteristics which may render it safer than gasoline when handled properly (Reference 5.3). Appropriate standards, codes, and industrial practice have resulted in a very good safety record.

In spite of the good safety record, the public is unfamiliar with hydrogen and lacks confidence in their ability to use it safely. In addition, while fleet use of hydrogen can provide trained personnel and controlled settings similar to those in industrial settings, making hydrogen safe in a broader commercial and private use setting presents concerns with use by the general public. Consequently, as identified in Chapter 2, an extensive effort is underway to develop standards and codes appropriate to broader use of hydrogen. To familiarize the public with hydrogen, the DOE and US DOT demonstration projects have a significant public awareness effort.

Public concerns with safety are being addressed through public outreach and education programs. Many of these are associated with demonstration programs. As demonstrations and publicity concerning them increase, more information on hydrogen-fueled vehicles will start to allay these concerns. However, current demonstrations are in other states, so they are of limited value to Connecticut officials or the public.

While hydrogen fueling of fleet vehicles by professional and trained operators is considered to be safe, there are safety concerns, expressed by a number of parties, associated with safe operation of hydrogen fueling stations by the general public. In the case of CNG, a similar fuel, these concerns are addressed by making the fuel dispenser operate only when a card key issued to a trained and qualified operator is used.

DEVELOPMENT OF NATIONAL, INDUSTRY AND INTERNATIONAL STANDARDS FOR ALL ASPECTS OF HYDROGEN-FUELED TRANSPORTATION

Some concern has been expressed that development of the standards at this stage of product and infrastructure development and experience may result in unnecessarily stringent or

prescriptive standards. Some interested parties would prefer delaying final development of standards until more experience with hydrogen-fueled vehicles and infrastructure is obtained.

The effort to develop appropriate codes and standards at the national and international level is comprehensive, as illustrated in Chapter 2, Section 2.6 and Appendix C. These standards will be tested to some degree by the demonstration programs, and the demonstration experience will undoubtedly identify areas in which they need to be changed to be more effective.

One issue identified in early demonstrations is that fiberglass-wound tanks are permitted onboard vehicles, but are not permitted for use in stationary facilities such as fueling stations. Since storage is a significant component of fueling station cost, further efforts to establish recognition of this type of storage tank is recommended.

INCORPORATION OF APPROPRIATE NATIONAL AND INDUSTRY STANDARDS INTO STATE AND LOCAL CODES AND REGULATIONS

Once national, industry, and international standards for broad use of hydrogen are developed, the standards must be adopted and used properly by state and local permitting officials. Currently, the effort required to secure permits for demonstration hydrogen facilities is significant and it is very difficult to establish a comprehensive list of requirements prior to starting the permitting process. In some cases, new codes are identified only after the permitting process has been underway for some time, and this results in additional time and expense for permitting.

For Connecticut to be ready to deal with hydrogen infrastructure codes and standards, new national and industry standards must be incorporated into local codes. Since codes and standards are adopted and modified over a multi-year period, usually on a regularly scheduled basis, state and local codes will inherently lag behind newly developed standards. Until demonstrations or deployment of hydrogen-fueled vehicles begin in Connecticut, it is unlikely that state and local code officials will have significant interest in learning about or adopting these documents.

IDENTIFICATION OF APPLICABLE CODES AND STANDARDS FOR STATE AND LOCAL JURISDICTIONS SO THAT PERMITTING AND DESIGN CAN BEGIN WITH A COMPREHENSIVE UNDERSTANDING OF REQUIREMENTS

When demonstration and deployment within Connecticut begin, there will probably be many concerns and questions and it will be very difficult, particularly for companies involved with fuel infrastructure construction and operation, to identify requirements which must be met at the beginning of the design and permitting process. Not only will this cause delays, it will increase cost if completed work must be revised to account for requirements identified after the work has been completed.

A suggestion in this regard is that a single point of contact be established for the state regarding hydrogen codes, standards and regulations so that local permitting officials and companies involved with deployment can easily identify state requirements and possible local variations on these requirements. Having a state focal point will also facilitate identification of issues which need resolution.

FIRST RESPONDER TRAINING

First responder training will be required to ensure safety in the event of accidents or natural disaster. The number of first responders is large and this training will be expensive compared to the number of hydrogen-fueled vehicles anticipated during early stages of deployment.

The location of fueling stations is fixed, but vehicles can operate at the limits of their range, so many first responders could be involved even if very few vehicles are operating and even if the number of fueling stations is limited and geographically concentrated. This means first responder training must be extended over a wide geographic area, even though it is unlikely that most of the first responders will be exposed to hydrogen-fueled vehicles, much less accidents involving hydrogen-fueled vehicles. Because there will be little experience in the first stages of deployment, frequent training will be needed to keep the first responders alert to the issues and trained in approaches to deal with them.

The Connecticut Fire Academy already has a training unit on hydrogen, and national programs to provide first responder training materials and to improve training of first responders with regard to hydrogen used in transportation are underway as described in Appendix C.

ABILITY TO OBTAIN LIABILITY INSURANCE

One interested party indicated a concern with ability to obtain liability insurance because of the lack of risk experience with hydrogen-fueled vehicles and the supporting infrastructure. Insurers of industrial facilities have experience with hydrogen, but insurance carriers for commercial and private facilities probably do not.

Demonstration programs will provide some experience for the companies who have clients involved with these programs, but risks will be judged on the basis of the experience base. A low experience base will probably mean that liability costs will be high during early demonstration and deployment activities, or it will be difficult to obtain insurance. At least one state, New Mexico, is addressing hydrogen liability through state action. The New Mexico House passed a resolution directing the New Mexico Hydrogen Business Council to convene a task force to draft appropriate legislation to address this liability issue (Reference 5.4). Contacts with two insurance companies and the Director of Insurance and Risk Management for Connecticut resulted in the conclusion that insurance availability and cost have not been a problem for fuel cell installations in the state and that legislative action is not warranted by current status. They do, however, recommend the situation be monitored as more experience with hydrogen-fueled transportation accumulates.

5.2.4 Business and Market Development Concerns

While technical challenges identified above are significant, a major change in transportation fuel will require significant business initiative and investment. The primary concerns identified in this area are the following:

- A long investment in research and demonstration delays investment return and increases risk.
- Meeting technical and economic objectives for hydrogen-fueled transportation remains a difficult challenge with uncertain results.

- Alternative technologies may provide benefits similar to hydrogen-fueled transportation before hydrogen transportation is deployed.
- All aspects of hydrogen transportation will have high cost during the initial deployment period.
- Success in bringing hydrogen-fueled transportation to fruition requires positive decisions and good execution by many independent organizations.

A LONG INVESTMENT IN RESEARCH AND DEMONSTRATION DELAYS INVESTMENT RETURN AND INCREASES RISK

Development of hydrogen-fueled transportation is a long-term effort. Development and deployment expenses are very large and, at this stage of development, there are significant concerns with regard to the success of the development activity in producing products with attractive characteristics and in producing a fuel with acceptable cost. The DOE program plan discussed in Chapter 2, Section 2.6 doesn't produce a commercialization decision until 2015, and assessment with respect to interim goals doesn't occur until 2010.

Federal government support of hydrogen research and demonstration activity reduces investment burden on manufacturers and fuel suppliers. Demonstration programs and periodic assessments by objective third parties provide regular assessments of progress in the effort (Reference 5.5). Information on alternative technologies will be available as a result of early deployment experience.

MEETING TECHNICAL AND ECONOMIC OBJECTIVES FOR HYDROGEN-FUELED TRANSPORTATION REMAINS A DIFFICULT CHALLENGE WITH UNCERTAIN RESULTS

As previously noted in Chapter 2, Section 2.8, opinions vary widely regarding the timing and probability of meeting the technical and economic goals for hydrogen-fueled transportation.

Annual reporting on program progress combined with precise goals for 2010 and 2015 achievement and third party evaluation will provide greater clarity as the program progresses.

ALTERNATIVE TECHNOLOGIES MAY PROVIDE BENEFITS SIMILAR TO HYDROGEN- FUELED TRANSPORTATION BEFORE HYDROGEN TRANSPORTATION IS DEPLOYED

The fact that other alternatives provide similar advantages, albeit not to the same degree as hydrogen, introduces additional uncertainty and risk to public and private investment decisions.

Clear, comprehensive, candid, documented and timely performance and economic information will be necessary to convince many customers that hydrogen-fueled transportation is economically attractive. Even after a decade of deployment of CNG vehicles, there is strong disagreement on whether CNG is a viable economic option. Among the interested parties, there are a significant number on either side of this question.

Regular reviews of the characteristics of alternative vehicle fuels and technologies will be needed to guide investment decisions with regard to hydrogen-fueled transportation.

ALL ASPECTS OF HYDROGEN TRANSPORTATION WILL HAVE HIGH COST DURING THE INITIAL DEPLOYMENT PERIOD

Minimizing cost during the early stages of deployment is another concern. Fueling stations will require a minimum level of business volume to reach acceptable economics and there may not be a sufficient number of vehicles to support this business. Likewise, vehicles will be limited in their applicability by the lack of a sufficient number and distribution of fueling stations.

Some fraction of the current participation in government programs is based on preparing for the possibility of hydrogen-fueled transportation rather than a belief that it is a viable business opportunity. With natural gas vehicles, the slow pace of market development caused both vehicle and infrastructure companies to abandon their participation and some felt that, after an initial period of enthusiastic support, government efforts diminished without ever achieving necessary commercial status.

A public-private partnership may be needed to minimize costs during initial deployment.

SUCCESS IN BRINGING HYDROGEN-FUELED TRANSPORTATION TO FRUITION REQUIRES POSITIVE DECISIONS AND GOOD EXECUTION BY MANY INDEPENDENT ORGANIZATIONS

Several parties interviewed voiced concern regarding the inability of their company to achieve success without cooperation of others, including the government, over the long period required to achieve a sustainable business. At a minimum, vehicle manufacturers need to be confident that fuel suppliers will have sufficient infrastructure to make hydrogen available where it is needed, and their supplier base needs a sustained business to maintain their interest and participation. On the other hand, energy companies providing hydrogen need confidence that a sufficient number of vehicles will be available to make their infrastructure investment economic. The owners of fueling stations, which in most cases are not the major oil companies, need support of the major oil companies not only in supplying fuel, but in providing franchise agreements that support hydrogen fuel. Fleet operators, who in many cases have specific vehicle needs, need assurance those vehicles will be available; this has not been the case, for example, with natural gas vehicles – the models offered in many cases do not meet many fleet needs. When vehicle manufacturer offerings are limited, competitive bidding is not effective, so fleet operators are concerned there will be only one or two manufacturers offering the vehicles they need.

Both vehicle manufacturers and infrastructure companies need assurance that government incentives will be present over an extended period to ensure the market can develop to self-sustaining levels. Some interviewed parties noted that government policies need to address all appropriate issues. For example, the Energy Policy Act of 1992 requires 75% of state light-duty vehicle fleet purchases to have alternative fuel capability; federal fleets also have a requirement that they operate on the alternative fuel. State fleets with flexible fuel capability, however, are not required to operate on the alternative fuel, so that in some cases, the extra investment in equipment does not result in the alternative fuel benefits because the alternative fuel is not used.

The DOE demonstration program involves many of the independent entities as members of research, development, and demonstration teams. For example, vehicle manufacturers, fuel cell

manufacturers, hydrogen storage equipment manufacturers, major oil companies, industrial gas companies, and manufacturers of electrolysis and methane steam reforming equipment are all involved in one or more of the DOE vehicle demonstration programs. These teams may alleviate concerns that other parties will not participate and could be the forerunner of public-private partnerships. An approach to minimize cost during early deployment has been proposed by Shell Hydrogen (Reference 5.2). This proposal involves large joint ventures in public-private partnerships involving all the participants required for success. A London Hydrogen Partnership has been established to address this issue and may provide a model for Connecticut action (Reference 5.6). It has also been suggested that initial deployment concentrate on fleet vehicles and then on concentrations of vehicles in a limited number of areas to ensure rapid growth to full utilization of the infrastructure. As deployment proceeds, these local areas would be extended until the entire country has adequate infrastructure.

5.3 CURRENT HYDROGEN-FUELED TRANSPORTATION ACTIVITY IN CONNECTICUT

There are several aspects of hydrogen-fueled transportation activity in Connecticut:

- Industry development and demonstration activities
- Higher education activities
- Connecticut Hydrogen and Fuel Cell Coalition
- Related support from Connecticut Clean Energy Fund and Connecticut Innovations, Inc.
- Incorporation of national and industry codes and standards into Connecticut codes and regulations
- Training for first responders
- Transit bus demonstrations
- Government planning and legislation

Connecticut has a significant portion of the US and world fuel cell development activity as well as a number of companies involved with hydrogen generation and distribution. It is estimated that Connecticut has 1,000 people working in these areas, compared to 6,300 people working worldwide in fuel cells (Reference 5.7). There are additional people working worldwide in hydrogen, but no comparable information on number of employees has been located. Following are highlights of Connecticut industrial efforts.

UTC Fuel Cells is developing hydrogen PEM fuel cell power plants for automobiles and buses. The company works with a number of vehicle manufacturers and systems integrators to provide fuel cells for automobile and transit bus demonstrations in the United States and abroad. UTC Fuel Cells and its partners participate in the DOE automobile and US DOT bus demonstration activity (Reference 5.8).

Proton Energy Systems is developing and demonstrating its electrolysis systems in hydrogen fueling stations, and has commercial electrolysis products which serve laboratory and industrial applications (Reference 5.9).

UTC Fuel Cells and FuelCell Energy (Reference 5.10) are the global leaders in large fuel cell power plants for stationary application, with many power plants installed worldwide. These activities provide significant background and experience for use in research, development, design, and demonstration of fuel cells for transportation.

FuelCell Energy will be testing a modification to its stationary power plant that permits it to produce hydrogen as a co-product along with electricity and heat. This power plant could be located at fueling stations (Reference 5.11). FuelCell Energy is also doing research on PEM fuel cells, which is the fuel cell type most likely to be used in vehicles.

Praxair, an industrial gas company, is headquartered in Connecticut. Praxair generates and distributes hydrogen to industrial and laboratory customers in Connecticut and elsewhere (Reference 5.12).

Infinity Fuel Cells (<http://www.infinityfuel.com>), Avalence (<http://avalence.com>), Hamilton Sundstrand division of UTC (Reference 5.13) and Treadwell Corporation (Reference 5.14), which manufactures electrolysis systems, are some of the other Connecticut companies participating in hydrogen generation and fuel cell activities.

