

Strategy for the Integration of Hydrogen as a Vehicle Fuel into the Existing Natural Gas Vehicle Fueling Infrastructure of the Interstate Clean Transportation Corridor Project

April 22, 2004 — August 31, 2005

Gladstein, Neandross & Associates
Santa Monica, California

Subcontract Report
NREL/SR-540-38720
September 2005

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



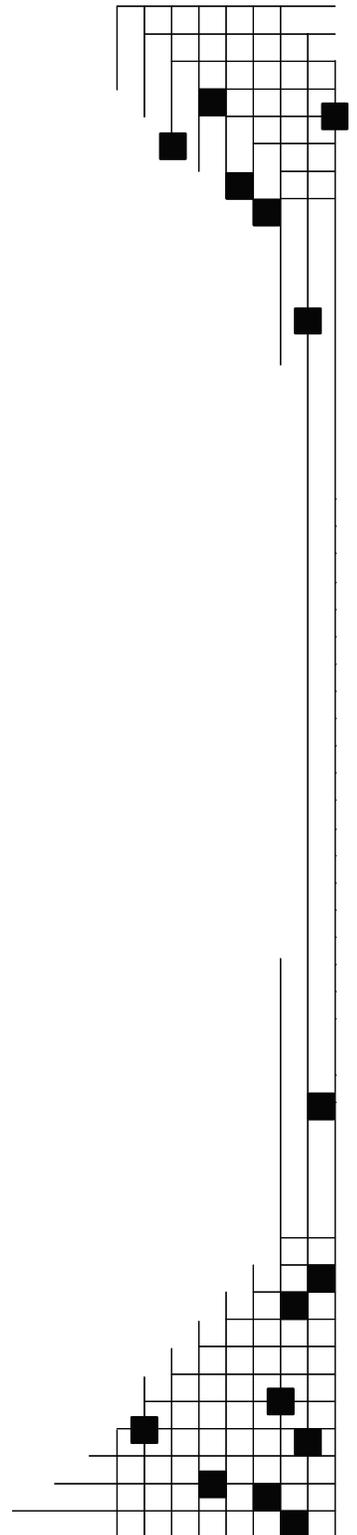
Strategy for the Integration of Hydrogen as a Vehicle Fuel into the Existing Natural Gas Vehicle Fueling Infrastructure of the Interstate Clean Transportation Corridor Project

April 22, 2004 — August 31, 2005

*Gladstein, Neandross & Associates
Santa Monica, California*

NREL Technical Monitor: R. Parish
Prepared under Subcontract No. LCM-4-44175-01

Subcontract Report
NREL/SR-540-38720
September 2005



National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>

This publication received minimal editorial review at NREL



Table of Contents

Table of Contents.....	i
Index of Tables and Figures.....	ii
Executive Summary.....	iv
Introduction and Background.....	1
Scope of Work.....	4
Opportunities and Challenges to the Integration of Hydrogen into the ICTC.....	7
Criteria for Selection.....	18
Prospective Targets for NG-H ₂ Demonstrations.....	22
Integration of ICTC NG-H ₂ Sites into Existing Hydrogen Development Efforts.....	30
Hydrogen Reformation from Natural Gas.....	32
Potential Site Issues.....	34
Site Specific Recommendations.....	37
Vehicle Integration Issues.....	38
Projected Program Costs.....	43
Next Steps.....	45
Conclusion.....	48
Bibliography.....	51
Appendix A - Leading Programs to Promote Hydrogen Vehicles.....	52
Appendix B - Possible Funding Sources for Hydrogen Vehicle and Infrastructure Projects.....	60
Appendix C - California Fuel Cell Partnership Map of Current Hydrogen Vehicle & Station Development Projects.....	66
Appendix D - Map of Current Hydrogen Vehicle & Station Development Projects with Proposed ICTC Hydrogen Demonstration Projects Added.....	67

Index of Tables and Figures

List of Figures

Figure 1: USA Waste in Fresno	23
Figure 2: Harris Ranch.....	29
Figure 3. Sunline Transit’s fuel cell powered Z-Bus at its hydrogen fueling station	50
Figure 4: SCAQMD Hydrogen Fueling Station Projects	53

List of Tables

Table 1: Constituents in Natural Gas	10
Table 2: Average LNG Composition for California Vehicle Fuel	11
Table 3: Energy Densities of Comparative Fuels	13
Table 4: Weight to Volume Ratios for Hydrogen.....	13
Table 5: Comparable Energy Content.....	14
Table 6: Hydrogen Costs & Transportation Fuel Equivalents.....	17
Table 7: Projected Costs for HCNG Vehicle Demonstration Project.....	44
Table 8: SCAQMD “Five Cities” Funders	52
Table 9: South Coast AQMD Projects.....	52
Table 10: California Fuel Cell Partnership Projects	54
Table 11: DOE Hydrogen Fleet and Infrastructure Demonstration.....	57

List of Acronyms and Abbreviations

AFV	alternative fuel vehicle
ASME	American Society of Mechanical Engineers
ATR	autothermal reformation
Btu	British thermal unit
CA 99	California State Highway 99
CaFCP	California Fuel Cell Partnership
CAP	Clean Air Power
CARB	California Air Resources Board
CH ₄	methane
CHG	compressed hydrogen gas
CNG	compressed natural gas
CO ₂	carbon dioxide
CTI	Collier Technologies, Inc.
CVI TM	Constant Volume Injection TM
CWI	Cummins Westport, Inc.
DOE	U.S. Department of Energy
GGE	gasoline gallon equivalents
GNA	Gladstein, Neandross & Associates
H ₂	hydrogen
HCNG	fuel blend of hydrogen and natural gas
ICE	internal combustion engine
ICTC	Interstate Clean Transportation Corridor
kg	kilogram
LCNG	liquefied/compressed natural gas
LHG	liquid hydrogen gas
LNG	liquefied natural gas
MDAQMD	Mojave Desert Air Quality Management District
NG-H ₂	natural gas/hydrogen
NMHC	non-methane hydrocarbons
NO _x	nitrogen oxides
NREL	National Renewable Energy Laboratory
PEM	proton exchange membrane
PM	particulate matter
psi	pounds per square inch
psig	pounds per square inch gage
SCAQMD	South Coast Air Quality Management District
SMR	steam methane reformer
TRU	transportation refrigeration units
WI	Westport Innovations

Executive Summary

The U.S. Department of Energy (DOE) funds research and development that reduces U.S. dependence on imported petroleum and promotes better air quality. The work described in this report was supported through DOE's National Renewable Energy Laboratory (NREL).

NREL has contracted with Gladstein, Neandross & Associates (GNA) to survey opportunities to integrate hydrogen into the natural gas vehicles and fueling stations of the Interstate Clean Transportation Corridor (ICTC). The ICTC is an existing network of over 600 heavy-duty trucks and 20 fueling stations in California and Nevada that are fueled by liquefied natural gas (LNG). This project is intended to lay the groundwork for natural gas-hydrogen fueling infrastructure along the existing ICTC to facilitate the introduction and commercialization of hydrogen vehicles along this route.

The objective of this study is to evaluate whether the existing vehicle stock and fueling infrastructure of the ICTC can help form the foundation for the development of the "hydrogen highway" that many policy makers and stakeholders are interested in creating. This paper evaluates the potential for "piggy-backing" early hydrogen production, dispensing, and consumption onto the already successfully deployed natural gas vehicle projects pioneered by the ICTC. In addition, the authors have made recommendations for five specific demonstration projects (four primary and one alternate) that use existing ICTC fleets and infrastructure for hydrogen technology development. If successful, these demonstration projects could help smooth the way for the integration of hydrogen into the transportation sector by helping to reduce its cost, establish initial consumers, and provide early demand for hydrogen production. In addition, this project could provide the benefit of stimulating the development of technologies that could aid in accelerating the introduction of hydrogen-capable heavy-duty vehicles, and will help fill gaps in projected future hydrogen fueling infrastructure.

The authors have surveyed the infrastructure and deployment activities in the ICTC project and have determined that several of these sites will make excellent platforms for future hydrogen demonstration projects. These platform sites are all located in California, and include Harris Ranch near Coalinga, the City of Tulare, the City of Barstow, and USA Waste in Fresno. An alternate site has also been identified at the UPS facility in Ontario. Each of these sites enjoys substantial advantages for potential future hydrogen technology demonstration and deployment, including the strategic importance of the location, the willingness of the fleet operator to participate in a demonstration project, and the potential ease with which hydrogen dispensing or on-board fueling technology can be integrated into existing assets.

Introduction and Background

The U.S. Department of Energy's (DOE) FreedomCAR and Vehicle Technologies Program is working to reduce U.S. dependence on imported petroleum and improve air quality. DOE's National Renewable Energy Laboratory (NREL), led by the Center for Transportation Technologies and Systems, has the goal to help industry introduce alternative fueled vehicles into the marketplace by working with public and private organizations to develop and demonstrate innovative technologies to help reduce the nation's dependence on imported oil.

Developing alternatives to petroleum, particularly in transportation, which accounts for 80% of the nation's oil consumption, has never been more important. Although the nation is more energy efficient than it was during the energy crises of the 1970s, the health of our economy still depends on the price of a barrel of oil. In June, 2005 the spot price for a barrel of oil topped \$60, a historic high.¹ Given increased demand for petroleum, particularly in Asia, coupled with growing political instability in the Middle East and other oil producing countries, oil markets are expected to remain extremely volatile.

As the 20th Century came to a close, natural gas had emerged as the alternative fuel of choice, particularly as a substitute for diesel in heavy-duty trucks and buses. Over the last five years, however, much of the momentum enjoyed by natural gas as a transportation fuel has dissipated. Unfortunately, oil is not the only fossil fuel that has seen unprecedented price increases. The tripling of natural gas prices since 1999 has stalled efforts to promote methane as a transportation fuel.² Most energy analysts believe that current trends in fossil fuel prices are likely to continue for the foreseeable future.

One of the positive developments that resulted from escalating energy prices is renewed interest in the development of alternative vehicle fuels. In part driven by the simultaneous rise in oil and natural gas prices, and in part driven by the relentless effort on the part of the State of California to compel auto manufacturers to produce vehicles that emit zero or near zero pollutants, hydrogen has emerged as the primary future alternative fuel for policy makers and the transportation industry.

Hydrogen as a vehicle fuel presents many exciting and fascinating possibilities. Hydrogen is a ubiquitous element, found virtually everywhere, but always bound with other elements. Hydrogen is most prevalent in water, presenting the very real possibility of a virtually unlimited supply of energy from seawater. Hydrogen can either be burned in conventional internal combustion engines (ICEs) or used in fuel cells—devices that produce direct electrical current from electrochemical reaction. In either instance, the amount of pollution that results is dramatically less than that produced by contemporary

¹ See Jad Mouawad, "Oil Settles Over \$60 a Barrel As Iran News Rattles Market", New York Times, June 28, 2005, Section C, Page 9, Column 1. See the United States Energy Information Administration, [http://tonto.eia.doe.gov/oog/info/twip/'1-TWIP Crude Spot Prices!A1](http://tonto.eia.doe.gov/oog/info/twip/'1-TWIP%20Crude%20Spot%20Prices!A1) for details on crude spot prices.

² As of this writing, the cost of a 48-month contract beginning in August 2005 for natural gas at the Southern California Border was \$7.77 MMBTU. In contrast, in 1999 the same contract would cost a buyer \$2.32, a 235% increase.

vehicle technology. The promise of abundant, clean energy has been the focus of numerous research, development, and demonstration efforts recently.

Unfortunately, hydrogen will take a long time to develop into a viable alternative to conventional gasoline and diesel in cars, trucks, and buses. There are many unsolved issues associated with converting the nation's transportation infrastructure into a hydrogen-based system. The major auto manufacturers project that fuel cell vehicles will not begin to reach showrooms until 2012 at the earliest, with most carmakers predicting significant product offerings only after 2015. Vehicles equipped with ICEs fueled by hydrogen may make it to market earlier, but without a fueling infrastructure to support them, it is unlikely that these vehicles will make much of a showing. Hydrogen-fueled heavy-duty vehicles, particularly trucks, are expected to take even longer to make it to market.

To help resolve these issues, DOE's Hydrogen, Fuel Cells, & Infrastructure Program is working to validate system solutions for the use of hydrogen as a vehicle fuel as part of the Bush Administration's Hydrogen Fuel Initiative. One possible solution is to learn from the similar challenges experienced by natural gas vehicles, particularly when it comes to the issue of infrastructure. Since hydrogen fueling is different from that currently in use for diesel and gasoline, it will require the development of a vast new fueling infrastructure that is at least as comprehensive and convenient as the infrastructure that exists for today's vehicles.

Fortunately, the hydrogen future does not have to start from scratch. The groundwork for hydrogen infrastructure has already been laid, and it can be found at every natural gas fueling station and, in part, in many of the natural gas vehicles that are currently on the road. Natural gas vehicles and fueling infrastructure provide hydrogen proponents with a solid base upon which to introduce early hydrogen production and dispensing technology, while many heavy-duty natural gas vehicles present an opportunity to build early markets for hydrogen as a transportation fuel. Rather than starting at the bottom of the hill, hydrogen can take advantage of existing assets to begin the journey to commercialization from mid-way up the slope.

Existing natural gas fueling facilities can be used for several purposes. First, they can be used to provide the feedstock for the production of hydrogen. Second, they can be used as a platform upon which to build future hydrogen dispensing sites. Third, they can be used to provide access to potential early adopters of 1st generation hydrogen vehicle technology. Existing natural gas vehicles can be modified to use a mixture of hydrogen and natural gas (HCNG) which will help stimulate the development of hydrogen reformation and dispensing infrastructure. The combination of HCNG infrastructure and natural gas/hydrogen (NG-H₂) vehicles may prove to be essential for nurturing the infancy of the future hydrogen highway.

This approach to the hydrogen future is a path less traveled. Most programs focus on either light-duty or transit vehicles that use pure hydrogen in either an ICE or a fuel cell power plant. In addition, more public resources are being invested in renewable hydrogen

production technology than hydrogen from conventional fuels. Although important, these approaches may be ignoring a critical path to the hydrogen future. Light-duty vehicles do not consume the volumes of fuel necessary to make early fueling infrastructure economically viable, and renewable hydrogen is and will be very expensive for the foreseeable future. Lessons that have been learned by previous waves of alternative fuel technology development and deployment have a great deal to teach proponents of hydrogen in transportation.

NREL is interested in exploring the potential to use existing natural gas infrastructure for future hydrogen development; in particular the viability of HCNG. NREL and DOE recently completed a research project in partnership with Cummins-Westport, Inc. and SunLine Transit, to evaluate HCNG blends. This project demonstrated that not only is a HCNG blend a viable fuel, but it also has the potential to yield significant emission reduction benefits.³

The results of the SunLine Transit project show the tremendous promise for HCNG and for utilizing existing infrastructure and vehicles to nurture the development of the hydrogen highway. Further demonstration of how existing fleets of heavy-duty natural gas trucks and the fueling sites that serve them can help accelerate the commercialization of hydrogen in transportation as well as lead the way for the development of hydrogen production sites and hydrogen dispensing facilities.

An ideal platform for this effort is the Interstate Clean Transportation Corridor (ICTC). This is desirable for many reasons.

- First, since ICTC fleets are located along the transportation corridors between Las Vegas, Los Angeles, and San Francisco/Sacramento metropolitan areas, any effort can easily be coordinated to several of the nation's leading hydrogen highway development programs. The State of California and the South Coast Air Quality Management District (SCAQMD) have already expressed strong commitments to the transition to hydrogen and have plans for several hydrogen stations along the ICTC, providing a good opportunity for partnership in hydrogen projects.
- Second, since the ICTC Project is the nation's most successful effort to promote the use of clean alternative fuels in heavy-duty vehicles involved in goods movement, it makes sense to try and piggyback hydrogen onto the accomplishments of this program. The ICTC has an established model that works, and has thrived in the arena of coordinating fleets, fuel providers, infrastructure developers, government agencies, funding partners, and other interested stakeholders.
- Third, because of the ICTC's past success in the natural gas arena, it is likely that the project will be able to capitalize on the relationships it has developed over the years to integrate hydrogen into existing deployments.
- Fourth, most of the vehicles that the ICTC Project has helped to deploy are good candidates for modifications that will enable them to demonstrate HCNG.

³ Using a Twenty percent (20%) blend of H₂ mixed with Eighty percent (80%) CNG reduced NO_x emissions by Fifty percent (50%) vs. the emissions from the baseline natural gas engine.

- Finally, the fleets that have worked with the ICTC Project understand what is involved with purchasing and operating a new technology, and are more apt to be prepared for the ups and downs of a demonstration project. They've tried new fuels before, and will therefore be easier to work with.

As director of the ICTC Project, GNA was retained by NREL to evaluate opportunities to integrate hydrogen into the ICTC, determine the barriers to such an effort, and provide outlines for at least four specific projects that would utilize existing ICTC infrastructure to demonstrate the production of hydrogen from natural gas and the use of that hydrogen in either ICTC or new vehicles. Specifically, the objectives of this project are:

1. Work with stakeholders to identify key locations along the ICTC where existing natural gas fueling stations and fleets would make good candidates for NG-H₂ stations;
2. Work with existing ICTC stakeholders to evaluate interest in participating in potential HCNG demonstration projects;
3. Identify station specifications and configuration, site challenges, and applicable codes and standards for each of the proposed stations that have been identified in the first two objectives.

Scope of Work

To achieve the objectives outlined above, NREL and GNA developed a scope of work that is primarily focused on analyzing existing assets and developing proposals for how these assets can be modified to produce, dispense, and/or use hydrogen. The two primary tasks in this scope of work are to identify key locations and potential partners along the ICTC corridor for HCNG stations, and then, once identified, to describe the requirements for each of the proposed HCNG stations recommended.

Task 1 involved determining which existing sites in the ICTC Project would make good prospects for possible future HCNG demonstration projects. There were several subtasks that were necessary to accomplish Task 1. These include:

- Development and maintenance of an ongoing list of contacts with stakeholders who might be interested in participating in the HCNG demonstration projects identified by this effort. This list of contacts shall be known as the ICTC HCNG Database. This list of stakeholders is summarized in Appendix E.

GNA's database includes detailed information about every fleet that operates LNG vehicles in the United States, as well as many that operate compressed natural gas (CNG) vehicles and fueling facilities in California. GNA has used its existing database of ICTC stakeholders and expanded it to include contact information about existing and planned H₂ fueling infrastructure, H₂ ICE, and fuel cell vehicle demonstration projects in the three-state area (AZ, CA, and NV) of the ICTC Project. The database also includes other

stakeholders in the hydrogen highway arena, such as public agencies, vendors, fuel providers, and other parties that are engaged in natural gas and H₂ vehicle and fuel production, mobile fuel cell technology, and other related activities. The database does not, however, replicate the list of participants in Governor Schwarzenegger's California Hydrogen Highway collaborative, but focuses on the stakeholders of relevance to proposed integration of hydrogen into the ICTC. The list shall be updated on a regular basis to ensure that it is fresh and comprehensive.

- *Identification of key fueling sites and potential partners along the ICTC corridor for NG-H₂ stations.* This step involved an evaluation of the 23 natural gas deployment projects facilitated by the ICTC project for their compatibility with, interest in, and ease with which a hydrogen demonstration project might be integrated into the site. Also included in this task is the development and presentation of selection criteria that provide the rationale for the selection of each of the potential NG-H₂ sites proposed by this study.
- *Development of a map that identifies the location of the existing, proposed and potential NG-H₂ stations/demonstration projects along the ICTC.* Existing stations/demonstration projects would include those that have been pioneered by one of the several existing efforts now in play in the ICTC project area. Proposed stations/demonstration projects would include those that are planned or which have been proposed by the aforementioned hydrogen development programs. Potential stations/demonstration projects are those that are proposed in this report.

Included in this task is the development of maps that show the location of each proposed ICTC NG-H₂ project from various levels: statewide, region-wide; and street level (proximity to the corridor). This map can be found in Appendix D.

Task 2 revolved around developing specific proposals for NG-H₂ demonstration projects from the sites that were identified in the first set of tasks. There were several subtasks that were necessary to complete Task 2. These include:

- *Compilation of the steps that would be needed to enable each of the potential ICTC NG-H₂ demonstration projects to be successful.* Each of these plans would be a custom research, development, and deployment (RD&D) project, and include details pertaining to what is required to secure the participation of fleet operators, integrate H₂ into the facility, attract users for the H₂, and technological developments that would be needed to ensure a successful demonstration project.

The process whereby this task was undertaken involved the collection of the station, vehicle, and other relevant specifications from each of the stations identified in Task 1. These specifications include information about the owner, operator, and/or developer of the station, when the facility was built, the technology that is used there, the operating parameters, and other pertinent information. Those who were responsible for the construction and maintenance of

each facility have been contacted to discuss the steps that would be needed to integrate both small-scale natural gas reformation technology and/or a H₂ dispenser into the fueling infrastructure.

- *Research into the technologies that are needed to upgrade existing ICTC fueling facilities and vehicles to be able to utilize hydrogen.* This involved an investigation into the technologies needed to enable existing ICTC facilities to produce and store hydrogen from natural gas, the modifications necessary to upgrade existing natural gas fueling stations to be capable of dispensing both natural gas and hydrogen, retrofits that would enable existing natural gas vehicles to use hydrogen in their existing natural gas engines, and the availability of units that would mix natural gas and hydrogen both off- and on-board the vehicle. To the extent that they are available, cost estimates for both materials and labor have been included.
- In those instances where needed technology has not yet been developed, the research, development, testing, and demonstration requirements have been identified, including parties who have expressed interest in participating. Where possible and where information is available, projected costs and timelines for these RD&D efforts have been identified.
- *Development of a final report that summarizes all of the information collected from the tasks outlined above which identifies next steps, including a budget and timeline, for the implementation of NG-H₂ stations identified in Task 1 and 2.* This report includes specific recommendations on how NREL and DOE should proceed to implement the suggested next steps. A budget has been developed to provide detail on the projected costs of adding H₂ capability at every selected ICTC station, as well as the projected costs of integrating NG-H₂ blending technology on existing ICTC LNG trucks. A projection of the time that would be required to achieve these objectives, highlighting critical milestones is in the process.

Opportunities and Challenges to the Integration of Hydrogen into the ICTC

The ICTC presents both unique opportunities and challenges to the development of hydrogen fueling capability as well as hydrogen consumption in existing vehicles.

Opportunities

Every ICTC station presents an opportunity to create hydrogen production at a facility already utilized by a fleet familiar with the challenges and benefits of alternative fuel vehicle use. Most ICTC stations are in strategic locations along the state's most traveled transportation corridors. Finally, every ICTC station can be modified or expanded to dispense hydrogen (whether reformed from natural gas or delivered from some other source), and most of the heavy-duty trucks on the ICTC corridor can be modified to run off a combination of natural gas and hydrogen.

The ICTC Project is one of the few developed by the DOE that focuses on expanding the use of clean, alternative fuels in interstate goods movement. This is a sector that is generally not talked about when advocates promote the hydrogen highway, because hydrogen is not a good heavy-duty vehicle fuel. **Yet, heavy-duty trucks make excellent targets for alternative fuel vehicle development.** This is due to a confluence of factors that is often overlooked when policy makers and private stakeholders attempt to articulate their vision of how to facilitate and accelerate the advent of the hydrogen transportation future. These factors are described below.

Centralized Fleets

Heavy-duty trucks tend to be organized in fleets. Large aggregations of the same or similar vehicles provide several important structural opportunities familiar to those experienced in trying to build markets for alternative fuel vehicles. These include:

- **Return-to-Base.** Many heavy-duty truck fleets operate out of a home depot where the vehicles are housed overnight or on a regular basis. This enables fleet owners to concentrate fueling, maintenance, and repair activities, and makes it much easier on those who are trying to introduce new technology.
- **Centralized Fueling.** New alternative fuel vehicles need specialized fueling infrastructure. Return-to-base fleets have the advantage of coming back to the same location to fuel every day. This enables stakeholders to develop fueling stations deliberately and strategically.
- **Central Management and Control.** Fleets are generally controlled by a single decision maker, which provides substantial advantages when attempting to develop a demonstration project. In addition, centralized management presents opportunities for monitoring and data collection that would be much more difficult in other settings.

Prodigious Fuel Consumption

Investment in a new alternative fuel infrastructure is an expensive endeavor. Processing high volumes of fuel through these facilities both helps amortize the investment as well as ensure a long useful life for the facility. High utilization also helps to attract more private sector investment in the technology. Heavy-duty vehicles tend to consume prodigious volumes of fuel – they have one quarter the fuel efficiency of the average light-duty vehicle and are also inclined toward much higher annual mileage.

The fleets in the ICTC offer the kind of fuel consumption needed to justify investment in new technology. On average, ICTC trucks travel nearly 90,000 miles per year. They present an attractive platform on which to test and demonstrate hydrogen technology, as well as an opportunity to build critical hydrogen dispensing infrastructure.

Corridor Travel

Strategies for alternative fuel vehicle commercialization often envision the development of support infrastructure along major transportation corridors. This objective is facilitated by fixing attention on those vehicles who most often utilize these corridors and whose purpose is to travel between cities and states. Heavy-duty trucks are designed to carry goods long distances, and are much more likely to regularly use major transportation corridors than their smaller, light-duty cousins.

Serve a Larger Vehicle Population

Once hydrogen is produced and stored at an existing ICTC natural gas facility, it becomes a potential fuel for a variety of vehicles. It can be used to supply not only the heavy-duty trucks that result from the demonstration projects recommended here, but other hydrogen-consuming vehicles as well. In particular, local public and private fleets that are interested in purchasing first generation hydrogen ICE or fuel cell vehicles can also utilize hydrogen from ICTC stations. Seeking to leverage the existence of new, alternative fueling infrastructure is one of the primary missions of the ICTC Project. In particular, if local light-duty or transit fleet operators see that there is a local source of hydrogen, they may be more open to the idea of experimentation with these new transportation technologies.

These elements help make the ICTC Project an important potential tool for advancing hydrogen transportation technology. The strategic opportunity presented by using the ICTC as a platform upon which to launch the both the development of hydrogen infrastructure as well as encourage the consumption of hydrogen is clear.

Public Accessibility

Each of the stations that have been developed by the ICTC has the advantage of already providing public access to the existing fueling infrastructure. As these arrangements have already been negotiated, it would be natural for the facilities to provide public access to whatever hydrogen fueling capability is added to the ICTC facilities.

Existing Fleet

Since all of the fleets in the ICTC have already built LNG fueling infrastructure and deployed LNG trucks, the managers and drivers are already familiar with the use of alternative fuels. This is a tremendous advantage when trying to develop interest in a new transportation technology. One of the key elements of a successful alternative fuel vehicle deployment project is the comfort and acceptance of the drivers, mechanics, dispatchers, and other fleet managers with the technology. All ICTC fleets have been successful, and thus are poised for early adoption of hydrogen technology.

Existing ICTC fleets are not the only key players whose comfort with alternative fuels is essential to a successful deployment project. Local fire, planning, building, and safety and other permitting agencies are critical to the successful development of an alternative fuel vehicle (AFV) fleet. In the case of ICTC fleets, these critical agencies have already gone through the education process necessary to become familiar with high pressure and/or cryogenic fuels. They are far more likely to be accepting of hydrogen fueling stations and vehicles than their counterparts with no such experience. Thus, existing experience, both at the fleet and the permitting agency level, are significant advantages brought to hydrogen development by working with the ICTC.

The Advantages of LNG

All of the stations that have been developed by the ICTC in California offer LNG storage and dispensing. Some are equipped with the ability to dispense methane as CNG from the LNG stored on site (also known as LCNG facilities). Having LNG on site not only does not present problems for hydrogen production, but also presents several advantages for the development of hydrogen infrastructure.

LNG is a very “lean” form of natural gas. This term denotes natural gas that is high in methane content and contains relatively small amounts of more complex hydrocarbons (i.e. molecule chains that contain two, three, four, or more carbon atoms), inert gases (such as nitrogen or carbon dioxide), as well as other gases that might be harmful, such as sulfur. Natural gas that contains larger amounts of the heavier hydrocarbons, such as propane, ethane, and butane, are called “rich” gas. During the liquefaction process, most of the heavy hydrocarbons, inerts, and sulfur compounds typically found in natural gas as it is found in the ground are removed from the product stream. The result is a fuel that is virtually pure methane (> 98%), with minor amounts of ethane, propane, and nitrogen. Gas from a pipeline tends to be much richer (i.e. contains higher levels of the heavier hydrocarbons) than LNG (see Table 1). Rich gas burns hotter than lean gas, which can damage natural gas engine components, and presents a product management issue when reforming natural gas for hydrogen production.

Table 1: Constituents in Natural Gas

Constituent	CNG ¹	CNG ²	LNG ³
Methane	88%	92.84%	98.84%
Ethane	6%	3.22%	0.70%
Propane	3%	1.39%	0.06%
Nitrogen, CO2 and Inerts	4.5%	2.19%	0.22%
Other	1.4%	2.18% ⁴	0.49%

¹California Code of Regulations: Title 13, Division 3, Chapter 5, Article 3, Section 2292.5. This is the vehicle grade fuel specification. In the case of methane, the figure is the lower limit of methane content, while all of the other values are upper limits.

²Average CNG composition CARB bus tests, 2001. CARB conducted a series of emissions tests on CNG buses and these figure represent the average quality of gas that came out of the pipeline when these buses were tested.

³Monthly average from Topock, March 1999 thru March 2004. Topock, AZ, is the site of the Applied LNG Technologies natural gas liquefaction plant that provides most of the LNG supply to Southern California.

⁴Primarily Sulfur (H₂S)

Title 13, Section 2292.5 of the California Code of Regulations stipulates that pipeline natural gas must meet a minimum specification. Per this specification, natural gas in California typically has methane content of 88%, with the balance of the gas being comprised of 2% to 4% nitrogen, and no more than 6% ethane and no more than 3% propane. These requirements can be found in the CNG¹ column in Table 1. The CNG² column denotes the average composition of pipeline gas used in California. The LNG³ column shows the average composition of the LNG used as a transportation fuel in California. What is clear from this table is that LNG is far leaner and cleaner than pipeline natural gas, greatly reducing the potential problems that may arise when using natural gas as a feedstock for hydrogen.

Pipeline gas also presents another problem for hydrogen production. As required by the U.S. Department of Transportation, pipeline natural gas must also contain an odorant. To meet this requirement, typical pipeline natural gas is injected with methyl mercaptan, a strong odorant that allows one to easily smell if there is natural gas present. The chemical formula for methyl mercaptan is CH₄S, which is essentially a compound consisting of natural gas and sulfur. It is important to note that natural gas in its “natural” state typically does not contain sulfur. It is only because of pipeline safety regulations that sulfur components are added to the natural gas stream.

The presence of sulfur in the natural gas complicates the use of the fuel as a feedstock for hydrogen. If the natural gas is to be reformed in a standard steam reformer for the production of pure hydrogen, the sulfur must be removed. Sulfur contamination of hydrogen used in a fuel cell will adversely affect its performance and contributes to a much shorter useful life. To avoid “poisoning” the fuel cell with hydrogen fuel containing sulfur, investments must be made in “desulfurization” equipment in order to remove this sulfur prior to the reformation process. This adds cost and complication to the development of a hydrogen production facility.

LNG also avoids the problem of sulfur. LNG from a production facility does not contain sulfur as any natural sulfur in the gas stream is removed by the process of liquefaction.

LNG from pipeline gas also does not contain the odorant. Methyl mercaptan has a freezing point of -186°F, while methane does not liquefy until -260°F. Thus, the odorant is removed from the product.

When using LNG that is free from sulfur, the capital and operational costs of the sulfur removing equipment can be eliminated. Over the term of a project, this can lead to significantly reduced project costs. All of the suppliers of natural gas reformers interviewed for this report commented that there existed a definite advantage to using LNG instead of CNG due to eliminating the need to desulfurize the feed gas stream. Table 2 specifies the methane content of all of the major sources of LNG for the ICTC. As is evident from Table 2, the LNG that fuels the ICTC’s trucks has extremely high methane content, extremely low rich gas content, and virtually no sulfur, demonstrating that LNG used in the ICTC would be an excellent feedstock for hydrogen.

Table 2: Average LNG Composition for California Vehicle Fuel⁴

	Methane	Ethane	Propane	Nitrogen	Other
ALT N.M.	98.857%	0.697%	0.063%	0.203%	0.029%
BP Amoco	99.771%	0.083%	0.048%	0.067%	0.031%
Exxon	98.332%	0.000%	0.000%	1.668%	0.000%
Texas LNG	99.778%	0.000%	0.000%	0.226%	0.000%

The average gas quality of the LNG from each of the facilities, using monthly laboratory analysis taken from March 1999 through October 2004

Challenges

In order to develop a strategy for the successful integration of HCNG into the ICTC, it is also necessary to identify the challenges that must be overcome before the ICTC can realize this potential.

LNG Trucks

The ICTC is populated primarily by LNG trucks. This presents several challenges to the objective of integrating hydrogen into existing vehicles. Previously, the use of hydrogen in natural gas trucks has been restricted to vehicles fueled by CNG. For those vehicles, the blending of the CNG and hydrogen gas was done prior to the delivery of fuel onboard the vehicle.

⁴ Most of the LNG now being delivered to California for use in transportation is produced at Applied LNG Technologies’ “Needle Mountain” liquefier in Topock, Arizona. Other sources of LNG for the California transportation market include Exxon’s Shute Creek, Wyoming; BP Amoco’s Wyoming; and Texas LNG’s Willis, Texas facilities.

Enabling trucks that carry LNG in cryogenic tanks to blend natural gas with hydrogen creates a far more complicated and expensive puzzle. It is imperative to maintain LNG fueling systems onboard these vehicles. They were outfitted with LNG to provide the range they need and to avoid the installation of heavy high-pressure gas cylinders. Thus, starting from the premise that the vehicles' original LNG fueling system must be maintained, the dilemma becomes how to blend the natural gas and hydrogen. Although there is an experimental technology known as "Supercritical HythaneTM," that could deliver a blended cryogenic liquid onboard the vehicle containing both methane and hydrogen, it is not clear that this approach is ready for demonstration. Thus, the most promising approach to the integration of hydrogen into the ICTC would involve mixing hydrogen into the natural gas onboard the vehicle after it has been vaporized and before it is injected into the cylinders of the engine. These technologies are also in the experimental stage, but apparently would not involve the same kind of wholesale swap out of fueling systems that would be necessary with trying to manage cryogenic Hythane[®].

Another potential challenge presented by most ICTC trucks is that they are equipped with dual fuel engines. These are diesel engines (i.e. compression ignition) that have been outfitted with a second set of injectors for natural gas. In dual fuel engines, a small amount of diesel fuel is delivered to the cylinder along with a larger volume of natural gas during the compression stroke. The diesel ignites, kindling the natural gas, which provides most of the energy to force the piston downward. The two primary dual-fuel technologies, manufactured by Clean Air Power (CAP) and Westport Innovations (WI) are outfitted on Caterpillar and Cummins engines, respectively. Prior experience with NG-H₂ blends has been exclusively in spark-ignited engines. It is not clear what will happen when yet a third fuel is introduced into the mix.

On-Board Blending

Since the vast majority of trucks in the ICTC Project are fueled with LNG, and the goal of this effort is to use these existing trucks as a platform on which to build future demand for hydrogen fuel; the success of this strategy hinges on the ability to develop components that enable the blending of appropriate levels of hydrogen and natural gas onboard the vehicle. The mixing of the fuels can take place prior to injection in the cylinder, or at injection, but it must happen after the two fuels are delivered to their respective storage systems onboard the vehicle.

Accomplishing this objective will require the development of appropriate equipment for measuring, monitoring, and mixing the gas, keeping it at the optimal pressure, injectors that are capable of managing both gases, and other specialized technology. In addition, existing diagnostic equipment will have to be modified and control software revised in order to provide the necessary engine response to optimize performance. Clearly, the development of the on-board blending technology will be a significant challenge to integrating hydrogen into the ICTC.