Higher education institutions in Connecticut are also heavily involved with fuel cells and hydrogen. Highlights include:

- The University of Connecticut (UConn) has a major fuel cell effort located at the Connecticut Global Fuel Cell Center. In the past few years, more than \$4.3 million of research contracts have been carried out by a combination of over 150 students and faculty members (Reference 5.15).
- The Naugatuck Valley Community College conducts a fuel cell technician course (Reference 5.16).

The Connecticut Hydrogen and Fuel Cell Coalition was formed in 2005 to “advance the development, manufacture, and deployment of fuel cell and hydrogen technologies and associated fueling systems in Connecticut.” Recent activity included a briefing on hydrogen and fuel cells for the Connecticut legislature. The coalition website provides information on the organization and its members (Reference 5.17).

The Connecticut Clean Energy Fund (Reference 5.18) was established through state legislation and is funded with systems benefits charges on electric energy bills. Through its renewable energy programs, it supports stationary fuel cell demonstration programs as well as fuel cell technology programs and the Connecticut Global Fuel Cell Center at UConn. Activity also includes administration of Project 100, which mandates that local electric distribution companies contract a minimum of 100 MW of clean energy resources by July 1, 2007. Connecticut Clean Energy also sponsors clean energy seminars and the Connecticut Fuel Cell Summit as part of its public outreach activities.

Connecticut Innovations (Reference 5.19) serves as a capital investor in high technology start-up companies in Connecticut. It was funded initially by a state legislative appropriation, and currently funds new investments from returns on prior investments. Thirteen percent of its portfolio is invested in energy, with Proton Energy Systems being a prime example of its investments.

The state of Connecticut has designated stationary fuel cell power plants as a Class 1 Renewable, has supported fuel cell purchases through the Project 100 legislation, supported distributed generation through a recent Department of Public Utilities Control ruling (Reference 5.20), and provided other incentives for fuel cell manufacturers and purchasers.

The Connecticut Fire Academy offers a training module for fire responders who have industrial hydrogen facilities in their area. When additional information is developed by national organizations regarding fire responder training for hydrogen-fueled transportation, it can be added to this material.

Connecticut codes and regulations are updated regularly and approved national and industry codes and standards are incorporated into the Connecticut documents as they become available.

Two hydrogen bus demonstrations are in the design/planning stages in Connecticut. The New Haven Transit District is involved with the design and planning phase of an effort which will lead to delivery of hydrogen-fuel transit vehicles by 2008. The plan involves two hydrogen-fueled hybrid vehicles, using fuel provided by both electrolysis and steam methane reforming. One of the vehicles will use an internal combustion engine and the other will use a fuel cell (Reference 5.21). Connecticut Transit is expecting delivery of a hydrogen-fueled, 40-foot transit bus in November 2006 which will utilize fuel cell power provided by UTC Power. The vehicle storage and maintenance will be at an existing CT Transit operating facility in Hartford. Vehicle fueling and maintenance of the fuel cell will occur at UTC Power in South Windsor. Special provisions in terms of facilities and procedures will be used to provide safe maintenance and storage of the hydrogen-fueled vehicle. Experience with design, construction and use of these provisions will provide input to planning and requirements for future hydrogen infrastructure facilities (References 5.22 and 5.23).

Several Connecticut planning documents on Energy (Reference 5.24), Transportation (Reference 5.25), and Climate Change (Reference 5.26) were reviewed.

Only the Connecticut Climate Change Action Plan mentions hydrogen-fueled transportation. The citation item associated with hydrogen, RA 6 Hydrogen Infrastructure and R&D Program, is assigned to Office of Policy and Management, the Connecticut Clean Energy Fund, and ConnDOT. This action item is one of 17 long-term items. The Recommended Action is to develop a comprehensive hydrogen infrastructure research and demonstration program. A strawman proposal, prepared by Environment Northeast, serves as the basis for discussion of this action item in the plan. The current status is described as "further Macroeconomic studies are to be conducted through REMI regional economic analysis modeling." The 2006 session of the Connecticut General Assembly considered a number of initiatives relative to hydrogen-fueled transportation, including development of a hydrogen roadmap (Reference 5.27). A hydrogen and fuel cell cluster activity and an activity to establish a plan for commercialization of hydrogen-based technologies and fuel cells were mandated by legislation enacted in 2006. The Department of Economic and Community Development is responsible for these activities. The plan will include both stationary fuel cells and hydrogen-fueled transportation and infrastructure. A preliminary report is required by January 2007 with the final plan submitted by January 2008 (Reference 5.28).

6. SUMMARY OF FINDINGS AND CONCLUDING REMARKS

6.1 SUMMARY OF FINDINGS

6.1.1 *Hydrogen-fueled transportation*

Hydrogen is produced in large quantities, primarily for petrochemical and other uses. Total US production is the energy equivalent of approximately 5% of the fuel consumed in vehicles in the United States. Most of the hydrogen produced is consumed within the plant where it is generated. A small amount is sold and transported by truck, rail, or pipeline to other users. Current cost of delivered hydrogen is much higher than the level that would be required to make its use for transportation purposes realistic and feasible.

Hydrogen offers advantages in terms of very low emissions of pollutants at the point of consumption and the ability to be derived from many sources, including hydrocarbons like natural gas and coal, which are indigenous to the United States, nuclear, and renewable sources. Fuel cells using hydrogen are quiet and their high conversion efficiency reduces the cost of developing a hydrogen infrastructure to serve transportation fuel markets.

A number of issues must be overcome to make hydrogen a viable transportation fuel. These include reducing generation cost; minimizing emissions of greenhouse gases during hydrogen production from fossil fuels; reducing distribution cost; minimizing the size of hydrogen storage onboard vehicles, in fueling stations, and in hydrogen distribution; achieving vehicle cost competitive with conventional or other alternative transportation fuels and technologies; and establishing equipment and procedures which provide for safe use of hydrogen in transportation.

A significant global effort is underway to address the issues of hydrogen transportation, including efforts by US and international governments; vehicle, infrastructure, and fuel cell manufacturers; and governments of many states. The National Research Council, in reviewing US plans for hydrogen-fueled transportation development, stated that: "This is a broad, very challenging research effort to assist in the development of high-risk technologies that will enable the vision of a clean and sustainable transportation energy future....The committee believes that research in support of this vision is justified by the potentially enormous beneficial impact for the nation."

Connecticut has a number of assets which could contribute to hydrogen-fueled transportation, including a number of hydrogen infrastructure and fuel cell companies who are participating in the global effort, a robust effort in stationary fuel cell demonstration and use, the beginnings of demonstration efforts for hydrogen-fueled transit buses, and legislation enacted in 2006 to establish a hydrogen and fuel cell plan for the state.

The potential for hydrogen-fueled transportation in Connecticut involves a vehicle population of nearly 3 million vehicles. Fleets, especially light-duty (3,000 vehicles), vans and small buses

(2,000 vehicles), and large transit buses (600 vehicles) owned or supported by the state, are likely to be the earliest applications of hydrogen-fueled transportation in Connecticut. The current fueling infrastructure serving these vehicles, along with tens of thousands of vehicles which traverse the state each day, involves 1,500 fueling stations, 70 of which are dedicated to state-owned vehicles and 23 of which are located at service plazas on major Connecticut highways.

6.1.2 Concerns of Interested Parties

A total of nearly 40 parties involved with safety, other alternative fuels, hydrogen infrastructure, fuel cells, and state agencies were interviewed to identify issues of concern regarding hydrogen-fueled transportation. Table 6.1 summarizes the most important concerns identified, along with an assessment of these concerns.

Area	Concerns	Assessment
Vehicle	Range, cost, operability in all weather conditions, performance, reliability and durability	Being addressed by government programs with regular reports and third-party assessments
Infrastructure	Hydrogen cost at the pump, greenhouse gas emissions, fueling station size, availability of fueling stations, fueling time	Being addressed by government programs with regular reports and third-party assessments
Safety, codes, insurance	Public perception of safety, slow development of standards and incorporation in local codes and regulations, lack of knowledge of permitting officials, first responder training, ability to obtain insurance	Being addressed at national level, case-by-case approach in Connecticut, insurance not limiting at present
Business and market development	Long-term development with uncertain results, availability of competitive vehicle models to serve application, requirement for cooperation of many independent parties to achieve success, comprehensive government involvement required, confidence in reliability and durability	Substantial government support during development and demonstration, demonstration programs include all required participants and public-private partnerships being considered, substantial related efforts in Connecticut

Table 6.1. Concerns with Regard to Hydrogen-Fueled Transportation

There were no fundamental barriers identified to the introduction of hydrogen-fueled transportation in the state. However, there are state actions which will be required to permit use of hydrogen-fueled transportation in Connecticut. These involve adoption of codes and

regulations which incorporate results of national standards efforts, first responder training, etc. Other actions would accelerate deployment of hydrogen-fueled vehicles. These include participation in demonstration activities, public outreach to improve understanding of the technology, and opportunity and participation in public-private partnerships to facilitate deployment.

SECTION 6.2 RECOMMENDATIONS

6.2.1 Approach to Recommendations

In preparing the recommendations which follow, the following principles were applied:

- Concerns of interested parties need to be addressed appropriate to state-level initiatives.
- Connecticut initiatives should complement, not duplicate, current activity.
- The recommended effort should be paced to be consistent with technology and business progress.
- The effort should involve all stakeholders and participants.
- Periodic reviews of the effort should be scheduled to keep it consistent with progress and other efforts.

While Connecticut has substantial related efforts in stationary fuel cells and a number of companies who are leaders in hydrogen infrastructure and fuel cell technologies, efforts in hydrogen-fueled vehicles are just beginning and it would be appropriate for the state to consider options for increased effort. Selection of specific options for action depends on the policy direction the state decides to pursue. Two action options are advanced for consideration by policy makers relative to a hydrogen-fueled transportation program.

- Option 1: The first option is a formalized monitoring program for Connecticut, whereby Connecticut monitors the status of development while performing modest preparatory activity to ensure that there are no roadblocks when commercial deployment of hydrogen-fueled transportation begins. The Connecticut activity would accelerate following initiation of deployment in other states.
- Option 2: The second option is a promotional program for Connecticut, whereby the state
 - undertakes activities which promote and contribute to the development of hydrogen-fueled transportation;
 - supports state industry participants; and
 - helps to accelerate the beginning of deployment and more rapid expansion.

With either option, it is recommended that Connecticut consider action as part of a regional effort to amplify the effects of Connecticut's efforts. Connecticut serves as a bridge between New York and the rest of New England. It shares with New York and Massachusetts a

congested transportation network, high levels of pollution, and dependence on imported energy from other states and countries through a constrained energy transport system. Consequently, it also shares interest in the environmental benefits and energy security benefits of hydrogen-fueled transportation. A regional effort is particularly recommended if multi-state activity, such as a hydrogen corridor along Interstate 95, develops beyond the current conceptual stage (Reference 6.1).

The options are described in Sections 6.2.2 and 6.2.3. While each option involves a number of activities, each activity can be undertaken independently. The separate activities can, however, be mutually reinforcing, a fact which should be considered in selecting and defining the option or activity. The response of the two options to concerns addressed by interested parties is described in Section 6.2.4. An approach for selection of the appropriate option is discussed in Section 6.2.5.

6.2.2 Option 1 - Monitoring Program

This option minimizes Connecticut's near-term investments, but positions Connecticut to respond quickly in order to participate in hydrogen-fueled transportation when commercial deployment begins. With this option, the initiative for hydrogen-fueled transportation is taken by the federal government and other states which, in all likelihood, will have strong influence on decisions regarding important key issues, e.g., standards, locations for early deployment of infrastructure and vehicles, etc.

Tasks would include the following:

- Task 1: Monitoring progress in hydrogen-fueled transportation
- Task 2: Establishing a proactive codes and regulation environment
- Task 3: Anticipating hydrogen-fueled transportation in infrastructure design and construction
- Task 4: Developing a comprehensive Connecticut or regional plan

While the activities are independent, it is recommended that all activities begin immediately. An evaluation of the program should be conducted every two years when assessments of the federal hydrogen-fueled transportation effort are released and subsequently when current demonstration efforts are completed, and it is recommended that an annual report, summarizing hydrogen-fueled transportation activities, be issued to keep policy makers informed. The annual report should include summaries of

- progress and status of Connecticut activities as well as federal and other states' activities based on annual progress reports;
- final reports of demonstration programs;
- biennial third-party assessments of the federal program;
- progress against interim and final technology goals of the federal program which are targeted for 2010 and 2015 respectively; and
- commercial deployment activities announced by manufacturers.

Execution of the plan could be a cooperative effort of the state agencies and departments responsible for executing individual tasks. Overall leadership could be provided via an inter-agency coordinating committee made up of representatives of each engaged entity with a permanent or rotating chair. This could be similar to what is being done in some other subject areas, e.g., Governor's Steering Committee on Climate Change.

The four tasks are discussed below.

Task 1. Monitoring Progress in Hydrogen-Fueled Transportation. The purpose of this task is to provide guidance for planning and execution of Connecticut's hydrogen activities. The results of this task are also the basis for determining when Connecticut's efforts should be accelerated.

There are a number of opportunities to monitor the status of hydrogen-fueled transportation in the United States. DOE conducts merit reviews of all elements of its program in the middle of each calendar year and a report on these Annual Merit Review Presentations is available at Reference 6.2. DOE also publishes an Annual Progress Report on its hydrogen program toward the end of each calendar year and that report is available at the same website. Annual meetings of the National Hydrogen Association in March of each year, the annual Fuel Cell Seminar in November of each year, and the Connecticut Fuel Cell Summit, generally held in October of each year, are opportunities to assess progress and to have discussions with individuals involved with the activity. The National Research Council conducts a review of the hydrogen-fueled transportation effort every two years; the next review will probably be published in 2007. Beyond the national efforts, various state government-sponsored activities are underway and monitoring of information on these activities is recommended. Since alternative transportation fuels and technologies are important in assessing action on hydrogen-fueled transportation, the status of these alternatives should also be monitored, including experience with fleet vehicles owned by Connecticut, the federal government and other states.

Task 2. Establishing Proactive Codes and Regulation Environment. The purpose of this task is to facilitate permitting and approval of hydrogen infrastructure projects.

This task involves several elements:

- Changes to national standards and industry standards relevant to hydrogen-fueled transportation should be identified. This can be accomplished by regular monitoring of Reference 6.3, which updates national, international, and industry standards status on a regular basis. When a new or revised standard is approved, Connecticut should make its codes and regulations consistent with it.
- Connecticut should designate a point of contact for questions about codes and regulations applicable to hydrogen-fueled transportation in Connecticut, to facilitate associated permitting activities.
- When hydrogen infrastructure or demonstration activity is planned in Connecticut, the state's point of contact should provide training for permitting officials and first responders who are likely to be associated with that installation. The US hydrogen program provides support for these educational activities.

Task 3. Anticipating Hydrogen-Fueled Transportation in Infrastructure Design and Construction. The purpose of this task is to design new or remodel existing buildings that may be associated with hydrogen infrastructure in the future to be easily adaptable to hydrogen.

The safety of infrastructure associated with hydrogen-fueled transportation requires building designs to minimize fire and explosion hazards associated with a flammable gas which is lighter than air. The specific design requirements include the avoidance of roof designs which could trap hydrogen, avoiding electrical equipment in areas where hydrogen is likely to collect or installing explosion-proof electrical equipment in these areas, and providing adequate ventilation. Some of these provisions, such as explosion-proof electrical equipment and ventilation fans, can be added to buildings with little added cost at such time as the use of the building for hydrogen-fueled transportation is required. However, other provisions, such as the design of the roof structure to avoid trapping hydrogen or elimination of electrical equipment in areas where hydrogen is likely to collect, will result in high retrofit costs if they are not designed into the structure prior to start of construction. It is recommended that state infrastructure facilities that may be involved in hydrogen-fueled transportation in the future be designed appropriately, and that private parties who are likely to construct infrastructure be advised to anticipate the hydrogen requirements in their designs. These infrastructure elements include maintenance and garage facilities, etc.

Task 4. Developing a Comprehensive Connecticut or Regional Plan. The purposes of this task are

- to provide context and overall direction for Connecticut’s hydrogen activities so that the efforts of multiple departments and agencies will be well coordinated and without duplication;
- to provide the basis for integrating Connecticut activity with activities in other states and the federal government; and
- to demonstrate state policy support of hydrogen-fueled transportation.

The planning activity should follow the objectives set forth in the General Assembly actions defined in Reference 5.28. It is suggested the planning effort should begin with a review of federal plans by the DOE and US DOT as well as those of other states such as those described in Chapter 2, Section 2.7.2. This will avoid duplication and integrate Connecticut’s effort with the others. The plan should identify the activity, a schedule, and designation of the departments that would provide the planning for individual tasks. The plan should include milestones, drawn from other programs, at which modification of Connecticut’s plan should be considered.

6.2.3 Option 2 – Promotional Program

The promotional option should be pursued if Connecticut wishes to promote and accelerate the adoption of hydrogen-fueled transportation. This more intensive option permits Connecticut to influence key program decisions and ensures that Connecticut will be among the first states to secure the benefits of hydrogen-fueled transportation. From an economic development perspective, it supports demonstration and other efforts by Connecticut companies who are leaders in this field, and enhances prospects for employment growth in this industry in the state.

This alternative could be initiated immediately, or when the results of efforts elsewhere indicate that hydrogen-fueled transportation deployment is progressing well and firm plans for deployment are announced. Individual tasks may be accelerated before the entire promotional program is adopted. The promotional program includes tasks common with the monitoring effort of Option 1, but which involve more intensive activity, as well as three additional tasks. The additional tasks in the promotional program provide better information for the public, position Connecticut as a leader in hydrogen deployment, encourage private infrastructure investment, strengthen public acceptance, and support Connecticut industry.

In addition to more intense activity in tasks common with Option 1, Option 2 has three additional tasks which are described below.

Task 5: Funding Demonstration Programs. This effort includes demonstration projects initiated and funded by the state of Connecticut and support and monitoring in Connecticut of demonstrations funded by other entities. The purposes of this activity are: (1) to increase the possibility of demonstrations funded by industry or the federal government in Connecticut; and (2) to take advantage of demonstrations funded by others to enhance other program activities.

The activity could take the form of financial support and/or in-kind contributions of activity which are already funded in this program or other Connecticut programs. Inclusion of these state contributions in a proposal by private industry would increase the possibility of locating demonstrations in Connecticut.

Where demonstrations funded in Connecticut by external entities exist (such as the bus demonstrations planned in Hartford and New Haven), Connecticut could take advantage of opportunities to enhance those activities or to initiate activity with particular interest to Connecticut. Opportunities include:

- assessing the status of hydrogen-fueled transportation first-hand;
- using the demonstration for training of permitting officials and first responders;
- gaining experience with the design of hydrogen infrastructure facilities;
- providing a better foundation for planning Connecticut hydrogen activities; and
- establishing demonstrations focused on durability and reliability. This would be helpful to Connecticut companies developing vehicle and infrastructure technologies because their researchers can make first-hand observations without the time and expense of travel.

A number of state agencies and departments will be involved in any demonstration activity. However, it is recommended that one serve as the lead organization, coordinating the others and interfacing with the organizations executing and funding the demonstration.

Task 6: Public Outreach. The purpose of this task is to provide improved understanding of hydrogen-fueled transportation in order to establish public acceptance. Widespread public acceptance will facilitate deployment.

Recommended activities for this task include the following:

- Incorporation of the individual task reports recommended in the Option 1 monitoring program into a summary report on the entire effort on an annual basis.
- Establishment of a website describing monitoring results, the Connecticut program and its status, and providing links to broader information on hydrogen-fueled transportation. The website could also include information on state experience with other alternative vehicle fuels and technologies.
- Presentations to the Connecticut Fuel Cell Summit and national meetings.
- Programming on Connecticut Public Television (CPTV) and the Connecticut Network (CT-N).
- Outreach activity in conjunction with demonstrations in Task 5. These could include press releases and presentations to meetings of different organizations.

A recommended schedule for these activities includes launch of the website and the balance of the program activity on publication of the Task 4 plan one year after program initiation. Regular website updates are recommended. The other activities will depend somewhat on the pace of other program activities.

Task 7: Partnerships. The purpose of this task is to provide a mechanism to ensure that all parties necessary for successful deployment are involved and focused on the same objectives and plan.

The effort would include the following:

- Assessment of the overall requirements for successful deployment of hydrogen-fueled transportation.
- Enlisting appropriate organizations to participate in deployment. Vehicle manufacturers, energy companies, infrastructure companies, and government will all be required for success and one, and preferably multiple, participants from each type of organization will be required.
- Preparation of a plan of execution by candidate participants. The plan could include infrastructure locations, deployment schedules, state vehicle purchases, plans to secure purchases from private fleets, etc.
- Securing commitment to the partnership by all parties. The commitment is expected to be a binding legal obligation for activities over the extended period required to establish hydrogen-fueled transportation as a viable business.

Private organizations may take the lead on this activity. If no private activity results in a partnership that includes deployment in Connecticut, the state should take the lead, with the first step being an assessment of whether a partnership is needed and when the partnership should be formed. The assessment activity should begin a year after program initiation.

6.2.4 Addressing Concerns of Interested Parties

Both Option 1 and Option 2 address most of the concerns of interested parties identified in Section 5. Table 6.2 provides comments on how each alternative addresses the concerns.

	Area of concern			
	Vehicles	Infrastructure	Safety codes and insurance	Business and market development
Option 1: Monitoring program	Monitor only	Provides initial input to avoid higher cost in future	Facilitates permitting of infrastructure on a case-by-case basis	Reactive approach which reduces barriers
Option 2: Promotional program	Could have a positive contribution through demonstrations	Provides guidelines to minimize future costs; provides infrastructure plan to guide state and private infrastructure deployment	Establishes Connecticut as a state with favorable conditions for deployment including addressing insurance availability	Proactive approach which positions Connecticut to be an early state for deployment

Table 6.2. Identification of Activities to Address Areas of Concern for Each Option

6.2.5 Selecting the Best Policy Option

Selection of the policy option to pursue could be based on several factors:

- An economic assessment
- Hydrogen program progress
- Results with alternative fuels and technologies
- Deployment evidence

The economic assessment should estimate the effects of hydrogen-fueled transportation on state funding requirements, job creation, and tax revenues. The models of Regional Economic Models, Inc. are typically used for these purposes in Connecticut policy evaluations (www.remi.com).

Hydrogen program progress will be defined in terms of results demonstrated in laboratories and engineering tests, demonstration fleet performance, and assessments by third parties and DOE. The DOE, US DOT and National Academies websites, annual DOE review meetings and annual meetings of the National Hydrogen Association and the Fuel Cell Seminar also provide information.

Results with alternative technologies are available from experience with Connecticut state fleets, which now include vehicles fueled with natural gas, ethanol, and biodiesel, as well as hybrid vehicles. Advocacy organizations and publications associated with each fuel or technology are also sources of this information. Unfortunately, there is no single organization which reviews all alternatives on a consistent basis to determine application economics, local and general emissions of controlled pollutants and greenhouse gases and energy imports, but at least a qualitative comparison is recommended.

Deployment evidence includes announcements by vehicle and infrastructure companies with regard to availability of commercial vehicles and infrastructure. Formation of partnerships among vehicle and infrastructure companies and governmental institutions is another indication of deployment plans, as are actions by other states.

Consideration of all of these factors is suggested in selecting the action option. More positive results are the basis for more aggressive actions by Connecticut.

It is suggested that a multi-party group be assembled to consider the appropriate action option for Connecticut. The group should include all state departments and agencies which would be involved with hydrogen-fueled transportation. Efforts overseen by the Department of Economic and Community Development pursuant to the hydrogen and fuel cell cluster development and planning activity mandated by legislation enacted in 2006 may be included as a part of this activity. The group could determine a course of action from among the options presented above or an alternative course of action. The group could also determine the appropriate department or agency for carrying out the tasks.

APPENDIX A HYDROGEN CHARACTERISTICS

Hydrogen is a colorless, odorless, tasteless, and nonpoisonous gas under normal conditions on Earth. It is also the lightest element and also the most abundant, making up 90% of the universe by weight. It is not found in its pure form on Earth; rather, it is combined with oxygen in water or with carbon in coal, petroleum, natural gas, or other hydrocarbons. While it has very high energy content by weight, its light density makes it very low in energy content by volume (Reference A.1).

Table A.1 provides a number of hydrogen properties; some are used in this document. These data are from References A.1, A.2 and A.3, which are

- <http://www.eere.energy.gov/hydrogenandfuelcells/education/properties.html>
- <http://www.eere.energy.gov/afdc/pdfs/fueltable.pdf>.
- http://www.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm01r0.pdf

All these references provide additional information on hydrogen properties and the second and third have properties of other fuels for comparison. Generally,

- For gases at standard conditions, hydrogen has 31% of the heating value of natural gas.
- Hydrogen heating value on a weight basis is 2.4 times that of natural gas and 2.7 times that of gasoline.

Property	Units	Value*
Density-gas		
	Kg/cubic meter	0.08376
	Pounds/cubic foot	0.0052
	Kg/cubic foot	.00236
Density-liquid		
	Pounds per cubic foot	4.432
	Kg/cubic meter	70.8
Lower heating value		
	BTU/lb	51,500
	kWh/kg	33.2
	BTU/cubic foot (gas)	270
	kWh/liter	0.0289
	BTU/cubic foot (liquid)	227,850

*Volumetric values for gases are at standard conditions of temperature and pressure

Table A.1. Hydrogen Properties

APPENDIX B STANDARDS ORGANIZATIONS

The standards organizations discussed in the main body of this report are described below.

ANSI

American National Standards Institute

ANSI is a private, non-profit organization that administers and coordinates the US voluntary standardization and conformity assessment system. Although it itself does not develop standards, it provides all interested parties with a neutral venue to come together and work toward common agreement. It also is the sole US representative to the two major international standards organizations: the International Organization for Standardization (ISO) (*all subjects except electricity*) and the International Electrotechnical Commission (IEC) (*electricity*).

25 West 43rd Street
New York, NY 10036
(212) 642-4900
www.ansi.org

ASME

American Society of Mechanical Engineers

ASME is a professional organization focused on technical, educational and research issues of the engineering community. It is a world leader in developing codes, standards and assessment programs associated with mechanical engineering.

Three Park Avenue
New York, NY 10016
(800) 843-2763
www.asme.org

CGA

Compressed Gas Association

CGA is an industry organization dedicated to the development and promotion of safety standards and safe practices in the industrial gas industry. It develops and publishes technical information, standards and recommendations for safe and environmentally responsible practices in the manufacture, storage, transportation, distribution, and use of industrial gases.

4221 Walney Road, 5th floor
Chantilly, VA 20151
(703) 788-2700
www.cganet.com

CSA America

CSA (Canadian Standards Association) America is a standards writing body in the United States for appliances and accessories fueled by natural, liquefied petroleum, and hydrogen gases. These activities were formerly conducted by the American Gas Association Laboratories. It is affiliated with CSA International, which tests and certifies products to US, Canadian, European and other national standards.

8501 East Pleasant Valley Road
Cleveland, OH 44131
(216) 524-4990
www.csa-america.org

ICC

International Code Council

The ICC develops a series of Model Building Codes that are adopted by many states and other political jurisdictions and therefore carry the force of law, and are used by local building inspectors to approve building construction. These codes set forth minimum performance requirements for all aspects of commercial and residential construction, including building safety and structural systems, fire prevention, mechanical systems, plumbing systems, property maintenance and zoning.

5203 Leesburg Pike, Suite 600
Falls Church, VA 22041
(888) 422-7233
www.iccsafe.org

ISO

International Organization for Standardization

ISO is the world's largest developer of standards. It is a network of the national institutes of 156 countries, on the basis of one member per country, with a central secretariat in Geneva, Switzerland, that coordinates the system. Its scope is all subjects except electricity, and its US member is ANSI. (*All documents are available through ANSI.*)

1, rue de Varembe, Case postale 56
CH-1211 Geneva 20, Switzerland
+41 22 749 01 11
www.iso.org

NFPA

National Fire Protection Association

NFPA serves as the world's leading advocate of fire prevention, and as an authoritative source on public safety. Its mission is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training and education. Its 300 codes and standards influence almost every building, process, service, design and installation in the United States.

1 Batterymarch Park
Quincy, MA 02169
(617) 770-3000
www.nfpa.org

SAE
Society of Automotive Engineers

SAE is a professional society of engineers, executives and students from more than 97 countries who share information and exchange ideas for advancing the engineering of mobility systems. It develops Standards, Recommended Practices and Information Reports on all forms of self-propelled vehicles including automobiles, trucks and buses, off-highway vehicles, aircraft, aerospace vehicles, marine, rail and transit systems.

755 West Big Beaver, Suite 1600
Troy, MI 48084
(724) 776-4841
www.sae.org

UL
Underwriters Laboratories

UL is an independent product-safety testing and certification organization. It has developed more than 800 Standards for Safety for ensuring public safety and confidence, reduced cost, improved quality, and market products and services.