Range

As mentioned above, the reason that LNG has become the dominant fuel in the ICTC is because it minimizes the weight penalty of alternative fuel use and it can provide range comparable to diesel in heavy-duty trucks. Unfortunately, introducing hydrogen into the fuel mix diminishes the energy content of the fuel, and will create a reduction in range. This is due to the fact that the energy density of hydrogen is significantly lower at similar volumes and pressures than the energy density of natural gas. This is illustrated in Table 3 below.

Table 3 – Energy Densities of Comparative Fuels

Fuel	Energy Density (LHV)
Hydrogen	270 Btu/ft ³ ; gas a 1 atm and 60°F 48,900 Btu/ft ³ ; gas a 3,000 psig and 60°F 121,000 Btu/ft ³ ; gas a 10,000 psig and 60°F 227,850 Btu/ft ³ liquid
Methane	875 Btu/ft ³ ; gas a 1 atm and 60°F 184,100 Btu/ft ³ ; gas a 3,000 psig and 60°F 561,500 Btu/ft ³ liquid
Propane	2,325 Btu/ft ³ ; gas a 1 atm and 60°F 630,400 Btu/ft ³ liquid
Gasoline	836,000 Btu/ft ³ liquid
Diesel	843,700 Btu/ft ³ liquid
Methanol	424,100 Btu/ft ³ liquid

Source: College of Desert, Hydrogen Fuel Cells and Related Technologies, Rev 0, December 2001, p. 1-16

The result of the lower energy density of hydrogen means that if hydrogen is used to replace an existing volume of another transportation fuel, the range of the vehicle will diminish. This outcome was documented during the SunLine Transit experiment with Hythane[®]. In that project, two natural gas buses equipped with Cummins Westport Inc.'s B Gas Plus engine were modified to accept a variety of natural gas/hydrogen mixtures (between 20% and 32% hydrogen). The storage capacity of the vehicles was not altered. As a result of replacing natural gas with hydrogen, the range of the demonstration buses dropped 13% to 15%. Table 4 below illustrates the approximate loss of range that would result by replacing an existing volume of natural gas with hydrogen. The table projects, for example, that if 14% of the volume of the existing natural gas cylinder was taken up by hydrogen, the energy density would only increase by 5%, resulting in an approximate 9% drop in range.

Table 4: Weight to Volume Ratios
for Hydrogen

Volume	Weight
14%	5%
20%	7%
29%	10%
34%	12%
42%	15%

Another example of the difficulties presented by the low energy density of hydrogen is presented in Table 4. Fleets that participate in the ICTC primarily are fueled by LNG. A gallon of LNG has approximately 84,000 BTU, compared with 126,000 BTU in the average gallon of diesel fuel or 114,000 BTU in the average gallon of gasoline. By comparison, the average gallon of liquid hydrogen gas (LHG) has only about 28,500 BTU. Thus, a LHG-fueled truck with the same storage capacity as an LNG truck would only have about 34% of the range of its LNG counterpart. That same LNG truck would only have 22.5% of the range of a diesel-fueled vehicle. The low energy density of hydrogen presents major problems for the proliferation of the technology in the goods movement industry.

Table 5: Comparable Energy Content

	BTU	% of Diesel	% of Gasoline	% of LNG
Diesel	126,000	100.00%	110.53%	150.00%
Gasoline	114,000	90.48%	100.00%	135.71%
LNG	84,000	66.67%	73.68%	100.00%
LHG	28,500	22.62%	25.00%	33.93%
CHG (@ 3600 psi)	7,980	6.33%	7.00%	9.50%
CHG (@ 10000 psi)	17,100	13.57%	15.00%	20.36%

The only way to effectively deal with this issue would be to keep the existing LNG fueling system intact and add sufficient hydrogen storage capacity to enable the injection of hydrogen into the fuel stream. Referring back to Table 4 above, if the hydrogen storage capacity on an existing ICTC truck was one fifth that of the existing natural gas system (i.e. 20% by volume), the range of the demonstration truck should increase by approximately 7%, because the actual increase of energy density on the vehicle would be 7%.

Augmenting the existing fueling system avoids several potential pitfalls. First, the only modification to the truck is the addition of hydrogen storage, an on-board blending device, and whatever upgrades to the engine software are needed. Second, since the truck will likely be needed for revenue service, all of these modifications can be easily undone once the demonstration is over. Finally, and most importantly, enhancing the performance of the vehicle is a much more persuasive and compelling argument to convince fleet operators to participate in a demonstration or to eventually purchase and deploy hydrogen-based technology. New transportation technology that does not perform at least as well as what they are using now will not gain market acceptance.

A 3,600 psi compressed hydrogen gas (CHG) storage system will augment the range of the existing on-board natural gas fueling system in an LNG truck between 6% and 9.5%, depending on the type of engine powering the vehicle (compression or spark ignition). Hydrogen storage at 10,000 psi should increase energy storage between 13.6% and 20%, also with a comparable increase in range. Since, at a minimum, the objective of a demonstration project would be to increase the hydrogen content of the fuel that is fed to

the engine by at least 20% by volume, this will necessitate a hydrogen storage system about one fifth the size of the volume of the existing LNG capacity.

Storage and Weight

Another significant challenge to successfully integrating hydrogen into existing natural gas trucks is that of onboard fuel storage and the weight of that equipment. In the heavy-duty vehicle sector, weight is always a major consideration. One significant reason that LNG has become the alternative fuel of choice for heavy-duty trucks is the issue of weight. Given the 80,000 lb ceiling on the weight of a truck with four or more axles, every additional pound of truck is one less pound of cargo that can be carried. LNG contains 600 times the energy density of CNG at the same volume and pressure. LNG enables heavy-duty trucks to achieve comparable diesel range without adding many hundreds of pounds of heavy CNG storage cylinders. Although LNG fuel tanks are heavier than their diesel counterparts, LNG is lighter than diesel, thus almost making up the added weight of LNG storage.

For the demonstration vehicles proposed herein it has been suggested that hydrogen storage be added to the existing LNG fueling system. This will provide a boost in range. But this increase in range can only be achieved by increasing the weight of the vehicle, since both the hydrogen storage system and the fuel blending technology will likely add several hundred pounds to the vehicle. In weight-constrained applications (for instance, less-than-truckload cargo carriers), this could present severe limitations. For demonstration technology, this does not present a problem, but it may present a barrier for the commercialization of NG-H₂ technology.

The addition of the hydrogen system, as recommended here, will have the benefit of improving range but the disadvantage of increasing weight. For this reason the kind of hydrogen storage system that is used onboard the vehicle becomes an important consideration, as equipment should be explored that mitigates the weight that is added to the vehicle.

There are several ways to store hydrogen onboard vehicles. The most common and readily available include compressed gas, cryogenic liquid, in a solid metal hydride, or in another form to be reformed on-board the vehicle. For a host of reasons, not the least of which is weight, on-board reformation of another fuel does not make sense. In addition, there are several advanced methods of hydrogen storage that are being supported by the DOE's Hydrogen Fuel Cells and Infrastructure Technology (HFCIT) program, including adsorbed hydrogen, complex metal hydrides, and chemical hydrogen storage. These advanced systems, however, are in the nascent stages of development and will not be considered for the demonstration projects recommended here.

Of the existing three storage methods, the one that appears to be preferred by automakers is compressed gas storage. Given the long history of use of compressed gas cylinders, the relatively large number of producers, and the industry's familiarity with the technology, CHG ranks high as a primary storage medium for demonstrating the use of hydrogen in existing ICTC trucks. In addition, since natural gas is delivered to the engine as a

compressed gas, this increases the ease of integration into existing LNG vehicles. In addition, most natural gas cylinders do not need to be modified in order to carry HCNG blends of as much as 30% hydrogen.⁵

The most significant challenge associated with CHG storage is the volume to weight ratio. As shown in Table 5, existing 3,600 psi compressed hydrogen cylinders carry the least amount of energy to volume. This can be mitigated, somewhat, through the development of tanks that can store hydrogen gas at significantly greater pressures, such as 10,000 psi. Yet even this storage technology comes with additional drawbacks. Given current technology, the rapid fill of a 10,000 psi tank generates significant heat, expanding the gas in the tank. As the gas cools, the actual pressure in the tank settles to about 7,000 psi, thus reducing the energy content in the tank by about a third. In order to obtain a “full fill”, manufacturers are exploring ways to monitor tank data during refueling, refrigerating the dispensed gas, and new tank designs that reduce the adverse heat impacts of rapid pressurization.

Solid metal hydrides and cryogenic tanks, however, cannot be discounted as potential storage options for heavy-duty vehicles. Liquid hydrogen storage systems (LHG) are particularly attractive options because of the high energy density (400% greater than 3,600 psi CHG) and because of the fact that most ICTC stations and trucks are familiar with the use of cryogenic liquids because they use LNG. But hydrogen liquefaction is an energy intensive process that involves chilling hydrogen gas to -420°F, considerably lower than the -260°F needed to liquefy natural gas.

Cost

Another significant impediment to the integration of hydrogen into the ICTC is the cost of hydrogen as a vehicle fuel, the cost of hydrogen components on-board the vehicle, and the cost of hydrogen dispensing infrastructure. The cost of new transportation technology has been one of the primary impediments to the widespread adoption of alternative fuels in this country. Of these three cost elements, the most important appears to be the cost of the fuel. This is due to the fact that, in most states (particularly California), there are extensive grant programs that will pay the incremental capital costs of the purchase of alternative fuel vehicles and fueling infrastructure. If fuel costs are higher, however, there is no ongoing incentive for a fleet operator to switch to the new technology.

At current price levels, hydrogen is slightly too expensive to be a transportation fuel. In Southern California hydrogen providers report that they sell their product for between \$2.00 and \$2.50 per one hundred cubic feet delivered. This translates roughly in to a cost of about \$2.00 to \$2.50 a pound. Table 6 below illustrates how this hydrogen cost

⁵ The Sunline Transit HCNG buses used the same compressed gas cylinders with which they were originally outfitted. These include Type-3 Lincoln Composite and SCI tanks with aluminum inner tank and carbon fiber wrap, each rated at about 3,600 psi. Each tank costs between \$4,000 and \$5,000, and are certified for a useful life of 15 years. Every two years these tanks are cycle tested to a 3:1 ratio, i.e. they are tested to withstand three times rated pressure without rupture (10,000 psi). There have been no failures up until now, although officials have not been collecting official test data on the tanks. Tank performance is something that the SCAQMD and other agencies plan on testing in the future.

compares to other transportation fuels. A \$2.00/lb price for hydrogen translates into a nearly \$4.00/gallon price for diesel. For comparison, the average cost of a gallon of diesel in California as of this writing was \$2.52.⁶

There are several factors that could contribute to high fuel costs for hydrogen. First, unless the hydrogen comes from an existing source as a by-product from the production of some other product, it can be very expensive to produce hydrogen from natural gas or water. Both processes require the feedstock of gas or water, and both require prodigious amounts of energy to convert the feedstock in to hydrogen. Second, because of hydrogen's low energy-to-weight or volume ratio, it takes greater quantities of hydrogen to provide the same range or power as conventional fuels or natural gas. Although such costs can be accommodated in a demonstration project, the premium that must be paid may place substantial pressure on project funders. Third, not only does hydrogen cost significantly more than conventional or alternative fuels, but the cost of the equipment is also substantially more. Higher maintenance costs must be factored in as well. Consequently, the higher cost for hydrogen can and will be a major impediment to the commercialization of the technology.

It is clear, however, from the data in Table 6 that hydrogen is not far from being competitive. As shown below, if the cost of hydrogen were to drop 50% to \$1.00 per pound delivered, the fuel would have a significant cost advantage over both gasoline and diesel. However, given current prices, the cost of hydrogen exceeds that of today's petroleum-derived gasoline and diesel fuels. For hydrogen to succeed, economies of scale will have to translate in to a substantial reduction in the price of the commodity.

Table 6: Hydrogen Costs & Transportation Fuel Equivalents

Hydrogen Cost	Therm	LHG	Gasoline/ CNG	Diesel	LNG
[\$/lb]	[\$/therm]	[\$/gal]	[\$/gal or gge]	[\$/gal]	[\$/gal]
0.32	0.50	0.14	0.57	0.63	0.42
0.50	0.78	0.22	0.89	0.98	0.66
1.00	1.57	0.45	1.79	1.98	1.32
1.40	2.19	0.62	2.50	2.76	1.84
1.50	2.35	0.67	2.68	2.96	1.97
2.00	3.13	0.89	3.57	3.94	2.63
2.50	3.92	1.12	4.47	4.94	3.29
3.00	4.70	1.34	5.36	5.92	3.95
3.25	5.09	1.45	5.80	6.41	4.28
3.50	5.48	1.56	6.25	6.90	4.60
3.75	5.88	1.68	6.70	7.41	4.94
4.00	6.27	1.79	7.15	7.90	5.27

Assumes 28,500 BTU per gallon of LHG, 114,000 BTU/gal of Gasoline or CNG, 126,000 BTU/gal of diesel, 84,000 BTU/g of LNG; Based on a table courtesy of Collier Technologies Inc.

⁶ See Transport Topics, July 4, 2005, p. 26.

Criteria for Selection

In order to evaluate the opportunity to implement a successful NG-H₂ demonstration project, a set of project criteria have been developed. These have been applied to all of the sites in the ICTC, and have been used to determine that the proposed NG-H₂ demonstration projects outlined herein are the most likely to succeed.

The rationale for site selection involves a range of pertinent factors. These are explored in detail below.

Strategic Location

One of the most important criteria is the location of the existing natural gas fueling station. Given the interest of both the State of California and the DOE in beginning the process of developing a web of hydrogen fueling infrastructure, this effort focused on existing natural gas locations along crucial transportation corridors. These sites have helped expand the availability of natural gas as a transportation fuel, and can do the same for hydrogen.

Filling a Gap

An aspect of the strategic location of a particular site is its proximity to other hydrogen development projects. In this instance, the distance from other existing or possible hydrogen stations was considered. In studying the efforts of other programs, an effort was made to propose demonstrations where none were planned. In this manner the NREL program could help to fill gaps in the nascent hydrogen highway. This greatly facilitates the DOE's objective of helping to build the fueling infrastructure necessary to promote commercialization of hydrogen-powered transportation technology.

In California, there are a number of hydrogen infrastructure projects that have been implemented or proposed for the San Francisco Bay and Sacramento areas, and an even greater number that have been located or proposed for the greater Los Angeles metropolitan area. But a review of the map of existing and proposed sites (See Appendix B) reveals that there is no infrastructure that exists or has been proposed for the center of the state that would link north and south. Nor is there infrastructure that could link Southern California to hydrogen development projects in the Las Vegas area. These are the gaps that the proposed ICTC hydrogen development projects hope to fill.

Availability of Willing Fleets

With several years of experience developing low emission and alternative fuel vehicle deployment projects, the ICTC understands the importance of the attitude of the fleet/station operator for the success of any new technology project. Generally, it can be said if a fleet operator wants to make a project work, they will find a way. The interest of each of the ICTC stakeholders in participating in a hydrogen demonstration project was

gauged before making a recommendation for their inclusion. Only stakeholders who expressed a high level of interest in participating in a potential future NG-H₂ deployment project were considered.

Although not an evaluation criteria, it is important to note that these are all fleets that have experience with deploying a new, alternative fuel transportation technology as well as the development and operation of a natural gas fueling system. These operators understand the ups and the downs, stops and starts of such endeavors. Given their history with alternative fuel vehicles, their willingness to participate in a NG-H₂ demonstration project is especially valuable. They understand that they will need to be patient, that they will likely have to put some of their own money up, that it will require training, and that processes are long and paperwork is endless. They also understand that the performance of new technology doesn't always match that which they are used to from their conventional diesel units. These fleets make good prospects for the proposed demonstration projects because they will not be easily discouraged.

Availability of Willing Vendors

Similar to the discussion above about the willingness of fleet operators to participate in NG-H₂ demonstration projects, another important criterion is the willingness of the vendors of the existing stations, trucks and engines to engage in the effort. If manufacturers of the existing engines, fueling systems, dispensing technology and other crucial components that make up the elements of any ICTC project are not willing to work on the modification of their products to be compatible with hydrogen, there is little more that can be done to push a proposal forward. This is particularly true in the example of existing natural gas engine technology, which must be modified to burn a hydrogen-natural gas mixture. Thus, one factor that played a role in the selection of potential demonstration projects was the interest of the vendors of the in-use products to work with NREL on some future demonstration project.

Production of Hydrogen from Natural Gas

Another of the criteria for selecting a site to be listed as a potential demonstration project is the ability to locate a natural gas reformer at the facility. One of the primary purposes of this study is to evaluate the potential to utilize existing natural gas infrastructure as a foundation for future hydrogen production and dispensing capability. Thus, in each of the projects proposed herein, it was determined that hydrogen could be produced from natural gas at the site. In some cases, however, it may make sense to utilize other sources of hydrogen in the initial stages of project development. This might be the case in those locations that have access to relatively inexpensive sources of hydrogen. Eventually, however, if hydrogen vehicle development grows in any of the demonstration projects proposed herein, natural gas can be reformed and dispensed at site.

Variety of Engine, Storage, Blending and Dispensing Technologies

One factor that was taken into consideration was a desire to demonstrate a variety of hydrogen technologies in the proposed demonstration projects. There are many vendors who are trying to develop hydrogen engines, storage, management, reformation, blending, and dispensing technologies. In order to provide a platform for research into a broad array of potentially successful technologies, an effort was made to develop potential projects that can showcase a number of different approaches to integrating hydrogen into existing natural gas infrastructure. Another consideration was an effort to propose at least some projects that would enable both light- and heavy-duty vehicles to utilize the same site.

Coordination with Other H₂ Vehicle Activities

This factor is related to the last point made above. Although filling gaps in the emerging map of hydrogen fueling is an important criterion, in some instances the proximity of another existing or proposed H₂ vehicle deployment project was considered. This is due to the belief that there is value in demonstrating the ability to support multiple kinds of vehicles from the same fueling infrastructure. These would include light-, medium-, and heavy-duty vehicles, dedicated hydrogen and NG-H₂ vehicles, and hydrogen ICE and fuel cell technologies. Someday the market will decide which products make sense, but for now NREL can best facilitate the hydrogen future by providing a platform for the demonstration of as broad a range of hydrogen transportation technology as possible.