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APPENDIX C

STATUS OF NATIONAL, INTERNATIONAL AND INDUSTRY CODES AND STANDARDS FOR HYDROGEN-FUELED TRANSPORTATION

C. 1 INTRODUCTION

A survey was conducted of national, industry, and international codes and standards activities that address safety issues associated with the generation, storage, transport, and use of hydrogen as a fuel in an over-the-road transportation application.

National standards – those accredited by the American National Standards Institute – are developed as a consensus of those directly and materially affected by the standard, such as a balanced committee of manufacturer, user, regulatory and insurance interests. Industry standards are generally developed by the organization’s members. Both types of standards are referenced in federal, state, and local regulations. An international standard would generally first have to be adopted as a US standard before it would be referenced by federal, state, or local regulations.

A short description of all codes and standards organizations referenced below, along with their contact information, is provided in Appendix B.

The resulting information is organized by:

- Hydrogen infrastructure issues including:
 - On-site hydrogen generation
 - Hydrogen storage
 - Hydrogen piping
 - Hydrogen pipelines
 - Over-the-road transport of hydrogen
 - First responders
- Use of hydrogen as a fuel including:
 - Vehicle design
 - Service station design
 - Hydrogen dispensing
 - Garages
 - Tunnels
 - First responders
- Government Oversight

The information includes approved codes and standards except where it is indicated that the standard is under development or development is scheduled.

C.2 HYDROGEN INFRASTRUCTURE ISSUES

On-Site Hydrogen Generation

The international community is taking the lead in developing equipment standards for hydrogen generators. These activities are being conducted by the International Organization for Standards (ISO), Technical Committee 197 – Hydrogen Technologies. The standards under development, which include requirements such as safety design, testing, marking, and quality, are:

ISO 22734-1 (*under development*)
Hydrogen Generators Using Electrolysis Process
Part 1: Industrial and Commercial Applications

ISO 22734-2 (*under development*)
Hydrogen Generators Using Electrolysis Process
Part 2: Residential Applications

ISO 16110-1 (*under development*)
Hydrogen Generators Using Fuel Processing Technologies
Part 1: Safety

All three of these documents are in an advanced draft phase and should be published in the 2006-2007 time frame.

In the United States, Underwriters' Laboratories is developing three standards in this area:

UL 2264A (*under development*)
Gaseous Hydrogen Generating Appliances Using
Electrolyzer Technology

This activity is waiting for the adoption of ISO 22734-1, and, at that time, it will be harmonized into a UL standard and proposed as a US national standard.

UL2264B (*under development*)
Gaseous Hydrogen Generating Appliances Using
Water Reaction

A draft standard has been released for preliminary technical review by interested parties.

UL2264C (*under development*)
Gaseous Hydrogen Generating Appliances Using
Fuel Processing Technology

This activity is being co-sponsored by CSA America, and is waiting for the adoption of

ISO 16110-1. When that standard is approved, it will be harmonized into a joint UL / CSA America (FC5) standard and proposed as a national standard.

In the meantime, manufacturers can use the in-house document,

**CSA International Requirements No. 5.99
Hydrogen Generators**

or applicable sections of various standards to have their products third-party certified.

Currently, there are no standard activities, either nationally or internationally, dealing with siting of hydrogen generators. Such a standard would typically address the issues of spacing, access, flammability sensors, shutoffs, and fire fighting. In the absence of a standard,

**NFPA 853
Installation of Stationary Fuel Cell Power Plants**

could be used as a design guideline. This standard addresses similar safety issues associated hydrogen use.

Hydrogen Storage

The design of stationary pressure vessels falls within the scope of

**ASME
Boiler and Pressure Vessel Code**

The American Society of Mechanical Engineers (ASME) is currently reviewing the Boiler and Pressure Vessel Code to increase its usefulness for hydrogen applications. New areas being addressed for hydrogen include: composite materials, tube trailers, and material compatibility.

The installation of hydrogen pressure vessels falls within the scope of

**NFPA 55
Standard for the Storage, Use and Handling of Compressed Gases and Cryogenic
Fluids in Portable and Stationary Containers, Cylinders, Equipment and Tanks**

The 2005 edition of this standard has expanded coverage of hydrogen issues. Previous stand-alone standards, **NFPA 50A, Gaseous Hydrogen Systems at Consumer Sites** and **NFPA 50B, Liquefied Hydrogen Systems at Consumer Sites**, have been incorporated into NFPA 55. In addition, as a complement to NFPA 55, the Compressed Gas Association has published several documents that support the safe installation of hydrogen vessels, including:

**CGA PS-17
CGA Position Statement on Underground Installation of Liquid Hydrogen Storage
Tanks**

**CGA PS-20
CGA Position Statement on the Direct Burial of Gaseous Hydrogen Storage Tanks**

CGA PS-21
CGA Position Statement on Adjacent Storage of Compressed Hydrogen and Other Flammable Gases

CGA H-3
Cryogenic Hydrogen Storage

CGA Publication G5.4
Hydrogen Piping Systems at Consumer Sites

CGA P-12
Safe Handling of Cryogenic Liquids

The 2006 edition of **NFPA 52, Vehicular Fuel Systems Code**, addresses some aspects of hydrogen storage. (see below in *Hydrogen Dispensing*)

Hydrogen Piping

The design of pressure piping (generally with a diameter of 3 inches or less) and pipelines falls within the scope of the ASME B31 Piping Series. In 2004, ASME initiated activity on a new standard

ASME B31.12 (*under development*)
Hydrogen Piping and Pipelines

This standard activity was formed to develop a new code for hydrogen piping and pipelines that contain requirements specific to hydrogen in power, process, transportation, and distribution, commercial and residential applications. The publishing of this standard and its adoption as a national standard and code (having the force of law) is probably several years away.

As noted above, the Compressed Gas Association has published

CGA Publication G5.4
Hydrogen Piping Systems at Consumer Sites

This is intended to assist designers with installation of safe hydrogen supply systems.

Hydrogen Pipelines

The design of pipelines falls within the jurisdiction of the federal government, and thus will not be discussed here. It should be noted, however, that there are already several hydrogen pipelines in existence in the United States.

Over-the-Road Transport of Hydrogen

Transport tanks, specifically portable tanks, cargo tanks, and rail tank cars, are currently covered under US DOT specifications and 49 CFR (Code of Federal Regulations) requirements. In 2004, ASME published

ASME Boiler and Pressure Vessel Code, Section XII Transportation Tanks

This covers the same type of equipment. ASME has recently formed a project team to expand this standard to address requirements for hydrogen tanks.

First Responders

Although not a subject for nation standards, all hydrogen infrastructure facilities must address the safety issue of fighting a hydrogen fire and associated hazards to first responders. No system can be made 100% safe despite the most concerted effort. Accidents or other system failures can and do occur on a regular basis, as clearly illustrated in the historical record of traditional fuel use. Therefore, for any fuel, a suitably trained emergency response force is an essential component of a viable infrastructure. Because of the relative newness of hydrogen as a fuel, however, appropriate emergency response procedures are not yet well understood by responder work forces.

The California Fuel Cell Partnership (CaFCP), located in Sacramento, California, has already published an Emergency Response Guide for Hydrogen Fuel Cell Vehicles. CaFCP staff currently use this document to train emergency responders in Sacramento, San Francisco, and Los Angeles in the areas of hydrogen properties, fuel cell vehicle technology, and emergency response.

In 2005, the National Association of State Fire Marshals (NASFM) formed the Hydrogen Executive Leadership Panel (HELP) to bring together emergency responders, government regulators, scientists, consumers, and experts from the automotive and energy industries to facilitate a safe and orderly transition to hydrogen and other alternative fuel sources.

Another organization that will be involved as training material is developed is the National Association of Fire Training Directors (NAFTD).

The US Hydrogen Fuel Initiative, announced in the president's 2003 State of the Union address, identified training of emergency response personnel, permitting/code enforcement officials, and others as one of the critical needs for developing the future hydrogen economy. As a result, the DOE has charged its Volpentest Hazardous Materials Management and Emergency Response (HAMMER) Training and Education Center, located on DOE's Hanford facility in Richland, Washington, with this responsibility.

HAMMER is intended to be the national focal point for hydrogen safety training activities involving the collaboration of numerous organizations such as:

- International Code Council
- National Hydrogen Association
- California Fuel Cell Partnership

Existing HAMMER capabilities include classroom, long-distance, and computer-based learning, as well as hands-on practice with life-sized "training as real as it gets" props. Additional props under consideration include those that demonstrate or simulate the following:

- Time required for a pressure relief device to empty a tank
- Accident between a hydrogen vehicle and a gasoline vehicle
- Bulk transport of hydrogen
- Hydrogen storage canopy and fuel-dispensing station for hydrogen vehicles

C.3 USE OF HYDROGEN AS A FUEL

Vehicle Design

The design and approval of road vehicles fall within the jurisdiction of the federal government, and thus will not be discussed here except to note various standards under development on the subject. Because of the international nature of the automobile industry, the US federal regulations will probably be influenced by international agreements and other nation's regulations. Some of those activities are also listed.

Society of Automotive Engineers

SAE J2572 *(under development)*

Recommended Practice for the Measuring the Exhaust Emissions, Energy Consumption and Range of Fuel Cell Powered Electric Vehicles Using Compressed Gaseous Hydrogen

SAE J2615

Performance Test Procedure of Fuel Cell Systems for Automotive Applications

SAE J2616

Performance Test Procedure of Fuel Processing Subsystem of Automotive Fuel Cell System

SAE J2617 *(under development)*

Performance Test Procedure of PEM Fuel Cell Stack Subsystem for Automotive Application

SAE J2722 *(under development)*

Recommended Practice for the Durability Testing of PEM Fuel Cell Stacks

SAE J2594

Fuel Cell Recyclability Guidelines

SAE J2578

Recommended Practice for General Fuel Cell Vehicle Safety

SAE J2579 *(under development)*

Recommended Practice for Hazardous Fluid Systems in Fuel Cell Vehicles

SAE J1766

Post Vehicle Collision Electrical Energy Storage System

CSA America

HGV2 *(under development)*
Standards for Hydrogen Vehicle Fuel Containers

HGV3 *(scheduled for development)*
Fuel System Components for Hydrogen Gas Powered Vehicles

HPRD1 *(under development)*
Basic Requirements for Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers

ISO TC22 (Road Vehicles) / SC21 (Electric Vehicles)

ISO 23273-1 *(under development)*
Fuel Cell Road Vehicles-Safety Specifications
Part 1: Vehicle functional safety

ISO 23273-2 *(under development)*
Fuel Cell Road Vehicles-Safety Specifications
Part 2: Protection against hydrogen hazards for vehicles fueled with compressed hydrogen

ISO 23273-3 *(under development)*
Fuel Cell Road Vehicles-Safety Specifications
Part 3: Protection of persons against electric shock

ISO 23274 *(under development)*
Hybrid-Electric Road Vehicles-Exhaust emissions and fuel consumption measurements-non externally chargeable vehicles

ISO 23828-1 *(under development)*
Fuel Cell Hybrid Electric Road Vehicles-Energy consumption measurement - Part 1: Using compressed hydrogen

ISO 23929-1 *(under development)*
Pure Fuel Road Vehicles-Energy consumption measurement- Part 1: Using compressed hydrogen

ISO TC197 (Hydrogen Technologies)

ISO 13985 *(under development)*
Liquid Hydrogen-Land Vehicles Fuel Tanks

ISO 15869 *(under development)*
Gaseous Hydrogen and Hydrogen Blends-Land Vehicle Fuel Tanks

United Nations

Global Technical Regulations (GTR's)
Hydrogen Vehicles *(under development)*

European Union

European Integrated Hydrogen Project (EIHP)

Work Package 4 – Hydrogen Vehicles (under development)

Japanese Government Regulations

Japanese Hydrogen Fuel Cell Vehicle Regulations (HFCV)

Service Station Design

The State Building Code will be critically important for the design of service stations that will dispense hydrogen as a fuel. The State Building Code identifies the standards to be evoked for equipment, such as, hydrogen generators, hydrogen storage systems, piping, and, of particular interest, specifies minimum distances between hydrogen systems and other equipment. A key factor in these distances is to separate potential hydrogen leaks from potential ignition sources. Currently outdoor minimum separation distances for gaseous hydrogen, dispensers, compressors, generators, and storage vessels can be found in the

International Fire Code-2003 edition with supplements, and

NFPA 55-2005 edition

Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary containers, Cylinders, Equipment and Tanks

The separation distances, found in both of these documents, have their origin in circa 1960s standards:

NFPA 50A

Gaseous Hydrogen Systems at Consumer Sites

NFPA 50B

Liquefied Hydrogen Systems at Consumer Sites

No technical basis/substantiation for those distances exists. Many experts are of the opinion that these distances are overly conservative and will have a negative impact on the siting of hydrogen at many existing vehicle refueling stations.

At the urging of DOE in 2000, the ICC established the Ad Hoc Committee for Hydrogen Gas. It is primarily through this committee's efforts that hydrogen is now covered in five ICC codes:

- **International Building Code**
- **International Residential Code**
- **International Mechanical Code**
- **International Fuel Gas Code**
- **International Fire Code**

Coverage is fairly comprehensive (2003 edition – hydrogen piping and fuel supply systems; 2006 edition – underground and atop canopy storage), with the exception of two glaring shortfalls:

hydrogen storage in metal hydride containers, and the previously mentioned separation distances at refueling stations.

The Connecticut Building Code is based on the various editions of the International Code Council (ICC) Model Code Series. The state of Connecticut adopted the 2003 editions of the International Building Code and the International Fire Code in 2005.

In 2002, at the urging of Michael Swain, a noted hydrogen researcher and expert on safety issues at the University of Miami, Sandia National Laboratories commenced a research project in an effort to scientifically substantiate hydrogen separation distances. Swain's work concentrated on establishing lower flammability limits in the vicinity of hydrogen leaks, and will eventually lead to a better understanding of safe separation distances for hydrogen systems.

In September 2004, a report entitled "Hydrogen Clearance Distances," written by Andrei Tchouvelev and a group of Canadian experts, was submitted to National Resources of Canada for the Canadian Transportation Fuel Cell Alliance. The report was based, in part, on the work done by Swain and Sandia Laboratories. It put forth reasonable separation distances and the rationale supporting its recommendations in a code-friendly fashion. Currently, the codes and standards community is reviewing the report.

In parallel with this effort, the NFPA's Fire Protection Research Foundation, under the direction of its executive director, Kathleen Almand, has initiated a new project on separation distances, approaching the issue from the viewpoint of past experience with other fuels and the level of risk society has accepted with those fuels. The same risk factors would then be applied to hydrogen.

Modification of minimum separation distances based on these activities could be introduced into later editions of the ICC Model Codes.

In 2006, a Hydrogen Industry Panel on Codes (HIPOC) was created to harmonize the fixed-facility hydrogen codes and standards activities of the ICC and NFPA. This stand-alone activity is directing ICC and NFPA change proposals to the appropriate development activities.

The DOE Office of Energy Efficiency and Renewable Energy, in collaboration with the National Fire Protection Association, the International Code Council, Pacific Northwest National Laboratory, and the National Renewable Energy Laboratory, has developed the *Regulators' Guide to Permitting Hydrogen Technologies*. This guide is designed to help regulators sort through the multitude of codes and standards that apply when permitting hydrogen facilities.

Module 2 of this guide, "Permitting Hydrogen Motor Fuel Dispensing Facilities," addresses service stations that

- receive hydrogen produced offsite and delivered to the station;
- have long-term storage of liquid hydrogen or compressed hydrogen gas or both; and
- dispense hydrogen (as a gas or liquid) to fuel cell vehicles and vehicles with hydrogen-powered internal combustion engines.

This Module, which can be found at http://www.pnl.gov/fuelcells/docs/permit-guides/module2_final.pdf , provides a brief description of the basic installation, an overview of the safety requirements, requirements for systems and components, and case studies of hydrogen facilities already in operation in the United States.

The 2006 edition of **NFPA 52, Vehicle Fuel Systems Codes**, addresses some aspects of service station design. (see below in *Hydrogen Dispensing*)

Hydrogen Dispensing

The 2006 edition of

NFPA 52 Vehicular Fuel Systems Code

has been expanded to present the latest fire safety rules for hydrogen fuel systems, in addition to compressed and LNG fuel systems, on all vehicle types, and their respective compression, storage, and dispensing systems. This standard addresses design, manufacture, installation, operation, and inspection of fuel systems. It has new material on gaseous and liquefied hydrogen storage and dispensing for vehicles, and five new chapters covering hydrogen applications, including requirements for siting hydrogen fueling systems.

Standards under development for the dispensing of hydrogen into a vehicle include:

SAE J2600 Compressed Hydrogen Vehicle Fueling

This standard deals with the design of dispensing nozzles and receptacles, and is currently being harmonized with the international standard on the same subject:

ISO 17268 Gaseous Hydrogen - Land Vehicle Filling Connectors

Another standard addresses wireless communication between the vehicle and the refueling station:

SAE 2601 (under development) Compressed Hydrogen Vehicle Fuel Communication Devices

CSA America is also developing a series of standards that addresses components within fuel dispensing equipment. Those standards are:

CSA America HGV4 (under development) Series for Fuel Dispensing Equipment and Components

- 1.1 Hydrogen Dispensers**
- 1.2 Hoses and Hose Assemblies for Hydrogen Vehicles and Dispensing Systems**
- 1.3 Temperature Compensating Devices for Hydrogen Dispensing Systems**

- 1.4 **Breakaway Devices for Hoses Used in Hydrogen Vehicle Fueling Stations**
- 1.5 **Priority and Sequencing Equipment for Hydrogen Dispensing Systems**
- 1.6 **Manually Operated Valves Used in Gaseous Hydrogen Vehicle Fueling Stations**
- 1.7 **Automatic Pressure Operated Valves for Use in Gaseous Hydrogen Vehicle Fueling Stations**
- 1.8 **Hydrogen Gas Vehicle Fueling Stations Compressors**

Finally, whenever hydrogen will be sold as a fuel, a meter will have to be used that is approved by a state's "weight and measures" agency. The National Institute of Standards and Technology (NIST) Weights and Measures Division is developing a

Hydrogen Gas Meter Code (*under development*)

that could be adopted by "weights and measure" jurisdictions for regulating hydrogen-fueling equipment.

Garages

There appear to be two schools of thought on the design of garages that house hydrogen vehicles. The general consensus within the automobile industry is that the design requirements for the vehicle will be such that no special requirements will be necessary for garages. California, on the other hand, requires in its building code no potential ignition sources within eighteen (18) inches of the ceiling of a garage that houses hydrogen vehicles. (Note: California also requires no potential ignition sources within eighteen (18) inches of the floor of a garage that houses gasoline vehicles).

Tunnels

The introduction of hydrogen into tunnels is not relevant to Connecticut and will not be discussed here.

First Responders

See the First Responder section of Hydrogen Infrastructure above for hydrogen firefighting issues. Another potential hazard to first responders is a shock hazard at the site of an automobile accident. This issue has already been addressed in the Society of Automotive Engineers' standard:

**SAE J1766
Post Vehicle Collision Electrical Energy Storage System**

and will be proposed for federal rulemaking for hydrogen-fueled vehicles.

C.4 GOVERNMENT OVERSIGHT

As noted above, the federal government will have oversight of the safety issues associated with

- hydrogen pipelines;
- over-the-road transportation of hydrogen; and
- vehicle design
 - o fuel containment (fire hazards)
 - o first responders (shock hazards)

The state of Connecticut or its local jurisdictions will have oversight of the safety issues associated with

- on-site hydrogen generation;
- hydrogen storage;
- hydrogen piping;
- service station design;
- hydrogen dispensing;
- garages; and
- first responders (fire fighting)

APPENDIX D

EXPERIENCE WITH NON-TRADITIONAL TRANSPORTATION FUELS AND TECHNOLOGIES

Hydrogen-fueled vehicles are only one of the approaches to reduce dependence on petroleum imports and pollution. Approaches using other alternative fuels are at a more advanced stage of development, and the history of use of these fuels provides important background as well as technology for hydrogen-fueled vehicles. As will be seen, even after significant deployment of these vehicles, there is significant disagreement regarding their economic and environmental benefits. As clear results become available for these other approaches, the best approaches may become well entrenched, possibly depending on governmental policies. This could increase the difficulty of furthering the deployment of hydrogen-fueled vehicles and careful monitoring of the progress of these alternatives to hydrogen should be a part of Connecticut's efforts on hydrogen vehicles.

A number of alternative fuels and vehicle power systems have been deployed. They include natural gas vehicles (using either CNG or LNG), ethanol-fueled vehicles, biodiesel-fueled vehicles, and hybrid vehicles.

Use of these alternatives was accelerated with passage of the 1992 Energy Policy Act, which required the DOE to establish requirements for purchase of alternative fuel vehicles for federal, state, and utility light-duty vehicle fleets. The DOE issued a rule in 1996 requiring that 75% of fleet purchases be alternative fuel vehicles beginning in 1999 (Reference D.1). The 2005 Energy Policy Act requires federal and utility light-duty vehicle fleets to operate on the alternative fuels except in an emergency; this requirement is not applied to state fleets (Reference D.2). New York State goes beyond the federal mandate. It requires 100% of light-duty vehicle purchases by any state fleet to be alternative-fueled vehicles; exemptions are provided for police or emergency vehicles (Reference D.3).

Connecticut encourages ownership of alternative-fueled and hybrid vehicles through exemption of sales taxes (Reference D.4), exemption from gross earnings taxes on motor fuels, and state tax credits for cost associated with purchase of alternative fuel capability (Reference D.5). Federal tax credits for incremental costs of alternative-fueled vehicles (Reference D.6) and grants to purchase advanced vehicles for school buses and state and local governments are available for hybrid vehicles under the 2005 Energy Policy Act. Funding assistance for purchase of alternative-fuel transit buses is available from the Federal Transit Administration under the Transportation Equity Act for the 21st Century TEA-21, under the DOE Clean Cities Program, and under the Congestion Mitigation and Air Quality Improvement Program (CMAQ) of the US DOT Federal Highway Administration.

Fueling stations for alternative fuels rely on grants from the Clean Cities Program, the Congestion Mitigation and Air Quality (CMAQ) Improvement Program of the US DOT, and other grants and tax incentives to defray the cost of the stations. The 2005 Energy Policy Act

includes an Alternative Fuel Infrastructure Tax Credit equal to 30% of the cost of the alternative fueling property. The credit is limited to \$30,000 for a business and \$1,000 for home fuelers (Reference D.7). Connecticut exempts alternative fuel filling station construction cost from sales tax (Reference D.8). Connecticut also provides a Corporation Business Tax credit for 50% of the cost of construction of alternative fuel refueling stations (Reference D.9).

Hybrid vehicles are treated separately from alternative-fueled vehicles, even though they address similar objectives of reduced dependence on petroleum imports and reduced pollution. For example, the Connecticut Climate Change Action Plan requires the state to purchase hybrid light-duty vehicles in addition to the federal mandate for alternative-fueled vehicles (Reference D.10). Experience with the individual alternative-fueled and hybrid vehicles is discussed below.

D.1 NATURAL GAS

Experience with use of natural gas vehicles provide important insight relative to hydrogen-fueled vehicles because both fuels can be provided in either compressed gaseous or cryogenic liquid form, although hydrogen will require higher pressure for compressed storage and lower temperature for liquid storage. Consequently, issues associated with fueling stations and storage of the fuel in vehicles are somewhat similar. There is, however, an extensive pipeline distribution system for natural gas and it is naturally available, so the generation and distribution infrastructure issues are much less difficult for natural gas than for hydrogen.

There are 4.5 million natural gas vehicles worldwide, with 130,000 of these in the United States. Of the over 8,000 natural gas refueling stations in the world, 1,340 are in the United States. The United States lags behind Argentina, Brazil, Pakistan, Italy and India in the number of natural gas vehicles (Reference D.11).

A number of CNG transit buses and shuttle buses are operating in the United States. In 2005, an American Public Transit Survey showed nearly 13% of buses operated on CNG or liquefied natural gas.

While there are no CNG-fueled buses operated by transit districts/authorities in Connecticut, the Metropolitan Transit Authority in New York City operates 400 natural gas buses (Reference D.12) and the Metropolitan Transit Authority in Boston and the Logan Airport shuttle fleet have 40% and 100% CNG buses, respectively (Reference D.13).

Municipal and private vehicle fleets operate on CNG in Connecticut. Most noteworthy are the Hartford and Waterbury fleets of United Parcel Service, where up to 186 delivery vehicles out of a total of 315 operate on CNG (Reference D.14) and the City of Norwich, Connecticut, where 38 vehicles of the city public utility and 3 school buses operate quite successfully and economically on CNG (Reference D.15).

Advances in clean diesel technology and hybrids are achieving environmental and efficiency performance which is very competitive with CNG vehicles. That, combined with the lack of infrastructure and lack of offerings from the vehicle manufacturers, has caused UPS to begin retiring its CNG fleet (Reference D.16).

While a number of CNG vehicles have been offered by auto manufacturers, currently there is only limited availability.

The size of CNG tanks on vehicles, concern with compressed gas fueling and limited availability of refueling stations have limited the appeal of natural gas vehicles other than for medium and heavy duty vehicles.

In light-duty CNG vehicles purchased by Connecticut in the early response to the mandate for use of alternative-fueled vehicles, virtually all of the trunk space was consumed by the CNG tank. This limited the vehicle utility. Vehicle operators also were concerned with the operation of gaseous fueling equipment (Reference D.17).

Only eleven CNG fueling stations are located in Connecticut (Reference D.18). A few of these stations are public access, but most are private access stations. An additional station is under construction (Reference D.19). Total volume of fuel dispensed by these stations is much smaller than that of gasoline stations. For example, a station in Greenwich sells 180,000 gallons of gasoline per month and only 1,000 gallons of gasoline equivalent for CNG (Reference D.20). Another example is the City of Norwich, which delivers 2,500 gasoline-equivalent gallons per month at its CNG refueling station (Reference D.15). CNG consumption for the Hartford and Waterbury UPS fleets is about 24,000 gallons of gasoline equivalent per month, so these dispense fuel equal to the smallest-volume gasoline stations in Connecticut (calculated based on data presented in Reference D.14).

New York State has been more aggressive with CNG vehicles and has over 50 DOT-owned fueling stations available for state vehicle refueling. Eight of these are now open for public use (Reference D.21).

Experience with LNG-fueled vehicles is limited to heavy-duty vehicles. In February, 2004, there were 2,411 LNG vehicles in the U S (1,614 of the total were located in California) and 49 LNG filling stations in the United States (35 located in California). An interstate Clean Transportation Corridor provides LNG filling stations between Stockton, California and Ogden, Utah; between Ogden and Anaheim, California; and between Anaheim and Stockton, California. Other filling stations are along the routes from Anaheim and San Diego and Anaheim and Phoenix, Arizona (Reference D.22).

Significant lessons learned from the natural gas vehicle experience include the necessity to modify standards and codes to address issues of gaseous fuels, the interdependence of vehicle and infrastructure (fuel delivery, storage, and dispensing equipment) purchases, range limitations associated with the high volume required for storage onboard vehicles, and resistance of the public to an unfamiliar fueling apparatus. Experience with resolution of these issues is a valuable input to the development of hydrogen-fueled transportation.

D.2 ETHANOL

A significant national effort is underway to increase use of ethanol as a transportation fuel. The 2005 Energy Policy Act mandates an increase of ethanol blended into gasoline from the 3.4 billion gallons in 2004 to 7.5 billion gallons in 2012. That act also provides a \$0.51 tax credit for gallon of ethanol used as motor fuel. For example, a fuel containing 20% ethanol would receive

a tax credit of \$0.102 per gallon. Currently, a number of vehicle manufacturers offer flexible fuel vehicles capable of operating on gasoline containing up to 85% ethanol. There are 600 fueling stations nationwide that provide 85% ethanol fuel (E85). Most are in the Midwest (Reference D.23). Two of the 70 filling stations for state vehicles in Connecticut have E85 available (Reference D.24).

Sources of ethanol include sugar cane (major source in Brazil), corn (major source in United States) and cellulosic products such as agricultural waste and crops grown specifically for ethanol conversion such as switchgrass.

There is considerable debate over the net energy and environmental value of ethanol and associated with that debate comes concern over whether the US ethanol fuel mandates are driven primarily by political agenda (Reference D.25).

Ethanol is currently produced primarily in the Midwest, so transportation to Connecticut is expensive. However, it requires minimum changes to filling stations and dispensing is no different than dispensing gasoline, so there are no consumer barriers. The primary issues are cost of the fuel if the federal tax credit were eliminated, land requirements for growing the crops used to produce it, and capital investment requirements for ethanol plants to meet the demand for ethanol transportation fuel.

D.3 BIODIESEL

The primary sources of biodiesel in the United States are soybean oil and yellow grease (used restaurant cooking oil). Nationwide 1,400 petroleum distributors provide biodiesel blends and 450 retail pumps with biodiesel are available (National Biodiesel Board; www.biodiesel.org). Most of the distributors and retail pumps are located in the Midwest, but five distributors are located in Connecticut and three of the 70 filling stations for state vehicles have biodiesel available (Reference D.24).