Cost of H₂ Integration

As with anything, cost is a major consideration. Although these are just demonstration projects, the authors realize that resources are scarce. Thus, one criterion in the selection of demonstration projects was the potential cost of integrating hydrogen producing and dispensing capability at the site. This has been a difficult criterion to apply, however, since these costs are not well understood. There are few examples to point to where hydrogen has been integrated into an existing natural gas facility. Although the hardware prices are relatively well established, engineering and installation remain a big question mark. Thus, for this criterion, it is best to consider the complexity involved with modifying an existing facility to include hydrogen production and dispensing infrastructure. Are there space limitations? Is the existing station manufactured by a vendor who is also entering into the hydrogen arena, or will a third parties' technology have to integrate into what is there? These and other similar questions helped to provide a basis for evaluating the various options among existing ICTC stations for demonstrating NG-H₂ technology.

Funding Opportunities

As with all new technology RD&D efforts, the availability of both public and private funding is a major consideration. Although there are many private interests who are willing to put some investment into the kinds of demonstration projects proposed herein, in almost every instance the majority of the funding will come from a public agency. Fortunately, there are many sources of grants for hydrogen development, at virtually every level of government. The availability of these grant programs, the potential to leverage grants from multiple programs, and the interest that these programs have in funding hydrogen-from-natural-gas demonstration projects, are all criteria that have played a role in the selection of proposed NG-H₂ demonstration projects.

These nine factors are the main criteria by which the ICTC projects listed below were selected for consideration by NREL for future development. The next section begins the discussion of the individual projects.

Prospective Targets for NG-H₂ Demonstrations

The ICTC Project has been in operation since its inception in 1996. The first deployment projects began to develop in 1997, and by the end of 1998 the first ICTC-assisted natural gas trucks and fueling stations were delivered and built. Through this and other natural gas vehicle deployment projects, the ICTC Project has developed close working relationships with almost every California operator of medium- and heavy-duty natural gas vehicles and LNG and L/CNG fueling stations. Preliminary contacts with these operators has yielded several potential partners along the ICTC for prototype NG-H₂ fueling infrastructure as well as parties interested in participating in demonstrations of the use of natural gas/H₂ blends in existing natural gas trucks. From these contacts, ICTC Project staff has identified four parties that we believe show the most promising potential for early NG-H₂ demonstration projects.

USA Waste, City of Fresno,

USA Waste of California, a Waste Management Company, holds the distinction of having the largest number of municipal and service district contracts of any hauler in the Central San Joaquin Valley. Located in Fresno, California, USA Waste services a residential, commercial, and industrial account base of customers.

The Fresno facility is in a crucial location along California's primary north-south transportation routes. It is located on East Jefferson Avenue, just off of California State Highway 99 (CA 99). As of this writing, no hydrogen fueling facilities are being proposed for the San Joaquin Valley.

Besides being a local service provider with a management team whose combined industry experience exceeds 100 years, USA Waste is able to rely on the resources of the Waste Management Inc. corporate structure. In California, Waste Management's 70 district offices provide solid waste collection services to 356 communities; curbside recycling is provided to 2 million single-family households and to more than 440,000 multi-family units. Waste Management operates more than 150 special yard waste collection and recycling programs.

Perhaps most important for the purpose of this report is Waste Management's extensive experience with natural gas and alternative fuel vehicle technology. Waste Management is the largest private operator of heavy-duty natural gas powered refuse trucks in the nation, with more than 300 now in service, mostly in California. Waste Management was one of the first companies in the nation to begin operating LNG refuse trucks with its pioneering project in Washington, Pennsylvania. In addition, the company is working with the Bay Area Air Quality Management District to develop the ability to produce LNG from landfill gas in one of its northern California landfills.⁷ Perhaps most notably,

⁷ Waste Management's landfill gas (LFG) to LNG facility is located at the Altamont Landfill in Livermore, California.

Waste Management is in the second year of its groundbreaking emissions trading program in El Cajon, California (near San Diego), where one of the industry's largest LNG fueling stations (45,000 gallon storage capacity) and 120 LNG trucks are now operating.⁸

USA Waste currently operates 13 LNG refuse collection trucks from their Fresno facility. All 13 units are Mack trucks powered by the 2.0 g/bhp-hr, nitrogen oxides (NO_x) certified Mack E7G dedicated natural gas engine. Used in place of diesel-powered units, USA Waste is effectively reducing 9.35 tons of NO_x and particulate matter (PM) emissions annually and is also reducing its consumption of petroleum by 156,000 gallons per year.



Figure 1: USA Waste in Fresno

Funding for these vehicles was obtained from the San Joaquin Valley Air Pollution Control District's Heavy-Duty Truck Program. The Clean Air Transportation Coalition and ICTC provided writing assistance on behalf of USA Waste. USA Waste anticipates that it will continue to grow its LNG powered fleet at this location as additional grant funding sources become available. Waste Management also recently assembled a Natural Gas Project Team that is responsible for identifying the operations most suitable for the use of natural gas vehicles, overseeing the deployment of such vehicles, and assisting in evaluating in-use performance data.

Working with USA Waste for the past several years, the ICTC assisted the company to secure partial funding for the Fresno facility and develop the preliminary site layout and specifications. Because Waste Management is developing several LNG facilities throughout California, the company initiated a competitive selection process to choose a contractor for all of its planned LNG facilities; including this one. Construction of the USA Waste LNG station in Fresno was initiated in the Spring of 2002, with the first load of fuel being delivered in September 2002. The station officially opened in the winter of 2002/2003, at which point it became accessible to outside LNG fleets and trucks traveling the CA 99 corridor.

The development of a NG-H₂ demonstration project at the USA Waste depot in Fresno meets several of the key criteria identified by the authors for including existing ICTC-assisted projects on this list. As mentioned above, Fresno is strategically located along one of California's three primary north-south transportation corridors (U.S. 101, I-5, and CA-99). Fresno is also one of the gateways to both Yosemite and Sequoia National Parks. Its strategic location is even further enhanced by the fact that placing a hydrogen fueling facility there will fill a tremendous gap in the existing and proposed hydrogen fueling infrastructure. This is made quite clear when viewing a map of the projects recognized by the California Fuel Cell Partnership (CaFCP). Virtually all of the existing and proposed

⁸ See http://www.wm.com/WM/environmental/documents/Environmental_Review.pdf for more detail into Waste Management's environmental initiatives. The El Cajon fleet is the nation's only example of emissions offsets being provided by a mobile source to enable a new power plant to be built.

hydrogen fueling facilities and vehicle deployment projects are located in the state's four major metropolitan areas (Los Angeles, Sacramento, San Diego, and San Francisco). Finally, Fresno is also the site of one of the state's more ambitious stationary fuel cell deployment projects, which helps make the community more receptive to additional hydrogen demonstrations.⁹

In addition, there is no more willing and capable a partner than Waste Management to demonstrate advanced, not-yet-commercial, transportation technology. The company has extensive experience not only with natural gas vehicle projects, but also with experimentation with novel, innovative technologies and emission reduction projects. They have already expressed interest in working with the ICTC Project on the integration of hydrogen into their existing fleet.

The San Joaquin Valley also presents some interesting new opportunities for obtaining third party resources to support this project. Not only can a proposed NG-H₂ pilot project take advantage of California's existing grant programs, but recently expanded funding programs to assist the San Joaquin Valley Unified Air Pollution Control District to address its deteriorating air quality.¹⁰

For this project, the ICTC Project proposes to structure a NG-H₂ demonstration project at USA Waste in Fresno with the following elements.

- Develop the capacity to produce hydrogen gas from the existing LNG fueling facility and store the hydrogen on site.
- Build a hydrogen refueling station adjacent to the existing natural gas refueling facility and enable it to provide pressurized hydrogen to either heavy or light-duty vehicles.
- Modify some of its existing LNG refuse fleet to utilize NG-H₂ fuel.
- Provide access to outside users to the hydrogen dispensers.

City of Barstow

There is a joke that has been circulating in the Mojave Desert for years: There are two reasons why people go to the City of Barstow—to fuel their vehicles on the way to Las Vegas and to fuel them when they return home. This is due to the fact that Barstow is almost exactly mid-way between the great Los Angeles metropolitan area and Las Vegas. Recognizing their role as an important transportation hub for interstate travel, the City of Barstow has taken a proactive stance in developing alternative fuel infrastructure. The Mojave Desert Air Quality Management District (MDAQMD), San Bernardino Association of Governments, the California Energy Commission, and City of Barstow have partnered in the development of a liquefied/compressed natural gas (LNG/LCNG)

⁹ Three 200 kW UTC fuel cells are being installed at the Fresno Federal Guarantee Savings Building in downtown Fresno.

¹⁰ In December 2004 the board of the air district voted to increase the vehicle surcharge on all vehicle registered in the area from \$5 to \$7 annually. See [http://www.valleyair.org/Recent_news/Media_releases/\\$2%20fee%20release%2012-16.pdf](http://www.valleyair.org/Recent_news/Media_releases/$2%20fee%20release%2012-16.pdf)

fueling station. The design phase of the project has been completed and construction is anticipated to be completed in the Fall, 2005. This publicly owned, public access LNG/LCNG fueling station can be easily reached from Interstates 15 and 40 and from California State Highway 58.

The station will serve the immediate needs of several local natural gas vehicles now operating in the City of Barstow as well as additional public and private fleet vehicles traveling in, around, and through the city. Furthermore, it is anticipated that the development of this LNG/LCNG station will provide an incentive for more fleet operators to deploy and convert their fleets to clean compressed and LNG. The facility not only will provide crucial natural gas fueling capability to light-duty vehicles making the round trip from Southern California to Las Vegas, but will also serve as a critical fueling stop for LNG trucks that carry cargo up and down I-15.

As of this writing, the authors have not been able to identify any plans to develop hydrogen fueling infrastructure or to deploy hydrogen-fueled vehicles in the Mojave Desert. Given the fact that there is an existing hydrogen fueling station in the City of Las Vegas, as well as several that are planned for the South Coast Air Basin, including one at Ontario Airport near the junction of I-10 and I-15 (the primary transportation link between from Southern California to Las Vegas), it appears that the development of a NG-H₂ facility in Barstow fills a critical gap in the emerging hydrogen highway. As made clear above, Barstow occupies a crucial strategic position in a key East-West/North-South transportation corridor.

The City of Barstow has proven to be a willing and cooperative partner in efforts to develop alternative fuel infrastructure and to deploy alternative fuel vehicles. The City has sought out inclusion in the ICTC Project, has invested hundreds of thousands of dollars into the development of their natural gas vehicle fleet and their L/CNG fueling station, and aggressively pursued third party funding for their efforts. When approached by the ICTC Project to gauge their interest in possible participation in some future NG-H₂ demonstration project, the City's response was enthusiastically positive.

The Barstow LNG/LCNG station is being built by Weaver Electric and NexGen Fueling. It includes a standard 45-foot tall state-of-the-art Chart LNG cryogenic storage tank, capable of storing 15,000 gallons of LNG. The facility is equipped with a LNG fueling system, a LCNG dispensing system, including a high-pressure liquid pump, vaporizer, storage bottles, and a dispenser capable of delivering 3,600 psi natural gas to CNG vehicles. In the construction of this facility, designers have already installed sufficient electrical conduits to connect a future expanded natural gas reformation system and hydrogen fuel storage and dispensing system in parallel with this natural gas station. Hydrogen compatibility was one of the design criteria.

The vehicles expected to be refueled at this LNG/LCNG station will be city-owned transit buses, ICTC trucks traveling the I-15 corridor, and possibly the local city waste collection company. Note that the three existing transit buses are 25-foot Goshen buses powered by Cummins 5.9L B Gas Plus dedicated natural gas engines. Each bus has a

capacity of 149.5 gge at 3,600 psi. These buses will be augmented with MST II CNG buses, also equipped with Cummins 5.9L engines. These new buses are equipped with pressed steel fuel tanks, with a capacity of about 50 diesel gallon equivalent (DGE). These vehicles have a range of about 200 miles, and typically travel about 100 miles a day.

In addition, the City of Barstow operates several natural gas medium-duty vehicles. The natural gas vehicles that the City currently owns include eight Aerotech 220s equipped with Ford V-10 engines (typically found on their 450 Series trucks).

For this project, the ICTC Project proposes to structure a NG-H₂ demonstration project in Barstow with the following elements.

- Develop a natural gas reformation capability at the Barstow LNG/LCNG station that will enable the production of hydrogen there. Develop sufficient storage capacity to support the proposed demonstration project(s).
- Integrate this hydrogen and natural gas into a blended fuel refueling station.
- Develop an ancillary clean fuel hydrogen refueling station at its existing natural gas refueling facility that is capable of dispensing H₂ only.
- Provide access to outside users to both the hydrogen and CNG/H₂ blended-fuel dispensers.
- Modify a Barstow Transit Bus to demonstrate feasibility of NG-H₂.
- Outreach to manufacturers of transportation refrigeration units (TRUs) and local trucking companies to develop hydrogen-based, fuel cell TRU demonstration projects.
- Secure industry support to have roadside billboard advertising station as a “come and see the future today” tourist attraction.
- Evaluate the willingness of the City of Barstow to purchase additional CNG vehicles as well as other non-city CNG vehicles that may require fuel at either 3,000 psi or 3,600 psi, thus the station should be capable of refueling both types of CNG vehicles to their rated pressures.

The City of Barstow has received a great deal of support for its natural gas vehicle deployment and station development project from the MDAQMD and the San Bernardino Associated Governments. The authors have explored the interest of these agencies to support a Barstow NG-H₂ demonstration project, and both have expressed keen interest in participating.

While the proposed demonstration project will include Barstow Transit buses, it will also target market sectors that are not currently anticipated to fuel at the station. Furthermore, immediate integration of hydrogen at the Barstow location will help create a tie between hydrogen transportation infrastructure in Las Vegas and Southern California, thereby helping to establish a true hydrogen corridor.

City of Tulare

The City of Tulare lies on the eastern side of the San Joaquin Valley, which is more populated than the western edge. CA-99 bisects the city, which is one of three primary north-south corridors in California. Not only is the western side of the Valley more populated, but it is also where most of the agricultural processing industry is located. In addition, Tulare is almost midway between Sacramento and Los Angeles, as well as near the portals to the national parks of the Sierra Nevada Mountains.

Tulare owns and operates a station capable of dispensing both LNG and CNG from LNG. The combined LNG/LCNG capability expands the universe of natural gas vehicles that can take advantage of this state of the art facility, allowing the City to operate a variety of light-, medium- and heavy-duty vehicles from this station.

This alternative fuel facility was commissioned in 2001 to support the City's growing fleet of natural gas vehicles. Set in motion by a 1995 City Council initiative, Tulare's natural gas vehicle program has grown quickly and now includes all 22 of the City's police patrol vehicles, 6 of the City's transit buses, 3 refuse collection vehicles, 2 transit taxis, and 9 pick-up and other utility trucks. While most of these vehicles utilize CNG as their fuel, the City is growing its refuse, transit, and heavy-duty truck fleet by adding vehicles that use LNG.

Existing Vehicles Specifications include:

- 1999 El Dorado National transit bus (Cummins 5.9L, dedicated CNG)
- 2000 Peterbilt refuse collection truck/side loader (CAT 3126 Dual-Fuel™ engine, LNG/diesel)
- Ford Crown Victoria (dedicated CNG)

As noted above, the City of Tulare is strategically situated between northern and southern California along one of the state's major transportation and goods movement routes. It is an excellent location for a natural gas station, as it serves the Eastern San Joaquin transportation corridor. It is an important location for hydrogen infrastructure as well, because of its central location between Fresno and Bakersfield. The fueling facility is immediately off of one of the state's most traveled north-south corridors. As with Barstow, there are no hydrogen projects planned for the community.

For this project, the authors propose the following NG-H₂ demonstration concept for City of Tulare:

- Develop an ancillary clean fuel hydrogen refueling station at its existing natural gas refueling facility.
- Integrate this hydrogen and natural gas into a blended fuel refueling station.
- Modify some of its existing CNG refuse fleet to utilize NG-H₂ fuel.
- Develop and demonstrate the use of NG-H₂ in police cars.
- Provide access to outside users to both the hydrogen and blended-fuel dispensers.

The San Joaquin Valley's increasing struggle to meet Federal attainment levels and the City of Tulare's historic role as a leader in innovative clean fuel vehicle projects makes this location an ideal link in the hydrogen corridor. The ICTC Project helped secure funding for Tulare's LNG/LCNG fueling station and many of its natural gas vehicles, shepherded the project through the bid process, and provided technical assistance during the construction and start up phases. This long standing relationship has provided insight into needs of local stakeholders and will greatly facilitate the development of a hydrogen aspect to the project.

In addition, as mentioned in the discussion of the proposed USA Waste project in Fresno, the San Joaquin Valley now has additional resources that can be used for the development of emission reduction projects, as well as projects that demonstrate new technology. This could prove to be an important boon to all three of the proposed San Joaquin Valley-based NG-H₂ projects discussed herein.

Harris Ranch, Near the City of Coalinga

The last of the San Joaquin Valley-based NG-H₂ demonstration projects is proposed for Harris Ranch. Located 200 miles north of Los Angeles on the western side of the San Joaquin Valley on I-5, Harris Ranch is one of California's largest and most successful agribusinesses. The company operates a variety of companies, including Harris Farms; Harris Ranch Beef Company; Harris Ranch Feeding Company; Harris Ranch Inn & Restaurant; Harris Farms – Thoroughbred; and the Harris Ranch Country Store. It is also the location of one of California's most successful and longest-lived LNG truck deployment projects and LNG fueling stations.

The Harris Ranch LNG truck deployment and station development project was initiated in 1997 and was made possible through a variety of public/private partnerships. With the help of the Clean Air Transportation Corridor team members, Harris Ranch was able to secure \$400,000 from the San Joaquin Valley Clean Cities Partnership. Additionally, \$432,000 in AB2766 monies was awarded to Harris Ranch by the San Joaquin Valley Air Quality Management District. Pacific Gas & Electric also pledged in-kind support for the project. Apart from the \$832,000 in public funding for the project, Harris Ranch made its own contribution of over \$1.1 million to get this project started.

The LNG station and the domicile for the LNG trucks that Harris Ranch operates is located five miles north of the famous Harris Ranch Inn & Restaurant on Interstate 5 at the headquarters for the Harris Ranch Feeding Company. Like Tulare, this facility is located nearly midway between the Bay Area/Sacramento regions and the Los Angeles metropolitan area. It has already proven to be a significant strategic location for the LNG industry, as some operators of LNG trucks use the station to fuel as they ply this otherwise desolate stretch of highway. As anyone who has driven "the bowling alley" (as this section of I-5 is often referred to) can attest, fueling facilities on this critical north-south transportation route are few and far between. Thus, any hydrogen infrastructure that can be located on this highway would be very important to the future development of California's Hydrogen Highway.

Harris Ranch has long been one of California’s business leaders, and this has translated into one of the state’s most visible alternative fuel vehicle success stories. This project has been featured in more than a dozen newspaper and trucking industry publications. Not only does the attention generated by this project speak to the success of the company’s LNG deployment project, but it has also helped to advance the LNG market overall. Through the leadership that Harris Ranch has demonstrated in the implementation of its LNG project, several other local fleet managers have taken notice of the benefits of alternative fuels. The Harris Ranch LNG project has proven to many non-believers that, in fact, clean fuel technologies work, are reliable, have the power needed to get the job done, and can even yield operational cost savings. In addition, throughout the life of its LNG project, Harris Ranch has actively participated in educational outreach to other California based fleets. Thus, NREL could ask for no better partner in the development of a potential NG-H₂ demonstration project.

Harris Ranch deployed 12 Freightliner Century Class tractors (C120s) equipped with the Caterpillar/CAP C-12, 425 hp dual-fuel LNG engine in October, 1999. These trucks deliver agro-products and feed for cattle throughout the San Joaquin Valley. These LNG trucks replaced 12 diesel tractors that, on average, each traveled 110,700 miles per year and consumed 21,211 gallons of diesel fuel annually, thus effectively reducing 28,080 pounds of NO_x and PM¹⁰ emissions per year. Incredibly, over the course of its LNG deployment program the company has demonstrated an average \$0.035 to \$0.039 per mile cost savings by utilizing natural gas instead of diesel fuel.

Harris Ranch was further awarded \$325,018 from the San Joaquin Valley Air Pollution Control District’s Heavy-Duty Motor Vehicle Emission Reduction Incentive Program to help fund the deployment of an additional 14 LNG trucks. Eight of these 14 trucks have already been placed in service and utilize the existing LNG fueling station already developed by Harris Ranch. Thus, the total size of Harris Ranch’s LNG fleet is 20 trucks.

The Harris Ranch LNG station is at the Harris Ranch Feeding Company’s cattle feed lot near the junction of I-5 at State Highway 145, near Coalinga, California. It was the first turnkey LNG station project developed by the ICTC Project, the first “commercially” developed LNG station in California, and the first “turnkey” project developed by NorthStar, Inc. The station includes a 15,000 gallon LNG storage tank, a single hose LNG dispensing system, and unlike its sister stations across the San Joaquin Valley, it does not dispense CNG. Although the facility is privately owned, it does allow public access to any LNG truck that can pay cash or that has an account with Harris Ranch.



Figure 2: Harris Ranch Station

Integration of ICTC NG-H₂ Sites into Existing Hydrogen Development Efforts

The nature of the ICTC dictates that each of its station and vehicle deployment projects are part of a broader network intended to accelerate the commercialization of clean, alternative fuel vehicle technology. Each individual project is intended to expand the availability of fueling infrastructure through the development of fueling facilities along key transportation corridors. Thus, each of the facilities discussed herein for possible inclusion in a program to integrate hydrogen technology into existing ICTC stations and fleets already enjoys many of the criteria necessary to be good prospects for further alternative fuel development. In addition, since the ICTC was always, first, and foremost, an effort to develop a “corridor” in which nodes of alternative fuel development could be organically linked by virtue of the fact that similarly equipped vehicles travel the same route, the projects suggested in this report can easily be integrated into other hydrogen corridor development efforts.

Another important element worth mentioning is that the ICTC Project shares the same leadership with each of the three primary hydrogen transportation development efforts (the California Hydrogen Highway, the CaFCP, and the SCAQMD Hydrogen Program) in the western United States. The ICTC was created and continues to be governed by all of the key agencies involved in these three programs, including the U.S. Environmental Protection Agency, DOE, the California Air Resources Board (CARB), the California Energy Commission, and the SCAQMD. The Steering Committee of the ICTC, which has met monthly via conference calls for nearly eight years, includes many of the same people who participate in the three other hydrogen vehicle programs. Thus, coordination between an ICTC Project and these other programs should prove to be relatively easy.

The only significant difference between the ICTC and these other hydrogen transportation efforts is the types of vehicles on which the ICTC focuses. Whereas the ICTC targets the commercialization of clean, alternative fuels in heavy-duty vehicles that are involved in the interstate movement of goods, the Highway, Partnership, and SCAQMD programs focus almost exclusively on light-duty vehicles and an occasional transit bus. Thus, the other three programs include extensive involvement of the light-duty vehicle auto manufacturers, whereas the ICTC project has had very little interaction with these parties. On the other hand, the ICTC has excellent working relationships with virtually every major heavy-duty engine and chassis manufacturer. This difference can prove to be particularly useful to all parties, since the ICTC projects bring the possibility of filling a gap in the technological development efforts of existing programs. In addition, the strategic location of the proposed ICTC NG-H₂ projects plug holes in the emerging map of hydrogen fueling infrastructure, particularly between the current geographic nodes of hydrogen development (San Francisco/Sacramento, Los Angeles, and Las Vegas).

On the other hand, it remains to be seen how this program integration will manifest itself. First, it is not at all clear, as of this writing, whether the “Hydrogen Highway” effort will result in any specific recommendations for projects or programs beyond what already exists. A comprehensive report on a variety of topics is being finalized now, the bulk of which includes information about emerging hydrogen technologies as well as recommendations for resources and policy changes that may facilitate the development of hydrogen as a transportation technology. But, until such time as these ideas become tangible, it is not possible to predict how to collaborate. Important elements of the ICTC NG-H₂ development efforts, such as utilizing existing natural gas infrastructure for future hydrogen production and dispensing, as well as using NG-H₂ fuel blends to develop early markets for hydrogen, have been incorporated into the California Hydrogen Highway final report.

In terms of the CaFCP and the SCAQMD hydrogen program, the NG-H₂ projects proposed herein are complimentary. In particular, it will be important to ensure that any hydrogen dispensing equipment that is deployed as a result of the ICTC NG-H₂ integration effort is compatible with a majority of the hydrogen vehicles that are being deployed as a result of the CaFCP and the SCAQMD hydrogen programs. In particular, NREL will want to ensure that the hydrogen Prius vehicles that are being sent to the five cities mentioned above can be serviced by the hydrogen nozzles used at ICTC stations.

Hydrogen Reformation from Natural Gas

Four companies now offer reformers to produce hydrogen fuel from hydrocarbon feedstocks such as natural gas: Ztek Corporation, HyRadix Inc., H2Gen Innovations Inc., and ChevronTexaco Technology Ventures. The authors have evaluated all four companies and the reformer products they offer. All four products are very similar in design, application, and suitability as part of a vehicle refueling station. Some commonalities among the products offered by these four companies include:

- Pre-packaged, skid-mounted (~ 10' x 10') equipment containing all components required for the reformation of natural gas to hydrogen.
- Required natural gas input specification of approximately 150 psi.
- Steam reformation, or a variation of steam reformation, is the process used to produce hydrogen.¹¹
- As de-ionized water is required for the steam reformation process, each reformer system either has a water purification system within the skid, or as an add-on component available from the manufacturer.
- Nominal electrical demand for the internal components of the reformer skid.
- Output hydrogen gas purity of 99.999 percent.
- Hydrogen production capacity of 500 gasoline gallon equivalents (GGE) of hydrogen fuel per day.
- Requirement to package the reformer skid with an independent hydrogen compressor skid, control system, storage vessels, and a hydrogen and/or blend fuel dispenser.
- Only one demonstration project on a vehicular application.
- All existing experience is with pipeline delivered natural gas.
- Relative uncertainty regarding total system costs due to the early R&D phase and prototypical state of their technology.

Each of the four reformer technologies now available for use in vehicular fueling station applications are limited in their production capacities. The largest of the technologies now available, the HyRadix unit, can produce up to 2400 Nm³ of 99.95% pure hydrogen per day (equivalent to approximately 800 GGE).¹² (NOTE: Although the HyRadix unit can produce up to 99.999% pure hydrogen, the efficiency and production capacity of the system is reduced.)

¹¹ Although different vendors will have slight variations to their reformation technology, all steam reformers basically operate on the same principles. Sulfur compounds are removed from the natural gas prior to reformation (typically in ZnO bed. After pre-treatment, the natural gas is fed in to a reformer with steam at 380 psi. The resulting synthesis gas is then piped in to high temperature shift and low temperature shift reactors where the water gas shift converts 90+% of the fed gas in to hydrogen. See Pamela L. Spath and Margaret K. Mann, "Life cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming," National Renewable Energy Laboratory, February 2001, NREL/TP-570-27637, p. 3.

¹² Nm³ is a measure for volume of gases, in cubic meter, under special conditions of pressure (1 atmosphere) and temperature (zero degrees centigrade). The name for this unity is Normal Cubic Meter.

While these first generation reformers are limited in their production capacities, they are suitable for use at any of the four natural gas refueling station recommended for pilot projects. This is due to the fact that, as demonstration projects, initial fuel demand will be very moderate. The only exception may be the Ztek unit, as it has a production capacity of only 384 Nm³ per day, or 129 GGE daily. While none of the vehicle demonstration projects proposed herein will consume this volume of hydrogen each operating day, if the project is successful in achieving one of its primary goals (expanding the availability of hydrogen infrastructure), within a short period of time beyond the initial demonstration project it is possible that the Ztek production capacity could be exceeded. This factor must be considered when making choices regarding reformation technology.

As fuel demand increases, it is generally accepted among vendors that a liquid hydrogen-based refueling station will be more economical than a facility that reforms pipeline natural gas. However, for the early hydrogen infrastructure development, including the fuel cell and H₂/CNG blend vehicle demonstration projects recommended as a part of this project, small-scale reformation technologies are more appropriate. This is due to several factors, including availability, cost, and ease of integration into existing technology. Further, it is interesting to note that many in the industry believe that the level of hydrogen demand where a switch from CHG to LHG systems makes sense is around 800 to 1000 GGE. It is at this daily demand volume that a switch to liquid hydrogen-based refueling stations makes economic and operational sense. The largest of the existing reformer technologies considered for ICTC demonstration projects, the HyRadix unit, has a maximum daily production capacity of approximately 800 GGE. Thus, those pilot projects that happen to be equipped with the HyRadix reformation system may be better positioned for the transition to a more sustainable hydrogen infrastructure, while those with smaller systems may require a second installment of reformation technology if growing demand for hydrogen at those facilities warrants the investment.

Potential Site Issues

The authors have selected four LNG refueling stations in California for this project for the reasons noted above (gap closure in existing H₂ fueling infrastructure development efforts, ICTC fleet willing to accept these types of projects, etc.). Two of these locations only have LNG storage and dispensing (Harris Ranch and Fresno), while the other two (Tulare and Barstow) have both LNG and LCNG fueling capabilities. At each of the locations selected, there is more than enough land available at the site to locate the necessary equipment to produce, store, and dispense hydrogen on-site.

For every site, however, there will be shared challenges that will have to be faced in order to modify the existing natural gas infrastructure into one that will both produce hydrogen and dispense either hydrogen or HCNG. This section explores some of these common concerns that will need to be addressed.

Electrical Requirements

At each site, the existing natural gas refueling station power supply is sufficiently sized to accommodate the electrical demands of the new hydrogen production, compression, storage, and dispensing equipment. The power supply at each of the four LNG and LNG/LCNG refueling sites is 480 V, 3-Phase, 250 amp. While this power supply is sufficient to operate the LNG/LCNG equipment at the site *and* the hydrogen equipment at the site, this service may not be sufficient to operate all of this equipment simultaneously. The equipment at the site having the largest electrical demands includes the LNG pumps, the high-pressure LCNG pump, and the hydrogen compressor. Because the LCNG pump also requires that the LNG pump be active in order to feed the LCNG pump with LNG, it is not likely that the hydrogen compressor could be utilized while this other natural gas equipment is operational. The same may be true for the LNG pump when being operated independently, particularly when offloading LNG from a tanker delivery truck.

Given the complexity of these calculations, a site-specific electrical study will be required in order to determine if the existing equipment can be operated simultaneously with the new hydrogen production and refueling equipment. In the event that the existing power supply is insufficient to accommodate both demands simultaneously, it is likely that the hydrogen control program can be programmed in order to disengage the hydrogen production and dispensing equipment when the natural gas equipment is required. This “prioritization” is likely to be allowed as the natural gas vehicles at the respective sites are “working vehicles,” while any hydrogen, blend gas, or fuel cell vehicles are more likely to be a part of a demonstration or R&D project. The alternative to this approach would be to upgrade the electrical service. Although expensive, it is likely that this upgrade will eventually be required to enable the facility to serve the needs of future NG-H₂ and dedicated hydrogen vehicles.

Unfortunately, hydrogen reformers are not designed for “stop-start” operations. Once operational, it is best to allow the unit to run in a continuous cycle. Start-up time on a hydrogen reformer can take 30 to 60 minutes or more. Therefore, in the design of a hydrogen reforming system, careful consideration must be given to natural gas refueling demands, fueling windows, etc. Where possible, the reformer technology and hydrogen compressor should be sized to produce, compress, and store all of the next working day’s hydrogen demand during off-peak times.¹³ Because the initial demand for hydrogen at these four sites is expected to be limited, it is likely that the volume of hydrogen required on a daily basis can easily be produced during these off-peak hours.

System Control Panel and Communications

It is not possible to integrate the controls for the hydrogen components within the existing natural gas refueling station control panel. A new dedicated hydrogen control panel will be required. Fortunately, at each site recommended in this report the existing natural gas refueling station control panels can easily accommodate an interconnect with a new control panel that will be required for the hydrogen refueling station equipment.

Telephone or high-speed broadband internet service will be required at the new hydrogen system control panels. At all four selected natural gas fueling sites, telephone service already exists as this is also required for the natural gas control panels. At each of these four sites, running additional telephone lines from existing service to the new hydrogen control panel can easily be accommodated. While none of the existing natural gas refueling stations are equipped with high-speed broadband internet service, this service is an easy and inexpensive upgrade. High-speed broadband service can easily be accommodated through the use of a standard telephone line, where it is available.

Hydrogen Equipment Requirements

At each of the four selected sites, very similar equipment will be required to produce, compress, store, and dispense hydrogen and, if needed, blend natural and hydrogen gas. This equipment will vary slightly for the LNG refueling stations and the LNG/LCNG refueling stations. All sites will be required to have appropriate safety equipment, including hydrogen and fire detectors.

For the LNG-only stations, the following equipment will be required in order to produce the feed gas for the front end of the reformer.

- A tie-in point to the existing LNG process piping.
- A short section of cryogenic pipe running to a heat exchanger/vaporizer.
- An ambient heat-exchanger to vaporize the LNG to a compressed gas (depending on the pressure of the LNG, the resulting gas will likely be between 65 psi and 125 psi).
- A small compressor to boost the pressure of the vaporized LNG to approximately 150 psi.

¹³ For purposes of both avoiding working hours as well as taking advantage of off-peak pricing of electricity.

At the locations where LCNG is available and the CNG is stored on-site, the following equipment will be required in order to produce the feed gas for the front end of the reformer.

- A tie-in point to the CNG storage system.
- A short section of high-pressure piping to deliver the gas to the reformer.
- A simple gas pressure regulator to regulate the gas from approximately 4,500 psi. to 150 psi.

Once the natural gas has been delivered to the reformer, hydrogen can then be produced, stored, and dispensed as a compressed fuel. It is only at the two refueling sites where CNG refueling is already taking place that blending and dispensing of hydrogen and CNG will be performed. At the two locations where there is only an LNG refueling station, the hydrogen produced will be stored and dispensed as a dedicated compressed gas fuel.

From the point of reformation, the following equipment will be required to store, blend, and dispense compressed hydrogen and/or compressed hydrogen/natural gas blends.

- High-pressure hydrogen-compatible piping and valving running from the reformer to a hydrogen compressor; from the compressor to the storage vessels; from the storage vessels to the dispenser(s).
- A hydrogen compressor to compress the gas to approximately 5,000 psi.
- Three ASME high-pressure storage vessels suitable for hydrogen storage at 5,000 psi.
- Dual dispensers capable of dispensing pure hydrogen through one of the fueling hoses and hydrogen/natural gas blends through the other. It would be ideal if both dispensers could operate off the same compressor, but this is not essential for the demonstration project.
- A card reader is optional should outside users need to be identified.

For projects in which a blended fuel will be delivered to a CNG vehicle, the mixing will have to take place prior to dispensing into the vehicle's high-pressure storage tanks. This will require an interconnection between the CNG subsystem and the hydrogen subsystem at a point immediately prior to dispensing.

Site Specific Recommendations

Because of the similarity of currently available reformer technologies in cost, design, applicability, and production capacities; the inexperience among all reformer suppliers; the lack of a clear superior reformer product; and a lack of experience in working with LNG as a feedstock, the authors recommend that one of each of the four existing reformer technologies be installed at each of the four sites selected for this project (i.e. one at each site). Because the two LNG sites are likely to have the least demand for hydrogen fuel (the blending sites could experience much more rapid demand increases), we recommend that the Ztek reformer be utilized at one of these two sites. Other than that, the authors have no specific recommendations as to which reformer should be installed at the other three sites. We do, however, recommend that additional discussions be held amongst each of the project stakeholders (site owner; natural gas fuel station equipment supplier; hydrogen reformer, compression, storage, and dispensing equipment manufacturers) in order to better select which of the other three reformers should be located at each of the remaining three locations.