Biodiesel is blended with diesel in concentrations up to 20% (B20). Because of its uncertain sourcing and composition, engine warranties have limited the use of biodiesel, but these warranty issues are diminishing as national fuel specifications have been developed.

Currently biodiesel is more expensive than diesel fuel from petroleum, but a federal tax credit of \$0.01 per gallon per percent biodiesel in the blend makes the price competitive (B20 would have a \$0.20 per gallon tax credit, Reference D.26).

Some heavy-duty vehicle fleets use biodiesel to provide fuel use credits against the federal mandate for alternative fuel light-duty vehicles. An example in Connecticut involves the heavy-duty vehicle fleet of Northeast Utilities. This fleet uses B20 in the summer only because the fuel does not flow well in the winter. While a ConnDOT fueling station with biodiesel is located nearby, the station is not accessible by the public. Consequently, fueling of the Northeast Utilities fleet is through a tanker truck operated by the fuel supplier which visits the fleet twice per week. At the beginning of deployment, lack of specifications for biodiesel meant that vehicle manufacturers would not offer warranties on trucks fueled with biodiesel. That problem has eased recently (Reference D.27).

As with the other alternative fuels, experience with biodiesel shows the importance of fuel availability in making its use feasible.

D.4 HYBRID VEHICLES

Hybrid vehicles are becoming more popular as a result of state and federal tax incentives for purchase and increasing availability from vehicle manufacturers. Hybrids have drive systems combining a conventional engine with batteries. The batteries add power during acceleration and low speed conditions and permit sizing of the conventional engine to be consistent with cruising, rather than peak power conditions. The conventional engine is able to operate closer to peak efficiency. Regenerative braking provides additional efficiency improvements as well as reduced brake wear. While hybrid vehicles offer operating cost advantages, they are more expensive than conventional vehicles and tax incentives are important in developing this market.

Hybrid technology is improving. For example, diesel hybrids may achieve 80 miles per gallon (Reference D.28) compared to the best hybrids which have EPA mileage estimates of 50-66 miles per gallon (Reference D.29).

As experience and development of hybrid cars continue to expand, “plug-in hybrids” which are charged from the electric grid and then use engines to recharge the battery during travel promise further reduction in petroleum use through substitution of electricity generated from coal, nuclear, natural gas, or renewable sources in the United States.

While hybrid vehicles cannot be used to meet the federal requirement, the Connecticut Climate Change Action Plan requires additional state purchases of light-duty vehicles to be hybrid vehicles (Reference D.10). The Department of Administrative Services has purchased 137 hybrid light-duty vehicles in the past year (Reference D.30).

ConnDOT and CTTransit, in collaboration with the University of Connecticut, CASE, and other partners, recently completed an 18-month study of two late-model, parallel-style hybrid diesel-electric buses and two late-model conventional diesel buses (Reference D.31). The study focused on fuel usage, exhaust emissions, and reliability. For fuel usage, the hybrid buses achieved a 10% percent improvement compared to the conventional buses. This relatively small improvement, compared to expectations, is likely related to the relatively large diesel engine used in the hybrid buses (a size identical to the conventional buses) and to the modest exercise of the battery pack. There is anecdotal information in the bus community that the use of a smaller engine and a more vigorous exercise of the battery pack would have resulted in further improvements (Reference D.32).

For exhaust emissions, the particulate matter (PM) emitted by the hybrid buses and also the conventional buses was greatly reduced by the use of a diesel particulate filter in the exhaust system and the use of ultra-low-sulfur (less than 15 ppm) diesel fuel. On many routes studied in this program, the PM emissions were below the levels of conventional measurement.

For reliability, both the hybrid buses and the conventional buses have performed substantially better than the remainder of the fleet, as measured by miles-between-road-calls and costs per mile. This improved performance was expected of the conventional buses, in that they are newer than the rest of the fleet. However, the study partners were very pleased that the hybrid

buses also performed better, even though they were a very new design, with all of the potential problems that a new design can have.

CASE has suggested to ConnDOT and CTTransit that they continue monitoring these buses, to evaluate their performance after several years of operation. Also, CASE has suggested the purchase of study quantities of newer hybrid design buses, to see whether or not the inherent advantages of the hybrid design can be realized.

APPENDIX E INTERESTED PARTIES

Interested parties include organizations or individuals who could influence the development and deployment of hydrogen-fueled transportation in Connecticut either positively or negatively. They also include those with related experience which may be helpful in understanding those issues and approaches from related technologies that could be applied to hydrogen-fueled transportation. The interested parties have been organized in tables associated with different categories; the relevance of the category and the individual parties is indicated on the table.

Table E.1 provides information on interested parties in the safety category. These contacts focused on state officials associated with codes and first responders.

Table E.2 provides information on interested parties who have relevant information from experience with other alternative fuels. Experience with other alternative fuels, particularly that with CNG, which is most like hydrogen in terms of infrastructure issues, vehicle issues and codes and safety, is helpful in providing information based on real experience rather than conjecture about a future scenario.

Table E.3 provides information on interested parties who have relevant information from experience with other alternative fuels in other states.

Table E.4 provides information on interested parties who participate in current commercial hydrogen activities or development of hydrogen-fueled transportation.

Table E.5 provides information on interested parties associated with Connecticut state planning activities. These parties were contacted to determine current activities and plans which may relate to hydrogen-fueled transportation in Connecticut.

The tables indicate individuals contacted and documents reviewed which relate to the subject. In many cases, the websites associated with the organization contacted were also reviewed.

Area of interest	Organization	Contact person	Relevance
Fire safety	Connecticut Fire Marshal's Office	John Blaschik John Doucette	Codes and standards, first responders
Fire safety	State Fire Administrator	Jeffrey Morrissette	Codes and standards, first responders
Insurance and standards	Hartford Steam Boiler	Donald Drewry, Chairman: NFPA 853 Working Group – Fuel Cell Installations	Insurance risk and mitigation
Insurance	Factory Mutual	James Emerson, Senior Consultant Engineer	Insurance risk associated with hydrogen
Risk management	State of Connecticut	Daria Cirish, Director of Insurance and Risk Management	State assessment of risk and probably insurance costs

Table E.1. Interested Parties in Regard to Safety and Insurance

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Area of interest	Organization	Contact person	Relevance
CNG-fueled package delivery fleet	United Parcel Service	Report: United Parcel Service CNG truck fleet: final results, Aug, 2002 Robert Hall, Fleet Operations	Experience with 186 CNG-fueled vehicles in Connecticut Experience with CNG and hydrogen/fuel cell vehicles
Utility fleet vehicles	Northeast Utilities	Ronald Thresher, Manager, Corporate Transportation	Experience with CNG and biodiesel fuel and electric vehicles
Transit bus operations in CT	ConnDOT	Michael Sanders, Transit and Ridesharing Administrator	Transit and Ride Share fleet. Experience with hybrid buses
Transit bus operations	CTTransit	Steve Warren, Assistant General Manager	Transit operation on alternative fuels
Connecticut state light-duty vehicle fleet	Department of Administrative Services	Tom Yuhas	Purchase and experience with alternative-fueled vehicles
CT state fueling stations	ConnDOT	Janice Snyder	DOT fueling stations for state vehicles
Service stations in Connecticut	Gasoline and Automotive Service Dealers of America	Michael Fox, President	CT service stations and CNG fuel
Owner of service station with CNG	Greenwich Automotive	Chris Canavan, Owner	CNG fueling experience
CNG station under construction	Santa Energy	Tom Santa	Construction of CNG station
Natural gas company	Yankee Energy	Tom Marano	Experience with CNG stations
CNG engine sales and vehicle conversion	Bell Power Systems	Alex Bell	Experience with sale and use of CNG vehicles
Clean Cities Program	Capitol Clean Cities Coalition	Peter Cassarella, Yankee Gas, Coalition Secretary	Information on CT CNG activities
City-focused CNG activities	The Norwich Community Development Corporation	Peter Polumbaitko, Project Manager	City-owned CNG fueling station and vehicles

Table E.2. Interested Parties with Experience with Other Alternative Fuels – Connecticut

Area of interest	Organization	Contact person	Relevance
Massachusetts activity in alternative energy	New England Natural Gas Vehicle Coalition	Michael Manning, Chairman	Alternative fuel activity in neighboring state
New York State alternative fuel activity	NY DOT	Joseph Darling	Alternative fuel activity in neighboring state

Table E.3. Interested Parties in other States with Experience with Alternative Fuels

Area of interest	Organization	Contact person	Relevance
Fuel cell bus operator	AC Transit, Oakland, CA	Jamie Levin	Responsible for 5 experimental fuel cell buses
Major oil company	Shell Hydrogen	Pana Ratana and Henk Mooiweer, Bus. Dev. Mgrs. for California and East Coast	Hydrogen Business Development Manager for California
Fuel cell OEM	UTC Fuel Cells	Frank Preli, Vice President Engineering; Michael Gorman, Director of Transportation Programs; Margaret Steinbugler, Manager, Transportation Fuel Cell Product Development	Experience with deployment of experimental fuel cell vehicles
Electrolysis OEM	Proton Energy Systems	L. Moulthrop, VP Product Dev.; Thomas Maloney, Fueler Prog. Mgr.; S. Goyette, Product Safety	Electrolysis-based fueling stations
DOE	Northeast Regional Office in Boston	Al Benson, Regional Representative for Hydrogen effort Michael Scarpino, Regional Representative for Clean Cities	Hydrogen and Clean Cities efforts of DOE
Major oil company	BP	Georgio Zoia	BP hydrogen activity
Major oil company	Chevron	Graham Moore, Sr. Analyst, Business Development and Planning	Chevron hydrogen activity

Table E.4. Interested Parties Involved with Development of Hydrogen-Fueled Transportation

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Area of interest	Organization	Contact person	Relevance
Connecticut Climate Change Action Plan	Connecticut Climate Change	Report: Connecticut Climate Change Action Plan, January 2005	Planning with regard to measures to mitigate climate change
Developing Connecticut Climate Change Action Plan	Connecticut Clean Energy Fund	Bryan Garcia	Participant in developing CT Climate Change Action Plan
CT Hydrogen and Fuel Cell Coalition	Connecticut Center for Advanced Technology	Joel Rinebold	Administers Connecticut Hydrogen and Fuel Cell Coalition
Connecticut transportation plan	Connecticut Transportation Strategy Board	Report: Transportation: A Strategic Investment, An Action Plan for Connecticut, 2003 to 2023, January 2003	Transportation plan for Connecticut
Connecticut transportation references	ConnDOT	James Sime, Research, ConnDOT	Contacts for other state references on transportation
Plans for Connecticut service plazas and rest areas		Daniel Smachetti, ConnDOT	Plans for upgrading Connecticut state-owned service plazas and rest areas

Table E.5. Interested Parties in Regard to Connecticut Planning

GLOSSARY OF TERMS

Biodiesel

A hydrocarbon with characteristics similar to diesel fuel derived from petroleum. Biodiesel is obtained from vegetable oil or animal fats, with soy being the most frequent raw material. It is usually blended with petroleum derived diesel in amounts up to 20 percent. A website for the biodiesel organization is at www.biodiesel.org.

California Fuel Cell Partnership

A collaboration of 31 member companies who are working together to promote the commercial-ization of hydrogen fuel cell vehicles. Their website is at www.fuelcellpartnership.org.

Chemical Hydrides

A medium for hydrogen storage where hydrogen combines chemically with metals or liquid chemicals. For more information, see www.eere.energy.gov/hydrogenandfuelcells/storage/materials.html

Clean Cities Program

An activity of the Energy Efficiency and Renewable Energy program at DOE which involves volunteer coalitions to promote use of alternative fuels and vehicles, hybrid vehicles and other approaches to clean transportation which reduces dependence on imported petroleum. More information is available at www.eere.energy.gov/cleancities

Congestion Mitigation and Air Quality Improvement Program (CMAQ)

An activity of the US Department of Transportation aimed at improved air quality and reduced transportation congestion. For more information, see www.fhwa.dot.gov/environment/cmaqpgs.

Compressed Natural Gas (CNG)

Natural gas compressed to 2000 pounds per square inch or more for use in transportation applications. For more information, see www.ngvc.org.

Connecticut Clean Energy Fund (CCEF)

An organization created by the Connecticut General Assembly to create clean energy supply for Connecticut; develop clean energy technologies; and to educate residents about clean energy's importance for the state's energy future. CCEF's funding comes from a surcharge on electric ratepayers' utility bills. More information is available at www.ctcleanenergy.com.

Connecticut Global Fuel Cell Center

A partnership between the UConn School of Engineering, Connecticut Innovations., and Connecticut industry to provide a focal point for fuel cell education, development and deployment. The center is staffed with University of Connecticut faculty, researchers and students and located in Mansfield, Connecticut. The website is www.ctfuelcell.uconn.edu.

Connecticut Hydrogen and Fuel Cell Coalition

A coalition of industry, labor, the government, and other stakeholder organizations working to advance the development, manufacture, and deployment of fuel cell and hydrogen technologies and associated fueling systems in Connecticut. The website is www.chfcc.org.

Connecticut Innovations

An organization created by the Connecticut legislature for the purpose of growing Connecticut's entrepreneurial technology economy by making venture and other investments. Its website is www.ctinnovations.com.

Electrolysis

An electrochemical process whereby an electrical current is passed between two electrodes converting water to hydrogen and oxygen. For more information, see www.eere.energy.gov/hydrogenandfuelcells/production/electro_processes.html.

Energy Carrier

An intermediate energy form created from one energy source and suitable for conversion to other forms of energy. The carrier can be derived from many different sources and can be converted for use in many different forms. Electricity is the most common example of an energy carrier. It can be produced from falling water, combustion of hydrocarbons, solar energy, wind energy or nuclear energy and can be converted to light, heat, mechanical power, etc. Hydrogen is another energy carrier which can be derived from the same sources and used for heat, electrical power generation, motive power generation, etc.

Energy Efficiency and Renewable Energy (EERE)

The Department of Energy Office responsible for improving energy efficiency and developing renewable energy sources. This office has responsibility for DOE's hydrogen program and for application of hydrogen to light-duty vehicles. Its web address is www.eere.doe.gov.

Ethanol

An alcohol which can be made from sugar, corn, cellulosic waste and crops grown specifically for ethanol production such as switchgrass. More information is available from the Renewable Fuels Association website: www.ethanolrfa.org

Fleet Vehicle

One of a number of vehicles owned, operated, fueled and maintained by a single organization. Fleet vehicles are often used in a local area and are dispatched and returned to a single site each day where they are fueled and maintained. Fleets are especially suited for introduction of new transportation technologies because they reduce infrastructure costs and are operated, fueled and maintained by professionals.