Vehicle Integration Issues

The stations that are proposed in this paper can provide hydrogen to vehicles that consume only hydrogen and to existing natural gas vehicles that are modified to burn HCNG. It is certainly the hope of the authors that the prospect of access to hydrogen will encourage both ICTC fleets and those fleets that are in close proximity to consider the demonstration and/or deployment of fuel cell and hydrogen ICE vehicles. This report, however, has focused on the issues that would be raised by the effort to integrate hydrogen into currently in-use natural gas vehicles.

The ICTC vehicles that have been selected for possible demonstration projects represent a cross section of in-use natural gas transportation technology. These include both LNG and CNG heavy-duty vehicles, as well as trucks that are engaged in over-the-road hauling, waste pickup, local delivery, and buses that are providing transit services. It is the intent of the authors of this report to provide NREL with as wide an array of possible hydrogen integration opportunities as possible. Each of these vehicle applications presents their own set of challenges and opportunities for the incorporation of hydrogen into existing natural gas vehicle technology. It is hoped that through this approach, we may enable the broadest possible investigation into the possibilities of future HCNG operations.

As mentioned, the multiple natural gas vehicle configurations present an abundance of technological and operational challenges to the assimilation of hydrogen in to these existing vehicles. The foremost of these obstacles is the fact that most of the vehicles in the ICTC are fueled by LNG. Although when the methane is injected into the engine it is a vapor, it is stored on-board the vehicle as a cryogenic liquid. Methane liquefies at -260°F. Hydrogen does not liquefy until the temperature reaches -407°F. This presents a significant challenge to engineers. At present, no commercial technology exists which can mix liquid methane and hydrogen, although one vendor claims to have such a technology in development.

Thus, in order to successfully integrate hydrogen onto a LNG vehicle would require either switching out the existing fueling system for a gaseous HCNG system or installing a parallel hydrogen fueling system on-board the vehicle. For most of the vehicles in the ICTC, scrapping the existing LNG storage system is neither feasible nor desirable. The reason these fleet operators sought to use LNG in the first place was for the important qualities that the fuel brought to their operations, most notably superior range and lower weight than CNG. Switching to HCNG would not only obviate these advantages, such a change would make matters much worse, since it would require many more cylinders of HCNG to match the range of CNG.

Thus, the only option that makes sense for today's LNG trucks is to install a parallel hydrogen fueling system on-board the vehicle. This would require the installation, in addition to the hydrogen storage system, of a mechanism to blend the hydrogen with the methane after the methane has been vaporized. This "on-board blending" technology is one of the critical technological developments that the authors feel should be a primary focus of the ICTC demonstration projects.

There are several vendors who claim to have technology that can achieve the necessary mixing on-board the vehicles. Each of these is explored in greater detail in the pages that follow and in the appendices. In keeping with the spirit of other recommendations we have made in this report, we recommend that several of these vendors be invited to bid on the demonstration projects that may arise from this effort. Given the potential importance of on-board blending technology to the future of the hydrogen highway, exploration of a wide array of possible solutions seems to be wisest course of action at this time.

The options for on-board blending are as follows:

- On-board storage of hydrogen as a gas with a unit that blends the hydrogen gas in a pre-set amount with methane after it has been vaporized.
- On-board storage of hydrogen as a cryogenic liquid with a unit that blends the hydrogen gas in a pre-set amount with methane after it has been vaporized.
- On-board production of hydrogen gas with a unit that blends the hydrogen gas in a pre-set amount with methane after it has been vaporized.

The authors of this report made extensive efforts to gauge both the interests of manufacturers in on-board blending as well as their experience/readiness to participate in demonstration projects. Although virtually every manufacturer of engine and storage technology expressed interest in pursuing on-board blending, relatively few were ready to pursue the approach in the near term. Most had no experience with the necessary technologies and few had already performed the preliminary engineering to develop such technology. Relative to other aspects of the emerging hydrogen industry, on-board blending is clearly a path less traveled.

There were, however, a couple of companies that claimed that they could provide the necessary technology and expertise in the near term (within the next year). These companies and their technologies are explored further below.

Constant Volume Injection™

The most prominent of the possible on-board blending HCNG technologies is one that is similar to the unit that was used on the SunLine Transit bus in Thousand Palms, California. Two CNG buses equipped with Cummins Westport 5.9L B Gas Plus engines were converted with the Constant Volume Injection™ (CVI™) technology developed by Frank Lynch, then of Hydrogen Components, and WI. By October, 2004 the two buses had logged over 24,000 miles of “revenue” service, and were declared by WI as ready for commercial applications.¹⁴ The project found that a 20% hydrogen content by volume provided the most cost effective operational and environmental benefits. This mixture,

¹⁴ Press Release quoting Dr. Sandeep Munshi, Westport's Senior Scientist and Manager - Hydrogen Technologies, in “Westport Announces Results of Hydrogen Enriched Natural Gas Bus Program”, October 24, 2004. See http://www.westport.com/investor/newsdetail.php?id=253&return_to=press.php.

called Hythane[®] by the patent holder, reduced emissions of NO_x from the natural gas engines original certification level of 1.8 grams per brake horsepower hour (g/bhp-hr) by 50%, and had the same level of reductions for non-methane hydrocarbons (NMHC). The Hythane[®] also provided the benefit of reducing CO₂ emissions by 7%, which is the same level of Hydrogen energy content of the fuel.¹⁵

CVI[™] is a sturdy mechanical fuel injection system that was originally invented in 1980 to avoid manifold backfiring in pure hydrogen engines. CVI[™] rapidly injects hydrogen in the middle of the engine's intake stroke, and does so more rapidly than any available electrical valve. Now equipped with advanced electronic controls, Brehon claims that CVI[™] will provide many advantages to contemporary natural gas and/or hydrogen engines, including long service life, equal fuel distribution throughout multi-cylinder engines, improved throttle response, and technical transparency of operating principles and maintenance.

CVI[™] technology is now owned by Brehon Energy, and its inventor, Frank Lynch, is a dedicated consultant to the development of the technology. Brehon feels confident that they can use the CVI[™] system as the foundation upon which to develop an on-board blending system for an LNG-fueled vehicle. Brehon proposes to create Hythane[®] on the vehicle using a blender and an electronic control box. It will also require the installation of a hydrogen tank, mounting brackets, and hydrogen plumbing that pipes the pure hydrogen gas to the blender. The CVI[™] system is driven by a timing belt from the crankshaft or the cam of the engine or can be driven from the injection pump in diesel derivative gas engines. To integrate the Hythane[®] and CVI[™] systems on-board the LNG vehicles, Brehon needs to know the minimum supply pressure of the LNG system, after the vaporizer, and the minimum acceptable fuel pressure needed by the engine.

The installation of the hydrogen fuel storage system and piping can be performed by those who normally service the vehicle. Installing the CVI[™] system requires a very thorough understanding of the engine on which the system will be mounted. It requires the following tasks:

- Fabrication of a robust mounting plate for the timing belt drive or a flange for a gear drive;
- Fabrication or adaptation of a timing belt or gear drive connection to the engine;
- Modification the engine's intake manifold or cylinder head to accommodate CVI[™]'s injection nozzles;
- Install and leak check high pressure tubing and gaseous fuel components;
- Install a wiring harness supplied with CVI[™];
- Install a wide range oxygen sensor in the exhaust system;
- Modify the spark timing of the engine's ignition system (for SI engines).

¹⁵ Most of the information in this section courtesy of Greg Egan and Frank Lynch via a confidential memo sent to Cliff Gladstein of GNA on January 10, 2005.

Brehon Energy believes that the maximum benefit would accrue through the use of a Hythane[®] mix of 20% by volume (7% by energy) Hydrogen and 80% natural gas. We propose that this system be added to the existing vehicle. Such a step would avoid the pitfall of producing demonstration vehicles with diminished range, and would actually increase the range of the participating trucks. Determining the volume size of the hydrogen storage system that would be necessary to utilize with the existing LNG system requires the following steps:

- a) Determine the capacity of the LNG tank in standard cubic feet of natural gas;
- b) Multiply by 0.25 to get the volume of hydrogen in standard cubic feet;
- c) To obtain the water volume of a 3,600 pounds per square inch gauge hydrogen tank, divide the result by 214.

Brehon's experience with Hythane[®] plus its efforts to market both the fuel and the technology around the world (Brehon recently negotiated an agreement with a cadre of Chinese interests to convert 10,000 natural gas buses there to Hythane[®]) make its technology a very compelling option for use in the projects proposed in this report.

HCNG₃₀

Another vendor that is prepared to help develop HCNG demonstration projects using on-board blending technology on existing natural gas vehicles is Collier Technologies Inc. (CTI). CTI is a major proponent of HCNG₃₀, a hydrogen-natural gas mix that contains 30% hydrogen by volume. CTI claims that the 30% hydrogen - 70% natural gas blend allows for improved volume and flow characteristics, which leads to increased engine life and reduced maintenance costs.

CTI's experience with the use of HCNG₃₀ in heavy-duty vehicles has primarily been through two initiatives it has undertaken. The most prominent is a partnership that it has developed with Daewoo Heavy Industries and Hess Microgen for the conversion of existing natural gas engines to units capable of being fueled by HCNG₃₀. CTI has modified an 11 Liter, six-cylinder Daewoo natural gas engine that was developed specifically for transit use using its HCNG₃₀ blended fuel. The engine is being optimized for operation on the HCNG₃₀ mixture, including redesigned and cast cylinder heads that allow a quiescent flow needed for hydrogen and HCNG operation. This engine, called the "City Engine" by its development partners, has been tested at NO_x emissions as low as 0.08 g/bhp-hr to 0.14 g/bhp-hr, which is well below the 2007 standard of 0.2 g/bhp-hr.¹⁶ If certified by air quality authorities at these low emission levels, the HCNG₃₀ City Engine could become one of the cleanest ICEs in the world.

Another significant project in which CTI is involved is the Hydrogen Bus Technology Validation Program of the Institute for Transportation Studies at the University of

¹⁶ Bill Siuru, "A Bridge Toward the Hydrogen Economy," in Diesel Progress, November, 2004. See http://www.bestemissions.com/pdf/diesel_paper.pdf.

California. The goal of this project, in which CTI is in partnership with the City of Davis, Yolo County Transportation District, the University of California, Davis (UC Davis), and UniTrans (the transit authority for the City of Davis and UC Davis), is to determine in the HCNG₃₀-fueled bus can “achieve fuel economy and power similar to a standard natural gas powered bus while still meeting California’s strict 2007 transit bus emission standards.”¹⁷ CTI’s role in this project is to convert a John Deere 8.1 CNG engine on a new 40-ft UniTrans bus to run on HCNG₃₀.¹⁸

CTI claims that the technology for on-board mixing of hydrogen and natural gas already exists. They believe that the most complex aspect of on-board mixing will come with engine control. Thus, they say that the “critical path for success of this program will be the ability to enlist the support of the engine OEM.”¹⁹ In addition to recalibrating the engine, CTI lists the following steps in the development of the on-board blending capability:

1. Investigate the vehicle’s size and location constraints
2. Use data from engine testing to size the components
3. Develop heat exchangers and compatible components
4. Determine the size of the needed regulators
5. Develop an electronic feedback control system based on fuel density and pressure
6. Test the integrated mixing system on the dynamometer
7. Install the test apparatus on the vehicle and test
8. Finalize the pre-production unit based on the results of the test

CTI believes that the two most difficult tasks will be working with the engine manufacturer to recalibrate the engine for HCNG₃₀ and the development of the electronic feedback control system. Although it remains to be seen whether CTI can live up to these claims, at least two companies that were contacted for this paper report that they can provide on-board blending technology.

The advantage of the on-board blending approach is two fold. By blending on-board the vehicle the vehicle owner can retain all of the existing engine and fuel storage components. If a project were to blend on-site, this would require the replacement of the existing on-board LNG storage system with compressed gas cylinders. Not only would this add significant cost, but it would also increase the weight of the vehicle while dramatically lowering its range. On-board blending creates the opportunity to actually improve the performance of the vehicle by increasing its range. In addition, by leaving the existing components on the vehicle, the owner need not worry about restoring the vehicle to its prior state once the demonstration project is over. For these reasons, CTI advocates on-board blending.

¹⁷ Marshall Miller, “Hydrogen Enriched Natural Gas Bus,” Institute of Transportation Studies, University of California, Davis, April 2004.

¹⁸ See “Hydrogen Bus Technology Validation Program (HBTVP) – Program Description”, University of California, Davis Institute for Transportation Studies, http://www.its.ucdavis.edu/fcvcenter/HCNG_BUS/.

¹⁹ Neal Mulligan, Chief Operating Officer, Collier Technologies, Inc. in e-mail correspondence, January 5, 2005.

Projected Program Costs

Although an aspect of the scope of work for this project, the authors found that projections for possible demonstration project costs were wholly unreliable. First, most vendors we were not willing to discuss their technology, engineering, and other development costs unless they were responding to a specific request for proposals (RFP). There were a variety of reasons given for this reluctance. Some cited competitive pressures, and wished to keep their costs of their technology from their industry rivals. Most, however, explained that hydrogen technology is so new that they had difficulty knowing what to include for cost projections. Second, those that were willing to offer “guesstimates” of their costs would not stand by them because of the tremendous uncertainties associated both with the scope of the projects and the ever-shifting costs of the components. Thus, the estimates of projected costs for the vehicles and the fueling stations that are proposed by this report and outlined below should be treated as undependable and not be relied upon until more work has been done to collect pertinent data.

The cost of hydrogen production technology is linked to the size of the production. As demonstrations serving a very small market, the hydrogen generation units that are first deployed as a result of this project should be sized accordingly. The National Academy of Sciences estimates that a contemporary 480 kg/day natural gas reformation facility would cost nearly \$1.8 million, but with further research and development, this cost could be reduced to approximately \$950,000.²⁰ The projected cost of the natural gas reformer (using autothermal reformation [ATR] technology) proposed for SunLine Transit in September 2002 was \$1,075,000, while the cost of the steam methane reformer (SMR) unit proposed by BP for use in its Long Beach, California, facility was \$1.5 million.²¹ SunLine’s ATR unit is projected to produce about 3 kg of H₂ per hour, or 72 kg/day. Thus, we can anticipate that the costs of installing hydrogen production at each of the ICTC project sites discussed herein will be in the \$1 million to \$1.5 million range.

Fortunately, the cost of developing and installing the on-board blending unit and the installation of the on-board H₂ storage is more predictable. Some reasonable estimates for the development of these components have been obtained. In Table 7 below is an estimation of the projected program costs that one vendor supplied for the development and installation of both the on-board blending unit as well the calibration of the existing engine to function on a HCNG mix.

²⁰ The upper limit is based on a per kilogram production cost of \$3,847. The lower limit is based on a \$2,000/kg/day production cost. See *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*; National Academy of Engineering, Board of Energy and Environmental Systems, 2004, p. 92.

²¹ See South Coast Air Quality Management District, BOARD MEETING DATE: September 13, 2002 AGENDA NO. 7, <http://www.aqmd.gov/hb/2002/02097a.html>.

Table 7: Projected Costs for HCNG Vehicle Demonstration Project

Task	Cost	Timeline
Recalibrating engine for HCNG	\$200,000	3-6 months
Emission testing	\$50,000	1 month
Installation of engine	\$60,000	1-2 months
Development, testing & installation of cryogenic H ₂ storage vessel	\$60,000	6-8 months
Development, testing & installation of on-board blending unit	\$200,000	4-9 months
	\$570,000	15 – 25 months

Provided by Collier Technologies, Inc., January 2005

These costs only reflect the costs of the conversion, not the base cost of the vehicle.

From the information above, it can be projected that the budget for each of the possible ICTC hydrogen development projects would be in the range of \$1.6 to \$2.2 million. Thus, the budget for development and demonstration of the four primary projects discussed herein would be between \$6.4 and \$8.8 million.

Next Steps

The ICTC provides an excellent opportunity for NREL to join with other energy, air quality, and transportation agencies in the development and demonstration of the integration of hydrogen into in-use heavy-duty natural gas vehicles and infrastructure. Four primary sites have been identified where hydrogen can be produced from existing natural gas fueling stations and integrated onboard existing natural gas vehicles. This proposed series of demonstration projects will help develop new hydrogen infrastructure in critical junctures of the emerging hydrogen highway where there are no current plans to build hydrogen fueling stations. These projects proposed herein will close existing gaps in ongoing Federal, State, and local efforts in the development of hydrogen transportation infrastructure in California and other western states. Further, with the development of these four proposed projects, a viable corridor of hydrogen refueling stations will be established to serve rapidly emerging hydrogen and fuel cell vehicle technologies. This will be the first true hydrogen corridor in the nation, stretching from Las Vegas down into the Los Angeles basin and up through the Central Valley into Northern California and the Bay Area, enabling light, medium, and heavy-duty hydrogen vehicles to navigate the state's highways without fear of running out of fuel.

Beyond establishing the nation's first successful corridor of hydrogen refueling infrastructure, the proposed projects will yield many additional benefits. The ICTC sites will help promote hydrogen use in transportation by encouraging the use of hydrogen in existing vehicles, thus expanding the market for this fuel significantly. These projects will help ease the cost of producing hydrogen for transportation by enabling hydrogen use by thousands of heavy-duty natural gas vehicles. Further, it will provide air quality officials with a powerful new tool to use in their efforts to reduce emissions from diesel powered vehicles by providing a blueprint to secure even further emission reductions from a large existing fleet of natural gas powered vehicles. Finally, the proposed project will lead to the development of important new transportation technologies that will help to accelerate the advent of the hydrogen highway.

If NREL and the DOE agree that the ICTC provides a valuable opportunity to advance the hydrogen agenda, there are a series of steps that the agencies should undertake. The steps outlined below assume that NREL and DOE decide to pursue the projects proposed herein. They are in a rough chronological order, recognizing that some steps can be pursued simultaneously, and that the agencies may prioritize these activities differently.

Identify and Define Needed New Technology

In order for the premise of this report to be achieved, i.e. that existing heavy-duty natural gas vehicles can provide a propitious and excellent platform upon which to build elements of the future's hydrogen highway, there are certain key technologies that will have to be developed and/or improved upon. The three most important include a durable and accurate on-board blending unit; robust and flexible engine/fuel control units that can keep the engine running smoothly even through variations in fuel composition; and

sturdy hydrogen storage technology that can withstand the rigors of heavy-duty truck use. In addition to conventional hydrogen storage, NREL and DOE may also elect to encourage the development of additional on-board hydrogen storage systems (aside from the two proposed by vendors herein), cryogenic storage (for liquefied hydrogen gas, or LHG), and supercritical Hythane[®], a super-cooled cryogenic blend of hydrogen and natural gas that has higher energy density than conventional LHG. The development of these new transportation technologies must be a goal of the next step of this project.

Allocate Resources/Secure Funding Partners

As indicated above, the tentative budget for each demonstration projects proposed herein is between \$1.6 and \$2.2 million. Further research can provide greater fidelity to these estimates, however, this range will provide NREL with a good working number for projected costs.

The Federal government, however, does not have to cover the entire cost of the ICTC hydrogen demonstration projects proposed in this report. There are many potential partners to share costs. First of all, vendors that will be participating in these projects should be required to provide a certain percentage of the budget. Second, since all of the projects proposed herein are located in California, it is highly likely that financial and technical resources can be contributed from sources in the State. These sources could include the State (either through the CaFCP, the Governor's Hydrogen Highway initiative, the Air Resources Board, or the California Energy Commission), local Air Districts (the San Joaquin Valley Unified Air District has substantial resources for such endeavors, as does the SCAQMD), local planning agencies (through a distribution of Congestion Mitigation/Air Quality funds), and other parties. If the Federal government were to provide no more than half of the budget projected above, the balance could very likely be secured from other non-Federal sources.

Assuming that NREL and DOE would like to receive matching funds for any resources that the Federal government may contribute, it is likely that some sort of project steering committee would have to be created in order to secure the commitments from third parties to fund the demonstrations outlined herein. Such a management committee could be administered in a fashion similar to the ICTC Steering Committee, in which project staff are in regular contact with steering committee members and organize, on a monthly basis, a conference call in which policy matters are addressed, progress reports are given, and questions can be asked and answered.

Secure Commitments from Participants

NREL should engage the potential participants in the four primary demonstration projects in formal negotiations to define the parameters of their involvement. Although all of the parties have, as a result of outreach conducted by the authors for this report, expressed keen interest in participating in the concept of HCNG demonstration projects, none have made a commitment to do so. These commitments should now be secured. This will involve securing agreements from the four parties to participate and negotiate their

contributions to the demonstration projects (i.e. responsibilities, in-kind contributions, ownership of technology and fueling infrastructure, access to data, will the trucks and facility be returned to the owner in their original state, etc.). Also, contracts must be negotiated, including non-disclosure and confidentiality forms, insurance coverage, and other administrative items.

Secure and Provide Specifications for the Sites

For vendors to bid on the construction of hydrogen production and dispensing systems that will be attached to existing natural gas fueling facilities, as well as the installation of hydrogen storage and HCNG blending systems on-board existing vehicles, they need to have fairly detailed information about the existing systems. Having these specifications up front will help vendors to determine whether or not their technologies are compatible with the existing fueling infrastructure and vehicles, as well as to perform some of the preliminary engineering prior to the award of the contract.

Although some of this information has been collected as a result of this report, much of it has not. As a part of the step outlined immediately above, NREL should secure existing component specifications and site plans. Thus, as a part of their commitment to participate in the project, site/vehicle owners will have to agree to release these specifications to those who reply to any future solicitation to perform this work. Should NREL and DOE elect to proceed, the ICTC Project can collect the necessary specifications from all of the sites that would be included in the ensuing scope of work.

Ascertain Potential Third Party Use of H₂ Stations

Not all of the vehicles that would use the ICTC hydrogen-dispensing infrastructure need to be existing natural gas vehicles. Other parties may be interested in using these facilities to fuel either future light-duty ICE or fuel cell vehicles or to pursue the development of fuel cell-based transit systems. In either case, the future existence of local hydrogen infrastructure may serve as a motivation for third parties, in particular local governments, to pursue hydrogen-fueled vehicle demonstrations/deployments that they had not previously considered.

Should NREL elect to proceed, it is recommended that the ICTC project contact its existing stakeholders to inform them of the potential for future hydrogen infrastructure and ascertain the interest of these and other potential third parties in using that infrastructure for their plans.

Conclusion

Natural gas vehicles and fueling infrastructure serves as the backbone of the nation's AFV efforts. Now these vehicles and the stations that have been built to serve them can serve as the backbone for the development of the nation's hydrogen-based transportation system. It is the conclusion of this study that the existing natural gas trucks and fueling infrastructure that has been established by the ICTC Project presents an excellent opportunity for accelerating the use of hydrogen in transportation as well as expanding the availability of crucial hydrogen production and dispensing infrastructure along key transportation corridors.

Utilizing the existing system of natural gas transportation technologies makes a great deal of sense for many reasons, not the least of which is that there are already tens of millions of dollars that have been investing in existing infrastructure and vehicles. This existing vehicle stock and potential hydrogen feedstock can be leveraged to serve as the foundation for the creation of the hydrogen highway. Although it will take at least a decade for the automotive industry to introduce significant numbers of fuel cell vehicles, steps can be taken now to create the fueling infrastructure that will be needed to enable commercialization of these hydrogen-dependent technologies. Modifying existing natural gas infrastructure to add hydrogen producing and dispensing technology as well as altering existing natural gas vehicles to consume HCNG blends not only establishes the appropriate market signals to hydrogen vehicle producers, but also provides much needed early consumers of the hydrogen this new infrastructure will produce.

Each of the projects outlined above enjoy a high probability of success. In addition, each adds a significant piece to the development of the future hydrogen infrastructure where none is being worked on now. What is more, the projects suggested here are each in an arena that is not being covered by existing efforts; that of how to integrate hydrogen into the heavy-duty goods movement sector. The proposed ICTC NG-H₂ projects will not only serve the heavy-duty vehicles that they target, but will also provide crucial refueling facilities to the light-duty vehicles being promoted by the other hydrogen development programs.

This report describes the existing natural gas infrastructure along the ICTC, as well as provides recommendations regarding the technology, partners, and steps necessary to integrate H₂ into each of the individual facilities selected. It lists specific elements of each of the proposed projects, as well as the features that will make each of these proposed deployments unique. The projects proposed herein offer NREL and DOE four opportunities to play a crucial and central role in the development of the hydrogen highway in the western United States.

Bibliography

California Hydrogen Blueprint Plan, California Environmental Protection Agency, May 2005. Available on the California Hydrogen Highway Network Web Site in Adobe Acrobat PDF at http://www.hydrogenhighway.ca.gov/plan/reports/volume2_050505.pdf. Accessed September 19, 2005.

Appendix A – Leading Programs to Promote Hydrogen Vehicles

California is home to many of the nation’s leading efforts to develop hydrogen as a transportation fuel. Hydrogen vehicle/infrastructure development programs include those by the SCAQMD, the California Fuel Cell Partnership (CaFCP), and Governor Schwarzenegger’s California Hydrogen Highway.

In order to ensure that the demonstration projects that are proposed in this report do not replicate efforts currently underway by one of these other hydrogen vehicle development projects, and to fill gaps in the infrastructure that may be proposed by these other programs, the authors remained in close contact with these other hydrogen promotion projects. In doing so, these other programs were made aware of the objectives of NREL’s work on HCNG and asked to provide information, where appropriate, of any conflicts, potentially interested stakeholders, and information about hydrogen vehicle demonstration projects that might be able to utilize the HCNG infrastructure that may result from this effort.

Below is a short summary of the primary hydrogen development efforts in the ICTC Project area. These summaries, as well as the project summary in Appendix E, are a comprehensive snapshot of the hydrogen development efforts at the time of writing this report.

SunLine Transit Agency

SunLine Transit Agency (SunLine), located in Thousand Palms, has been a leader in the use of alternative fuels ever since the entire fleet was switched to natural gas vehicles in the early 1990s. SunLine opened its hydrogen refueling facility in 2000 and has the capability to dispense 24 kg/day (of 205 kg/day generated) at 2000, 3600, or 5000 psi and storage capacity for 425 kg.

SunLine used their hydrogen station to fuel the first fuel cell bus placed into revenue service in 2002. This 30-ft bus, called ThunderPower, was a joint venture between ISE Research of San Diego and Thor Industries, which is based in Chino, CA. The prototype bus was



Figure 3. Sunline Transit’s fuel cell powered Z-Bus at its hydrogen fueling station

powered by a 60 kW Proton Exchange Membrane (PEM) fuel cell provided by UTC Fuel Cell, a division of United Technologies, and a deep-cycle, 600 volt, DC battery pack. The 34,000 GVWR vehicle can accommodate 26 passengers, and is powered by a dual motor/controller that has a continuous power rating of 170 kW (~230 hp). The Siemens ELFATM propulsion system is made up of two electric motors coupled with independent controllers to provide motive power to the wheels. Fuel was provided by delivering pure hydrogen gas into pressurized cylinders onboard the vehicle, which was produced by SunLine Transit either from natural gas or water using two prototype hydrogen production units from Stuart Energy (water) or Hydrogen Burner Technologies (natural gas). When a six month test period ended in April 2003, the bus proved to be 72% reliable in carrying passengers more than 100 miles a day.²² More importantly, the unit averaged about 11 miles per gasoline gallon equivalent, which proved to be more than twice as energy efficient as Sunline's comparable natural gas buses in similar duty cycles

With funding from DOE through NREL and SCAQMD, SunLine initiated a project to demonstrate two buses operating on a mixture of 80% natural gas and 20% hydrogen by volume. (also known as HCNG or Hythane®). Cummins Westport Inc. (CWI) upgraded the CWI B Gas Plus engines on the buses and Hydrogen Components Inc. of Littleton, Colorado also participated, providing valuable fuel expertise and knowledge. The demonstration produced impressive emission reductions, with NO_x and NMHC emissions reduced by 50%, while CO and CH₄ emissions were slightly reduced and CO₂ emissions reduced by 7%.

SunLine began a demonstration of a Hyradix 100 Nm³/h Adéo™ hydrogen fuel generator in May 2004. The Adéo hydrogen generator uses high pressure auto-thermal reforming technology to convert natural gas or propane into high purity, ultra-low CO hydrogen. The Adéo unit forms the core of the first reformer-based hydrogen refueling station operating in the State of California. SunLine is also involved with the hydrogen fueling station project at WinTec in nearby Palm Springs, which uses wind electrolysis with 3 Nordtank 65kW wind turbines to produce 3 kg/hr and the capability to produce up to 9000 kg H₂/yr with storage for 25 kg at 6,000 psi.

South Coast Air Quality Management District

SCAQMD has embarked on an effort to demonstrate a fleet of hydrogen ICE vehicles with a corresponding network of hydrogen refueling stations in the South Coast Air Basin. This effort will have Quantum Technologies convert 35 model year 2004 Toyota Prius vehicles to operate on hydrogen ICEs with refueling stations located at the "Five Cities" including: City of Burbank; City of Ontario; City of Riverside; City of Santa Ana; and City of Santa Clarita. This \$4 million project is being co-funded by the Department of Defense, Quantum Technologies, Texaco Ovonic Hydrogen Systems; the "Five Cities"; and the SCAQMD.

²² This means that on 72% of days the bus was able to carry passengers for 100 miles or more, which is a typical Sunline Transit route.

Table 8: SCAQMD “Five Cities” Funders

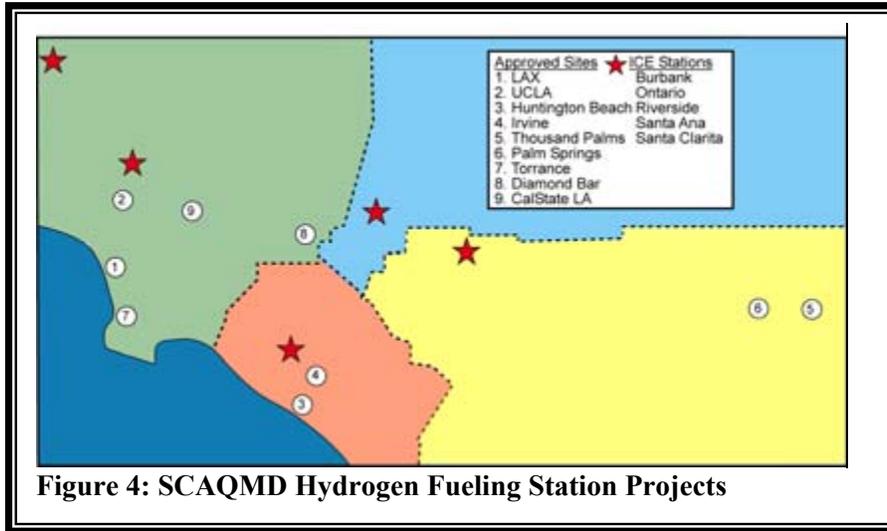
Name	Amount
Department of Defense	\$500,000
Quantum Technologies	\$535,780
Texaco Ovonic Hydrogen Systems	\$360,000
Five Cities	\$625,000
SCAQMD	\$2,030,000
Total	\$4,050,780

The SCAQMD has also been involved with the establishment of other hydrogen refueling stations in the South Coast Air Basin. SCAQMD held the grand opening of a hydrogen fueling station at its Diamond Bar headquarters on August 13, 2004 and its fleet includes 2 Honda FCV vehicles, which are also deployed at the City of Los Angeles and the City of San Francisco. The station utilizes an electrolyzer from Stuart Energy that has the capability to dispense hydrogen at 1 kg/hr production at 5,000 psi and has storage capacity for 60 kg in cascading tanks.

Table 9: South Coast AQMD Projects

Location	Project Team
South Coast AQMD – Diamond Bar	Stuart Energy, Honda, Quantum Technologies
City of Burbank	Five Cities, Air Products, Quantum Technologies
California State University, Los Angeles	Proton Energy, Honda, Quantum Technologies
City of Huntington Beach	South Coast AQMD
Los Angeles International Airport	Praxair, British Petroleum, US Department of Energy, California Energy Commission, DaimlerChrysler
City of Ontario	Five Cities, Praxair, Quantum Technologies
City of Riverside	Five Cities, Air Products, Quantum Technologies
City of Santa Ana	Five Cities, Air Products, Quantum Technologies
City of Santa Clarita	Five Cities, Air Products, Quantum Technologies
UCLA	British Petroleum, DaimlerChrysler
WinTec Wind Farm – Palm Springs	ISE Corporate

SCAQMD was a partner in the hydrogen station at Los Angeles International Airport that held its grand opening on October 22, 2004. This station utilizes a Stuart Energy HydroPac CPI electrolyzer dispensing 24 kg/day at 5000psi and has storage capacity for 60 kg steel cylinder at 6450psi with 307kg/2400psi tube trailer supplement. This project was a joint effort between Los Angeles World Airports, Stuart Energy, Praxair, British Petroleum, UCLA, and SCAQMD. SCAQMD is also supporting the existing hydrogen fueling stations at SunLine Transit and the WinTec Wind Farm, as well as the hydrogen fueling station projects at UCLA, City of Huntington Beach, and California State University, Los Angeles.



California Fuel Cell Partnership

The CaFCP was formed in 1999 to help advance the commercialization of fuel cell vehicles. The loose organization does not have an independent budget, and is staffed by Air Resources Board. Its membership is composed of more than 30 companies and organizations from around the world, including automobile manufacturers, fuel providers, fuel cell companies, and government agencies. The CaFCP operates a research facility in West Sacramento and a Hydrogen production facility in Richmond. The Partnership promotes public awareness programs regarding emerging fuel cell vehicle technology, and tries to steer resources from other public agencies to projects it endorses. The CaFCP is involved with the demonstration of seven fuel cell buses in three fleets, including Sunline Transit, Santa Clara Valley Transportation Authority, and AC Transit.

The CaFCP's hydrogen fueling station opened in November 2000, and dispenses CH₂ from trucked-in LH₂ via NG SMR; 3600 and 5000 psi with storage capacity for 4,500 gallons for LH₂. The station utilizes fueling appliances from Air Products and Praxair. There are several OEM's that maintain offices and demonstration hydrogen vehicles at the CaFCP, including: DaimlerChrysler, Toyota, Honda, and Hyundai.

Table 10: California Fuel Cell Partnership Projects

Location	Project Team
California Fuel Cell Partnership – Sacramento	Air Products, Praxair, DaimlerChrysler, Toyota, Honda, Hyundai
AC Transit City of Richmond Operating Division	Stuart Energy, AC Transit

The Alameda-Contra Costa Transit District (AC Transit), in coordination with the CaFCP, opened a hydrogen fueling station at its City of Richmond Operating Division, located at 2016 MacDonalD Ave, in October 2002. This station utilizes Stuart Energy's water electrolysis technology for generating hydrogen, and the fuel can be dispensed at either 3,600 or 5,000 psi. CaFCP vehicles fuel at this station, and AC Transit will be fueling its fleet of Van Hool fuel cell buses when they arrive in the summer of 2005. AC Transit is managing a \$15 million program to integrate UTC fuel cells into three Van Hool 40 ft-low floor buses. ISE Corporate will integrate the fuel cells and the hybrid-electric drive systems. Each bus is projected to cost \$3.13 million, plus a \$550,000 2-year warranty per bus. As originally planned, delivery of the three buses was projected to take place between July and December, 2004. This has been shifted into September, 2005. Operational data, therefore, will not be available, at the earliest, until mid-2006. This project uses the Sunline Transit ThunderVolt bus as a prototype, but will have advanced components. Primary funders include CARB, BAAQMD, FTA, CEC, and the DOE Clean Cities Program.

California Hydrogen Highway Network Action Plan

In April, 2004 California’s Governor Arnold Schwarznegger signed Executive Order S-7-04 committing the State to “achieving a clean energy and transportation future based on the rapid commercialization of hydrogen and fuel cell technologies.” The Executive Order also designated the state’s 21 interstate freeways as California’s Hydrogen Highway Network, and called on all pertinent state agencies to work with stakeholders to develop a plan by January 1, 2005 that would lead to the development of a network of hydrogen fueling stations that would enable every Californian to have access to hydrogen as a transportation fuel. In subsequent documents from the Governor’s office, Schwarznegger expounded upon his vision and established a goal of between 150 and 200 hydrogen fueling stations throughout the state.