FreedomCAR

The FreedomCAR and Fuel Partnership is an industry/government research initiative focused on collaborative, pre-competitive, high-risk research to develop the component technologies necessary to provide a full range of affordable cars and light trucks, and the fuel infrastructure to support them, that will free the nation's personal transportation system from petroleum dependence and from harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice. The FreedomCAR website is: www.uscar.org/freedomcar/index.htm.

Fuel Cell

An electrochemical device which converts hydrogen and oxygen to electricity, water and heat. The process is the reverse of electrolysis and, like electrolysis, requires an anode (fuel electrode), a cathode (oxygen electrode) and an electrolyte. For further information see the websites of the US Fuel Cell Council at www.usfcc.com or FuelCells 2000 at www.fuelcells.org.

Gasification

In this report, gasification refers to a process in which coal, air and steam are converted to a hydrogen-rich gas which can be converted to a pure hydrogen stream and carbon dioxide. For more information, see www.fossil.energy.gov/programs/powersystems/gasification/index.html.

Gasoline Energy Equivalent

In this report, gasoline energy equivalent refers to an amount of hydrogen which has the same energy content as a gallon of gasoline. That amount is one kilogram (2.2 pounds) of hydrogen. Note that when used in a fuel cell, the higher fuel cell efficiency will result in a range two or more times that provided by an equivalent gasoline energy content.

Greenhouse Gas

Any gas which, when released to the atmosphere, contributes to the greenhouse effect which is related to absorption and radiation of heat from the Earth's surface. The most commonly considered greenhouse gas is carbon dioxide, but methane, carbon monoxide, fluorocarbons, sulfur compounds and water vapor are also greenhouse gases. The gases have varying contributions to the greenhouse effect and widely varying lifetimes in the atmosphere. The Intergovernmental panel on Climate Change website provides additional information on greenhouse gases at www.ipcc.ch.

Hydrogen

The lightest element consisting of one proton and one electron. On Earth, hydrogen is available only combined with oxygen in water or with carbon and other elements in hydrocarbons. It can be derived from these naturally occurring compounds through a number of methods involving a variety of energy input sources and is considered an energy carrier like electricity rather than a raw source of energy like coal. Hydrogen has the highest combustion energy per unit weight and the lowest combustion energy per unit volume of any element. The primary product of hydrogen combustion is water vapor. A small amount of nitrogen oxides are the only controlled pollutants emitted in hydrogen combustion. When used in a fuel cell, high efficiency conversion to electricity can be obtained. Additional information on hydrogen is available from the National Hydrogen Association website at www.hydrogenus.com.

Hydrogen Highway

The term usually refers to California's effort to establish a network of hydrogen fueling stations to support hydrogen-fueled vehicles in the state. The website is www.hydrogenhighway.ca.gov. Other efforts in this regard are underway elsewhere in the United States and Canada.

Hybrid Vehicle

A hybrid vehicle includes a power plant to convert a stored fuel (examples are gasoline in an internal combustion engine vehicle or hydrogen in a fuel cell vehicle) as well as a battery/motor combination to supplement the output of the primary engine. Typically, the battery will be the primary source of vehicle power at low speeds and the fueled power plant will be the primary source of vehicle power at cruising conditions. Both power sources will be used in acceleration. The batteries are charged by the fueled power plant as well as from regenerative braking. A variation of hybrid vehicles, called "plug-in hybrids," is under development. In these vehicles, batteries would also be charged from the electric power grid when the vehicle is garaged. A description of hybrid vehicles is provided on the National Renewable Energy Laboratory website at www.nrel.gov/vehiclesandfuels/hev/hevs.html.

Liquefied Natural Gas (LNG)

Natural gas which is liquefied and stored as a cryogenic liquid. Additional information is available at www.naturalgas.org/lng/lng.asp.

Metal Hydrides

A hydrogen storage medium in which hydrogen is reacted with a metal. Usually, application of heat is required to deliver the hydrogen. These materials provide a low pressure method for hydrogen storage that operates near ambient temperature. Additional information is available at www.eere.energy.gov/hydrogenandfuelcells/storage/metal_hydrides.html.

National Renewable Energy Laboratory (NREL)

The primary research arm of the Department of Energy dealing with renewable energy and energy efficiency. Its website is www.nrel.gov.

Original Equipment Manufacturer (OEM)

The company which provides the final product to a customer. Auto companies are an example of an original equipment manufacturer.

Partnership for New Generation Vehicles (PNGV)

A partnership between the US government and US auto manufacturers formed in the 1990s to develop a more fuel efficient automobile.

Partial Oxidation

A chemical reaction of petroleum products with oxygen (air) with oxygen quantities less than the stoichiometric requirement to burn the fuel completely to carbon dioxide and water. The products of the reaction are primarily carbon monoxide and hydrogen, which is sometimes referred to as synthesis gas. These products can be combined with water to form additional hydrogen and carbon dioxide in a reaction known as the water gas shift reaction. Coal gasification is another example of partial oxidation.

Photobiological

A process using sunlight and green algae to produce hydrogen. For further information see www.eere.energy.gov/hydrogenandfuelcells/production/photobiological.html.

Photoelectrochemical

A process where hydrogen is produced from water using sunlight and specialized semiconductors. For more information, see www.eere.energy.gov/hydrogenandfuelcells/production/photoelectrochemical.html.

Photolytic

Photolytic processes use light energy to split water into hydrogen and oxygen. For further information, consult the DOE description of the processes which fall into this classification. This information can be found at http://www.eere.energy.gov/hydrogenandfuelcells/production/current_technology.html#photo.

Polymer Electrolyte Membrane (PEM)

Polymer Electrolyte Membrane (PEM) is the electrolyte component of a PEM fuel cell. It is a solid polymer which conducts only protons and blocks transport of electrons.

Regional Economic Models, Inc. (REMI)

A company which provides modeling tools for evaluating the total economic effects of transportation improvements. The company website is www.remi.com.

Sequestration of Carbon Dioxide

A process whereby carbon dioxide, captured from conversion of hydrocarbon fuels, is stored in geological structures like depleted oil wells, unmineable coal seams, deep saline reservoirs, or deep ocean areas. This process eliminates the product carbon dioxide from the atmosphere so that there is no greenhouse effect from the use of hydrocarbons. For more information, see www.fe.doe.gov/programs/sequestration/overview.html.

Steam Methane Reforming

A process whereby methane (the primary constituent of natural gas) and steam are reacted over a catalyst to produce hydrogen and carbon monoxide. The hydrogen and carbon monoxide can be reacted further with steam to produce additional hydrogen and carbon dioxide. This process is the primary hydrogen

production method in the United States. Further information is available at www.eere.energy.gov/hydrogenandfuelcells/production/natural_gas.html.

Thermochemical

This refers to a chemical process which uses heat from high temperature nuclear reactors or focused sunlight to feed heat to reactions involving water and intermediate chemicals to produce hydrogen. This is sometimes also referred to as high temperature water splitting. Further information is available at www.eere.energy.gov/hydrogenandfuelcells/production/water_splitting.html.

Tube trailer

A truck which incorporates a number of high pressure cylinders for transporting gases. Typical hydrogen delivery in tube trailers involves pressure of 3000 psi and this approach is used only for relatively small quantities of hydrogen transported under 200 miles. For further information on this and other hydrogen transportation approaches see www.eere.energy.gov/hydrogenandfuelcells/delivery/current_technology.html.

REFERENCES, NOTES AND ACKNOWLEDGEMENTS (LISTED BY CHAPTER)

CHAPTER 1: INTRODUCTION

- 1.1 Connecticut Academy of Science and Engineering 2001. *A Study of Bus Propulsion Technologies Applicable in Connecticut* for the Connecticut Department of Transportation and CT Transit™
- 1.2 Connecticut Academy of Science and Engineering. 2005. *Demonstration and Evaluation of Hybrid Diesel-Electric Buses* for the Connecticut Department of Transportation and CT Transit™
- 1.3 Connecticut Academy of Science and Engineering. 2002. *A Study of Fuel Cell Systems* for the Connecticut Department of Economic and Community Development and the Connecticut Economic Resource Center.

CHAPTER 2: ELEMENTS OF HYDROGEN-FUELED TRANSPORTATION SYSTEM: APPROACHES AND STATUS

- 2.1 US Department of Energy. 2005. "DOE Announces new Hydrogen Cost Goal." Press release of July 14, 2005. http://www.eere.energy.gov/hydrogenandfuelcells/news_cost_goal.html
- 2.2 National Hydrogen Association website. "Frequently Asked Questions." <http://www.hydrogenus.com/general/faqs.asp>
- 2.3 Romm, Joseph J. 2004. *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate*. Island Press.
- 2.4 Adams, Thad M. 2005. "Evaluation of Natural Gas Pipeline Materials for Hydrogen Service" Presented to Department of Energy Hydrogen Pipeline R&D Project Review Meeting, January 5-6, 2005.
- 2.5 Bellona Foundation. 2002. *Report 6: 2002 Hydrogen*.
- 2.6 Reference 2.6 has been deleted.
- 2.7 US Department of Energy website. "Carbon Sequestration R&D Overview." <http://www.fe.doe.gov/programs/sequestration/overview.html>
- 2.8 Communication from Dante Bonaquist, Director of R&D, Hydrogen and Energy Technology, Praxair. October 27, 2005.
- 2.9 Communication from Frank Preli, VP Engineering for UTC Power, on April 7, 2006.
- 2.10 National Hydrogen Association website. "Frequently Asked Questions." <http://www.hydrogenassociation.org>
- 2.11 Shell Venster. 2004. "Lighthouses for Hydrogen."

PREPARING FOR THE HYDROGEN ECONOMY: TRANSPORTATION
REFERENCES, NOTES AND ACKNOWLEDGEMENTS

- 2.12 Klara, Scott. 2003. "Carbon Sequestration, Media Background Briefing." National Energy Technology Laboratory, Department of Energy Office of Fossil Energy, briefing of June 16, 2003
- 2.13 US Department of Energy Energy Information Agency. "Basic Electricity Statistics." <http://www.eia.doe.gov/neic/quickfacts/quickelectric.html>
- 2.14 US Department of Energy website. "\$760 Million Devoted to Fossil Energy Programs in FY 2006." Issued February 7, 2005. http://www.fossil.energy.gov/news/techlines/2005/tl_fy06_budget_request.html
- 2.15 British Petroleum website. "Introducing Decarbonised Fuels." Issued June 30, 2005. <http://www.bp.com/sectiongenericarticle.do?categoryId=97&contentId=7006978>
- 2.16 US Department of Energy website. "Novel Carbon Sequestration Concepts: Advanced Chemical and Biological Approaches." <http://www.fe.doe.gov/programs/sequestration/novelconcepts/index.html>
- 2.17 Parkinson, Gerald. 2006. "Green Hydrogen Production: A Work in Progress." *Chemical Engineering Progress*, April 1, 2006
- 2.18 US Department of Energy website. "Hydrogen Storage." <http://www.eere.energy.gov/hydrogenandfuelcells/storage/basics.html>
- 2.19 US Department of Energy website. "Hydrogen Properties." <http://www.eere.energy.gov/hydrogenandfuelcells/education/properties.html>
- 2.20 US DOT Energy Efficiency and Renewable Energy Hydrogen Storage Program. "Grand Challenge for Basic and Applied Research in Hydrogen Storage, Statement of Objectives, Draft Dated 6/17/2003" http://www1.eere.energy.gov/hydrogenandfuelcells/docs/gc_h2_storage.doc
- 2.22 Hydrogen Forecast website. <http://www.hydrogenforecast.com>
- 2.23 Millenium Cell website. <http://www.millenniumcell.com/fw/main/Overview-12.html>
- 2.24 Pez, Guido and Alan Cooper. "2004 Progress Report, Design and Development of New Carbon-Based Sorbent Systems for an Effective Containment of Hydrogen." Air Products.
- 2.25 A. Nikitin, H. Ogasawara, D. Mann, R. Denecke, Z. Zhang, H. Dai, K. Cho, and A. Nilsson, *Physical Review Letters*, 95, 225507 (November 23, 2005)
- 2.26 HCE Company website. "New Technology Creates Hydrogen Storage Form Said to Mimic Gasoline." Press release of March 10, 2006. <http://www.hceco.com/pr31006.html>
- 2.27 Vinjamuri, Gopala Krishna. 2004. "Development of US-DOT Regulations for Hydrogen Transportation Systems." US Department of Transportation Panel Forum on Challenges of Hydrogen Pipeline Transmission; International Pipeline Conference and Exposition; Calgary, Alberta Canada; October 5, 2004.
- 2.28 US Department of Energy. 2004. *Hydrogen Posture Plan, An Integrated Research, Development and Demonstration Plan*.
- 2.29 Plug Power press release issued March 16, 2006.

PREPARING FOR THE HYDROGEN ECONOMY: TRANSPORTATION
REFERENCES, NOTES AND ACKNOWLEDGEMENTS

- 2.30 Lasher, Stephen, Brian James, Matt Ringer. 2004. "Forecourt Team Overview." Presented to National Hydrogen Association Conference, April 28, 2004.
- 2.31 California Fuel Cell Partnership website. "Hydrogen Fueling Stations and Vehicle Demonstration Programs." http://www.caafcp.org/fuel-vehl_map.html
- 2.32 Karner, Don, Scott McCamman and James Francfort. 2005. *Hydrogen, CNG, and HCNG Dispenser System – Prototype Report*. Prepared for US Department of Energy under Contract DE-AC07-051D14517, February 2005.
- 2.33 Department of Energy Energy Efficiency and Renewable Energy. 2005. "More Gasoline Stations in 2005." Fact #389. September 12, 2005.
- 2.34 Fuel Cells 2000 World Wide Stationary Fuel Cell Data Base. <http://www.fuelcells.org>
- 2.35 <http://www.fuelcellstandards.com>
- 2.36 Sperling, Daniel. 2001. "Public-Private Technology R&D Partnerships: lessons from US Partnership for a New Generation of Vehicles." Institute of Transportation Studies, Paper UCD-ITS-REP-01-18. October 1, 2001.
- 2.37 Department of Energy Energy Information Agency. *Impacts of Energy Research and Development (S.1766 Sections 1211-1245 and Corresponding Sections of H. R. 4) with Analysis of Price Anderson Act and Hydroelectric Relicensing, Energy Efficiency (Title SII, Subtitle A, Sections 1211 through 1214)*
- 2.38 "Hydrogen Fuel: A Clean and Secure Energy Future." White House Press Release, January 30, 2003.
- 2.39 US Department of Energy *National Hydrogen Energy Roadmap. 2002*. Based on results of the National Hydrogen Energy Roadmap Workshop, Washington, DC, April 2-3, 2002. Published November 2002.
- 2.40 US Department of Energy. 2004. *Hydrogen Posture Plan*.
- 2.41 National Research Council. 2005. *Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report by Committee on Review of FreedomCAR and Fuel Research Program*.
- 2.42 US Department of Energy Energy Efficiency and Renewable Energy Office. 2005. *The Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan*.
- 2.43 US Department of Energy. 2005. *Roadmap on Manufacturing R&D for the Hydrogen Economy, Draft for Stakeholder/Public Comment*.
- 2.44 Sisson, Barbara A. *Hydrogen and Fuel Cell Bus Initiative, Paving the Way Nationally and Internationally*. US Department of Transportation. Federal Transit Administration.
- 2.45 US Department of Transportation. 2005. *Research, Development, Demonstration and Deployment Roadmap for Hydrogen Vehicles & Infrastructure to Support a Transition to a Hydrogen Economy*.
- 2.46 AC Transit. Press release dated March 13, 2006.
- 2.47 SunLine Transit. Press release dated February 27, 2006.
- 2.48 National Hydrogen Association website. <http://www.hydrogenus.com>

PREPARING FOR THE HYDROGEN ECONOMY: TRANSPORTATION
REFERENCES, NOTES AND ACKNOWLEDGEMENTS

- 2.49 US Fuel Cell Council website. <http://www.usfcc.com>
- 2.50 Fuel Cells 2000 website. <http://www.fuelcells.org>
- 2.51 Breakthrough Technologies Institute, Inc. 2006. *State Activities that Promote Fuel Cells and Hydrogen Infrastructure Development*. Report to California Air Resources Board under Contract 05-101, April 2006.
- 2.52 Hoyle, Jason. 2005. "Summary of Hydrogen Roadmap Development Activities in the US" Appalachian State University Energy Center, presented at the North Carolina Hydrogen Roadmap Kick-Off Event in Raleigh, NC on September 22, 2005
- 2.53 California Fuel Cell Partnership website. <http://www.fuelcellpartnership.org>
- 2.54 California Hydrogen Highway Network website. <http://hydrogenhighway.ca.gov>
- 2.55 "US, Rochester Aiming to Become a Power in Fuel Cells." *Fuel Cell Today*. March 17, 2006.
- 2.56 *New York State Hydrogen Energy Roadmap Final Report*. Prepared for the New York State Energy Research and Development Authority, October 2005.
- 2.57 Ohio Fuel Cell Coalition website. <http://www.fuelcellsohio.org>
- 2.58 Ohio Third Frontier Project website. <http://www.thirdfrontier.com>
- 2.59 March 7, 2006 press release
- 2.60 Michigan Economic Development Corporation website. <http://www.michigan.org>
- 2.61 NextEnergy website. <http://www.nextenergy.org>
- 2.62 US Environmental Protection Agency website. "Fuel Cells and Vehicles." <http://www.epa.gov/fuelcell>
- 2.63 Ovonic Press Release. Issued March 18, 2006.
- 2.64 "East Coast leaders work to create Boston to D. C. 'hydrogen highway,'" *Allentown Morning Call*, March 5, 2000
- 2.65 "Northern Plains Partnership Seeking to Build Multi-Fuel Hydrogen Highway." *Fuel Cell Today*, March 22, 2006.
- 2.66 International Partnership for the Hydrogen Economy website. <http://www.iphe.net>
- 2.67 Analyst Briefing at Ballard, September 28-29, 2005.
- 2.68 Hydrogenics Corporation website. <http://www.hydrogenics.com>
- 2.69 Hydrogen and Fuel Cells Canada website. <http://www.fuelcellscanada.ca>
- 2.70 Government of Canada Hydrogen Economy Portal website. <http://www.hydrogeneconomy.gc.ca>

- 2.71 Hydrogen Energy in Europe website. <http://www.hyways.de>
- 2.72 Grubel, Holger. 2005. "CUTE-Clean Urban Transport for Europe, Hydrogen Infrastructure." Presented in Brussels, March 18, 2005.
- 2.73 Fuel Cell Europe website. <http://www.fuelcelleurope.org>
- 2.74 Japan Hydrogen and Fuel Cell Demonstration Project website. <http://www.jhfc.jp/e/>
- 2.75 *Fuel Cell Catalyst*, Volume 6, No 1, Fall 2005.
- 2.76 "Japan to Roll Out World's First Fuel-Cell Train." EFY News Network, May 4, 2006.
- 2.77 MSNBC report March 16, 2006.
- 2.78 *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate*. Island Press, March 2004
- 2.79 American Bar Association. *Legal and Policy Issues Leading to the Commercialization of Hydrogen Fuel Cell Technology*. Renewable Energy Resource Committee teleconference, January 18, 2006.
- 2.80 *HyWays, A European Roadmap, Assumptions, Visions and Robust Conclusions from Project Phase 1*, February 2006.
- 2.81 Kohler, Herbert. 2005. "DaimlerChrysler Fuel Cell Strategy." Presented at Ballard Analyst Meeting, September 28-29, 2005.
- 2.82 Duke, Armando D. "GM to Offer Hydrogen-Powered Vehicles in Four Years." *AXcess News*, March 3, 2006.
- 2.83 "Honda to Begin Producing Next Generation FCX Hydrogen Fuel Cell Vehicle." Press release issued January 8, 2006.
- 2.84 Woodall, Bernie. Reuters. 2006. "Hydrogen fuel adherents see 2020 as key year." March 17, 2006.
- 2.85 Blumenau, Kurt. "Is hydrogen economy years away or is it here?" *Allentown Morning Call*, March 19, 2006.

CHAPTER 4: SCOPE OF HYDROGEN FUEL REQUIREMENTS IN CONNECTICUT AND CURRENT EXPERIENCE WITH HYDROGEN IN CONNECTICUT

- 4.1 *Connecticut Climate Change Action Plan 2005, Transportation and Land Use Sector*
- 4.2 Tom Yuhas, CT Department of Administrative Services (DAS), discussions on January 11 and 19, 2006.
- 4.3 Mike Sanders, ConnDOT, discussion on December 28.
- 4.4 2004 Traffic Volumes, State Maintained Highway Network (Traffic Log) prepared by Division of Planning Inventory and Data, Bureau of Policy and Planning ConnDOT.

- 4.5 Survey results provided by Elizabeth A. Lagosh, Transportation Planner, ConnDOT, March 20, 2006 email.
- 4.6 E-mail from Paul A. Buckley, Transportation Supervisory Planner, CONNDot, April 3, 2006.
- 4.7 Connecticut Statewide Rest Area and Service Plaza Study website.
<http://www.ctrestareas.org>
- 4.8 Chandler, Kevin, Kevin Walkowicz and Nigel Clark. 2002. *UPS Truck Fleet Final Results, DOE/NREL Truck Evaluation Report*. August 2002.
- 4.9 Discussion with Jim Volk, Praxair on January 20, 2006.
- 4.10 Ohi, James. *Strategic Planning and Implementation*. Proceedings of the 2002 Department of Energy Hydrogen Program Review, NREL/CP 610-32405
- 4.11 Information from Dante Bonaquist, Praxair.

CHAPTER 5: CONCERNS OF INTERESTED PARTIES

- 5.1 Vincent, Bill. 2004. *Hydrogen and the Law, Safety and Liability*. Breakthrough Technologies Institute, June 11, 2004 at George Washington University Law School.
- 5.2 "New Mexico to Operate State Liability Program for Hydrogen Energy Systems." *Fuel Cell Today*, 14 February 2006.
- 5.3 King, Joseph M. and Michael J. O'Day. Applying fuel cell experience to sustainable power products. *Journal of Power Sources*, March 2000 Volume 86/1-2.
- 5.4 Shell Venster. "Lighthouses for Hydrogen." November 2004.
- 5.5 February 11 press release at <http://www.nmhbc.org/news.html>
- 5.6 *Review of the Research Program of the FreedomCAR and Fuel Partnership, First Report by Committee on Review of the FreedomCAR and Fuel Research Program, Phase 1 of the National Research Council of the National Academies, 2005*
- 5.7 London Hydrogen Partnership website. http://www.lhp.org.uk/article_flat.fcm?subsite=1676&articleid=170
- 5.8 *Reference 2005 World Wide Fuel Cell Survey*, US Fuel Cell Council
- 5.9 UTC Power website. <http://www.utcpower.com>
- 5.10 Proton Energy Systems website. <http://www.protonenergy.com>
- 5.11 FuelCell Energy website. <http://www.fuelcellenergy.com>
- 5.12 August 3, 2005 FuelCell Energy Press Release
- 5.13 Praxair website. <http://www.praxair.com>

- 5.14 Hamilton Sundstrand Corporation website. <http://www.hamiltonsundstrandcorp.com>
- 5.15 Treadwell Corporation website. <http://www.treadwellcorp.com>
- 5.16 Connecticut Global Fuel Cell Center website. <http://www.ctfuelcell.uconn.edu>
- 5.17 Naugatuck Valley Communit College website. <http://www.nvctc.commnet.edu>
- 5.18 Connecticut Hydrogen-Fuel Cell Coalition website. <http://www.ccat.us/chfcc.htm>
- 5.19 Connecticut Clean Energy Fund website. www.ctcleanenergy.com
- 5.20 Connecticut Innovations website. www.ctinnovations.com
- 5.21 "Companies To Get Incentives To Produce Their Own Power." *Hartford Courant*, March 28, 2006
- 5.22 Presentations to National Hydrogen Association Conference, March 2006 and press releases from Mobile Energy Solutions and Avalence LLC, September 2005.
- 5.23 CTTransit Request for Proposal \$09-06 dated April 24, 2006.
- 5.24 "Fuel cell technology comes to state's roads." *Stamford Advocate*, May 7, 2006
- 5.25 Connecticut Energy Advisory Board. 2006. *Energy Plan for Connecticut*.
- 5.26 Connecticut Transportation Strategy Board. *Connecticut's Transportation Strategy: 2003 through 2023*.
- 5.27 Governor's Steering Committee on Climate Change. *Connecticut Climate Change Action Plan 2005*.
- 5.28 "Renewable Energy Technology Gains Allure." *The Connecticut Tech Tribune*, May 2006.

CHAPTER 6: SUMMARY OF FINDINGS AND CONCLUDING REMARKS

- 6.1 "East Coast leaders work to create Boston to D. C. 'hydrogen highway'" *Allentown Morning Call*, March 5, 2000.
- 6.2 US Department of Energy website. "Hydrogen, Fuel Cells & Infrastructure Technologies." <http://www.eere.doe.gov/hydrogenandfuelcells>
- 6.3 Fuel Cell/Hydrogen Infrastructure Codes and Standards website. <http://www.fuelcellstandards.com>

APPENDIX A: HYDROGEN CHARACTERISTICS

- A.1 <http://www.eere.energy.gov/hydrogenandfuelcells/education/properties.html>
- A.2 <http://www.eere.energy.gov/afdc/pdfs/fueltable.pdf>.
- A.3 http://www.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm01r0.pdf

APPENDIX D: EXPERIENCE WITH NON-TRADITIONAL TRANSPORTATION FUELS AND TECHNOLOGIES

- D.1 Department of Energy Alternative Fuel Transportation Program: Final Rule, 10CFR part 490, March 14, 1996.
- D.2 Executive Order 13149.
- D.3 New York State Executive Order Number 111 “Green and Clean” State Buildings and Guidelines, Second Edition, December 2004.
- D.4 CT General Statutes 12-412-67.
- D.5 CT General Statutes 12-2171.
- D.6 HR6: Sec.1341.
- D.7 Section 1342 of the Energy Policy Act of 2005.
- D.8 CT General Statutes 12-412-67, 68, 69, and 115.
- D.9 CT General Statutes 12-2171.
- D.10 Connecticut Climate Change, Short Term Actions for Implementation to Reduce Greenhouse Gas Emissions in Connecticut.
- D.11 International Association for Natural Gas Vehicles website. <http://www.iangv.org/>
- D.12 New York City Transit website. “New York City Transit and the Environment.”
<http://www.mta.info/nyct/facts/ffenvironment.htm>
- D.13 Massachusetts numbers based on discussion with Mike Manning, Chair of the New England Natural Gas Vehicle Coalition on January 17, 2006.
- D.14 UPS Truck Fleet Final Results, DOE/NREL Truck Evaluation Report, Kevin Chandler, Battelle, Kevin Walkowicz, National Renewable Energy Laboratory, Nigel Clark, West Virginia University, August 2002
- D.15 Discussion with Peter Polubaitko, Project Manager, Norwich community Development Corporation on January 10, 2006
- D.16 2004 UPS Corporate Sustainability Report.
- D.17 Donald A. Larsen, Division of Research, ConnDOT discussion on February 6, 2006.
- D.18 Alternative Fuel Station Locator. http://afdcmap.nrel.gov/locator/station_instructions.htm
- D.19 Discussion with Tom Santa, Santa Energy Services on January 16, 2006.
- D.20 Discussion with Chris Canavan, owner, Greenwich Automotive, on January 6, 2006.

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REFERENCES, NOTES AND ACKNOWLEDGEMENTS

- D.21 Conversation with Joseph Darling, New York DOT on January 17, 2006.
- D.22 Gladstein, Cliff. 2004. "Interstate Clean Transportation Corridor: Update." Presented to Natural Gas Vehicle Technology Forum Technical Committee meeting in Sacramento, CA, April 15 2004.
- D.23 "Ford to Create new Midwest Ethanol Corridor." PR Newswire February 8, 2006
- D.24 Conversation with Janice Snyder of DOT on January 12, 2006.
- D.25 Farrell, Alexander E., et al. 2006. "Ethanol Can Contribute to Energy and Environmental Goals". *Science*, January 27, 2006, Volume 311.
- D.26 National Biodiesel Board website. <http://www.biodiesel.org>
- D.27 Conversation with Ronald Thresher, Manager Corporate Transportation, Northeast Utilities System on February 13, 2006.
- D.28 "French develop diesel-electric hybrids." <http://www.whatcar.com>. January 31, 2006.
- D.29 Specifications for Toyota Prius and Honda Insight.
- D.30 Discussion with Tom Yuhas, DAS on January 19, 2006.
- D.31 Connecticut Academy of Science and Engineering. 2001. *A Study of Bus Propulsion Technologies Applicable in Connecticut*.
- D.32 Conversation with Steve Warren, CTTransit on January 19, 2005.

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