In the months that followed, an ad hoc committee of dozens of volunteers worked tirelessly to fill in the details of Schwarznegger’s hydrogen highway vision. The effort, which was primarily coordinated by the staff of CARB and the California Energy Commission, focused on the development of a Blueprint Plan, a document designed to provide a detailed guide for how the state could accelerate to commercialization of

hydrogen and fuel cell technologies, which is an interim goal of achieving the Governor's 2010 infrastructure development objectives. The effort was divided into several "Topic Teams," each of which was charged with investigating and reporting to the Governor on certain aspects of the emerging hydrogen energy future. The authors of this report asked to participate on the Commercialization and the Applications Subgroups of the Blueprint and Timeline Teams. Each of the Topic Teams completed their work in December 2004, and submitted their draft reports to the Senior Review Panel for finalization. The final report was published in May 2005, and can be found on the web.²³

DOE's Hydrogen, Fuel Cells & Infrastructure Technologies Program

DOE has a long history of research, development, and demonstration of hydrogen technologies. During the last decade, this work has received a great deal more attention and resources. In February, 2002 the DOE published "A National Vision of America's Transition to a Hydrogen Economy – 2030 and Beyond," which serves as a guide for the Department's hydrogen energy development.²⁴ The program coordinates all efforts in the Department on hydrogen and fuel cell research, with an emphasis on promoting public-private partnerships to achieve multiple technological development goals. As enumerated on the Program's website, these objectives include:

- Overcome technical barriers through research and development of hydrogen production, delivery, and storage technologies, as well as fuel cell technologies for transportation, distributed stationary power, and portable power applications.
- Address safety concerns and develop model codes and standards.
- Validate and demonstrate hydrogen and fuel cell in real-world conditions.
- Educate key stakeholders whose acceptance of these technologies will determine their success in the marketplace.²⁵

To achieve these objectives, the Program has implemented a technology validation project. Each validation project is structured as a team led by automobile manufacturers or energy company that is developing a hydrogen fueled vehicle. The team leader is joined by additional team members, stakeholders in the target technology, including the fuel (hydrogen) suppliers, fuel cell manufacturers, utility or gas companies, fleet operators, system and component providers, academic/research institutions, and government entities that play a role in the development, demonstration, testing, and evaluation of a particular technology. In addition to assisting in the validation of the technology, the stakeholders work on the development of codes and standards, fire and safety protocols, and a comprehensive, integrated education and training campaign. Each team works in partnership to demonstrate not only the vehicle technology, but all of the elements that will eventually need to be in place in order to ensure the success of

²³ <http://www.hydrogenhighway.ca.gov/plan/plan.htm>

²⁴ See http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/vision_doc.pdf

²⁵ See <http://www.eere.energy.gov/hydrogenandfuelcells/about.html>.

hydrogen technology in real world environments. The goal of these demonstrations is to reach a point where the teams' progress can be assessed in reference to the goal of making a commercialization decision by 2015.

In April 2004, DOE selected five teams to participate in "learning demonstrations" that include testing, demonstrating, and validating hydrogen fuel cell vehicles and infrastructure and vehicle and infrastructure interfaces for complete system solutions. These teams are summarized in the table below.

Table 11: DOE Hydrogen Fleet and Infrastructure Demonstration

Lead	Partner(s)	Additional Team Members
Air Products and Chemicals, Inc.	Toyota Motor Sales; Nissan North America; American Honda Motors; ConocoPhillips; BMW	UTC Fuel Cells; Proton Energy Systems; University of California, Davis; Southern California Edison; California Energy Commission; California Air Resources Board; South Coast Air Quality Management District; Sacramento Metropolitan Air Quality Management District
DaimlerChrysler Corp.	BP America	DTE Energy; SAIC; SRI International; Ballard; NextEnergy; California Fuel Cell Partnership; National Hydrogen Association
Lead	Partner(s)	Additional Team Members
Ford Motor Company	BP America	Ballard; NextEnergy; Environmental Protection Agency; H2Systems; Sacramento Municipal Utility District; California Energy Commission; California Air Resources Board; Progress Energy
General Motors Corp.	Shell Oil Products	Air Products and Chemicals, Inc.; Praxair; GE Global Research; NextEnergy; Viewpoint Systems, Inc.; Strat@comm Inc.; Department of the Army; Port of Los Angeles; Maryland Energy Administration; New York State Energy Research and Development Authority
Texaco Energy Systems LLC	Hyundai Motor Co.	UTC Fuel Cells; University of California, Davis; AC Transit; Southern California Edison; South Coast Air Quality Management District; California Energy Commission; California Air Resources Board; New York State Electric and Gas/Rochester Gas and Electric

Appendix B – Possible Funding Sources For Hydrogen Vehicle and Infrastructure Projects

The following list represents some of the more prominent programs that can support low-emission vehicle deployment and fueling infrastructure development in California.

LOCAL FUNDING SOURCES

Bay Area Air Quality Management District (BAAQMD)

✧ Transportation Fund for Clean Air

Program Description: The TFCA is funded by a \$4 surcharge on motor vehicles registered in the Bay Area and covers a wide range of projects, including purchase or lease of clean fuel buses, purchase of clean air vehicles and shuttle buses to train stations. Any public agency such as a city, county, school district or state agency within the Air District's jurisdiction can apply for TFCA funds. BAAQMD jurisdiction encompasses all of Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, and Santa Clara counties, and the southern parts of Solano and Sonoma counties. Funds are available through two main channels: the Regional Fund and the County Program Manager Fund. The Regional Fund receives 60% of revenues and is allocated directly by the BAAQMD. The Program Manager Fund constitutes the other 40% of revenues and is allocated by the Bay Area's nine county congestion management agencies (CMA). Public agencies can apply for funding either directly through the Air District, or through their county CMA.

Level of Funding: \$20 million per year for both the Regional Fund and the County Program Manager Fund combined.

Proposals Due: Applications for the Regional Fund are typically due end of June and applications for County funding are due the end of April.

Contact: Juan Ortellado (Grants Program Manager) at 415-749-5183 or jortellado@BAAQMD.gov. Additional information is available at the BAAQMD website at http://www.baaqmd.gov/pln/grants_and_incentives/tfca/index.asp.

✧ The Carl Moyer Memorial Air Quality Standards Attainment Program

Program Description: State program with funds allocated by Air District (See description below in State Funding Sources section)

Level of Funding: Approximately \$2.5 million.

Proposals Due: RFP issued in July 2005 with proposals due in September 2005

Contact: David Burch 415-749-4641 dburch@baaqmd.gov

Mojave Desert Air Quality Management District (MDAQMD)

✧ The Carl Moyer Memorial Air Quality Standards Attainment Program

Program Description: State program with funds allocated by Air District (See description below in State Funding Sources section)

Level of Funding: \$100,000

Proposals Due: Accepted on an on-going basis

Contact: Roseana Navarro-Brasington 760-245-1661x5706
rnbrasington@mdaqmd.ca.gov

❖ **Mobile Source Emission Reductions Program**

Program Description: Assembly Bill 2766 authorized air pollution control districts and air quality management districts to impose a \$1 to \$4 motor vehicle registration fee to provide funds for air districts to meet new responsibilities mandated under the California Clean Air Act. As enacted in the California Health & Safety Code, AB 2766 states that the fees shall be used to support district operated planning, monitoring, enforcement and technical studies necessary to implement the CCAA. An additional allowable use is to support programs that reduce air pollution from motor vehicles. MDAQMD uses a portion of the AB 2766 fees that it collects to support projects which reduce motor vehicle emissions.

Level of Funding: Approximately \$600,000

Proposals Due: Next call for proposals in late 2006 or early 2007

Contact: Roseana Navarro-Brasington 760-245-1661x5706
rnbrasington@mdaqmd.ca.gov

San Diego Air Pollution Control District

❖ **The Carl Moyer Memorial Air Quality Standards Attainment Program**

Program Description: State program with funds allocated by Air District (See description below in State Funding Sources section)

Level of Funding: Approximately \$2 million

Proposals Due: 05-06 funding expected in January 2006 with an RFP issued in February 2006.

Contact: Chuck Spagnola 858-650-4700.

San Joaquin Valley Air Pollution Control District (SJVAPCD)

❖ **The Carl Moyer Memorial Air Quality Standards Attainment Program**

Program Description: State program with funds allocated by Air District (See description below in State Funding Sources section)

Level of Funding: \$2.8 million

Proposals Due: On-going and funds are distributed on a first-come first-served basis

Contact: Todd DeYoung 559-230-5800 for specific program questions, or applications are available from the hotline at 559-230-5858.

❖ **Heavy-Duty Engine Program**

Program Description: The SJVAPCD has funding available for the repower, replacement or retrofit of on-road diesel engines, as well as retrofitting or repower of locomotive engines and non-commercial marine vessel engines. Funding is also available for the development of infrastructure to dispense alternative fuel (either liquid or gaseous) for heavy duty vehicles. Small scale liquefaction facilities are also eligible. Since the funding is intended to decrease the expense associated with the purchase of cleaner technologies, the amount of money a project can receive will depend on the price difference between the reduced emission technology and engines meeting the current standards. Any public agency, company or individual may apply to receive funding under this program.

Level of Funding: Funding for this program varies as funds are provided through several sources, including the Carl Moyer Program and the Department of Motor Vehicles.

Proposals Due: Deadline is on-going and funds are distributed on a first-come first-served basis.

Contact: The San Joaquin Valley Air Pollution Control District at 559-230-5800 or visit the SJVAPCD website at www.valleyair.org.

South Coast Air Quality Management District (SCAQMD)

❖ **Technology Advancement Program**

Program Description: The SCAQMD's Technology Advancement Office (TAO) provides co-funding for research and development projects to assist in the commercialization of

advanced low-emission mobile and stationary technologies. The programs are designed to allow for voluntary introduction and market penetration of these new technologies. Mobile source projects have included development and demonstration of less-polluting automobiles, buses, trucks, construction equipment, boats, locomotives and other off-road vehicles. The technical areas identified as priorities include diesel alternatives, electric and hybrid-electric technologies, hydrogen and fuel cell technologies, as well as infrastructure development.

Level of Funding: Approximately \$8 million annually.

Proposals Due: Projects are solicited via specific requests for proposals on an as-needed basis; unsolicited proposals are accepted as well.

Contact: Matt Miyasato (Technology Demonstrations Manager) 909-396-3249 or visit www.aqmd.gov

✧ **Air Quality Investment Program (AQIP)**

Program Description: The AQIP is a fund created by the SCAQMD, which allows employers in the South Coast Air Basin to invest annually into a SCAQMD administered fund, rather than implement other programs to meet employers' vehicle miles traveled reduction targets. The objective of the program is to utilize revenues collected in the AQIP to fund alternative mobile source emission/trip reduction strategies that are potentially more effective and could result in greater overall emissions reductions. Some programs that could be considered to receive funding may include the procurement of low-emission, alternative fuel or zero emission vehicles.

Level of Funding: Approximately \$2 million

Proposals Due: Anticipated May 2005 with proposals due in summer 2005.

Contact: Fred Minassian (SCAQMD) at 909-396-2641. Full program details can be found at <http://www.aqmd.gov/trans/aqip.html>

Mobile Source Air Pollution Reduction Review Committee

✧ **Discretionary Fund from Motor Vehicle Registration Fees (AB 2766)**

Program Description: AB 2766 provides for the collection of an additional \$4 in motor vehicle registration fees to fund various air pollution efforts. Thirty percent of each dollar collected on this surcharge is deposited by the AQMD into a "Discretionary Fund" to be used to implement or monitor programs to reduce motor vehicle air pollution. To determine which projects should be funded by the Discretionary Fund, AB 2766 also provided for the creation of the Mobile Source Air Pollution Reduction Review Committee (MSRC) which develops a Work Program for evaluating projects and makes a final recommendation to the SCAQMD Governing Board. Funds for FY04-05 have been allocated and the 05-06 Work Program is expected to be adopted in the third quarter of 2005. MSRC funding is available for public or private projects. Core programs that have typically been approved include: On Road Heavy Duty Alternative Fuel Program, Off Road Heavy Duty Alternative Fuel Program, Local Government Match Program and Alternative Fuel and Advanced Technology Transit Bus Program

Level of Funding: Approximately \$20 million each year.

Proposals Due: Anticipated release of 05-06 RFPs is in the fall of 2005.

Contact: Ray Gorski (MSRC Technical Advisor) at 909-396-2479.

✧ **Local Government Subvention Funds**

Program Description: Forty percent of the AB 2766 funds collected are distributed to local governments based on a pro-rated share of population and must be used to reduce mobile source emissions. These funds are used primarily by municipalities for their own projects, which can include the purchase of alternative fuel and electric vehicles and related infrastructure. These monies also can be allocated by cities and counties for public-private partnerships to pursue alternative fuel projects. Funds not expended carry over from year-to-year.

Level of Funding: Local governments in the South Coast Air Basin receive approximately \$16 million annually.

Proposals Due: Not applicable.

Contact: Larry Rhinehart (SCAQMD), at 909-396-2398 or Oscar Abarca (SCAQMD), at 909-396-3242 or visit www.aqmd.gov.

STATE FUNDING SOURCES

California Air Resources Board (CARB)

✧ The Carl Moyer Memorial Air Quality Standards Attainment Program

Program Description: The Carl Moyer Program provides grants for operators of heavy-duty, on- and off-road vehicles and equipment to purchase *new* low-emission vehicles and retrofit *existing* vehicles with low-emission technologies. The funds support the purchase of low emission trucks, off-road equipment, marine vessels, auxiliary power units, locomotives and stationary agricultural pumps. In addition, AB923, which was recently signed by the Governor, significantly expands the scope and funding of the program to include light-duty vehicle programs, projects that reduce only ROG or PM (such as PM traps), agriculture sources such as confined animal facilities and heavy-duty fleet modernization programs. Local air districts administer the Moyer Program and have established their own respective program guidelines, which must comply with CARB-established minimum criteria.

Level of Funding: Up to \$140 million per year for each of the next ten years (\$1.4 billion in total)

Contact: For information on contacting your local air district, call 800-242-4450 or visit the ARB website at: www.arb.ca.gov/msprog/moyer/contacts.htm

FEDERAL FUNDING SOURCES

U.S. Department of Energy (U.S. DOE)

✧ State Energy Program ~ Clean Cities

Program Description: The U.S. DOE allocates funds to states under the State Energy Program (SEP). The program is administered by state energy agencies, such as the California Energy Commission, for a variety of projects that promote the conservation of energy. Program categories typically include: the purchase of light, medium and/or heavy-duty alternative fuel vehicles; the development of alternative fuel refueling infrastructure; facility/shop modifications for working on natural gas vehicles; and personnel training.

Level of Funding: Approximately \$4 million annually.

Release Date: February 2006

Proposals Due: March 2006

Contact: Clean Cities Coalition Coordinator in your region
<http://www.eere.energy.gov/cleancities/coordinators.html> or Peter Ward (CEC) at 916-654-4639

U.S. Environmental Protection Agency (U.S. EPA)

✧ West Coast Diesel Emissions Reductions Collaborative

Program Description: The EPA has convened the West Coast Diesel Emissions Reductions Collaborative to focus on reducing toxic diesel emissions in some of the most highly impacted communities on the West Coast. The Collaborative includes U.S. EPA, U.S. Department of Agriculture Natural Resource Conservation Service, U.S. Department of Energy, U.S. Department of Transportation, Canada and Mexico, as well as state, local, non-

profit and private sector partners from Alaska, California, Oregon and Washington. The Collaborative will create incentives for early application of federal and state diesel engine and fuel standards, apply market-based incentives to reduce air pollution from diesel sources such as ships, railroads, trucks, buses, and construction and agricultural equipment and will support on-the-ground mobile and stationary diesel engine retrofits, rebuilds and replacements, anti-idling measures and cleaner fueling infrastructure projects.

Level of Funding: In the fall of 2004, the Collaborative highlighted \$1.5 million in EPA grants that leveraged over \$9 million in matching funds. In addition, as part of Faster Freight Cleaner Air's opening remarks, EPA will announce a Request for Proposal for additional projects. These awards are part of a larger Collaborative vision to leverage millions of dollars in federal funding for over the next 5 years.

Contact: <http://www.epa.gov/air/westcoastdiesel/about.html>

FEDERAL/STATE JOINT PROGRAMS

✧ Congestion Mitigation and Air Quality Improvement (CMAQ) Program

Program Description: The CMAQ program was first authorized when Congress adopted the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991, receiving about \$6.0 billion. The Transportation Equity Act for the 21st Century (TEA-21) increased CMAQ authorizations to \$8.1 billion. CMAQ funding in current TEA-21 reauthorization proposals range between \$8.9 billion to \$13.4 billion. CMAQ funds are allocated to states for surface transportation and other related projects that contribute to air quality improvements and reduce congestion in areas designated as nonattainment or maintenance for primary pollutants, such as transportation control measures (TCMs). In addition to more traditional traffic flow and transit improvement projects, the CMAQ program supports efforts to promote the use of alternative fuels and allows its funds to be expended on public-private partnerships. The flexibility provided by the CMAQ program and the myriad of eligible projects often result in more demand for CMAQ funding than what is available or can reasonably be assumed to become available. This is complicated by the practice of administering agencies to program several years' worth of CMAQ funding in advance with the result that future-year CMAQ allotments may already be programmed. Therefore, it is recommended that interested parties contact the local county transportation commission or metropolitan planning organization as soon as possible to determine whether funding is available and what application deadlines are approaching.

Level of Funding: California received about \$2.0 billion in CMAQ funds between Fiscal Year 1998 and Fiscal Year 2003, or about \$334 million a year.

Proposals Due: Tied to the planning cycles of metropolitan planning organizations or county transportation commissions.

Contact: Your local county transportation commission or metropolitan planning organization.

TAX INCENTIVES

✧ Federal Tax Deduction for Alternately Fueled Vehicles

Program Description: The Federal government allows for a tax deduction on the purchase of a new original equipment manufacturer (OEM) qualified clean fuel vehicle, or for the conversion of a vehicle to use a clean-burning fuel based on the gross vehicle weight (GVW) and types of vehicles. The tax deduction for clean fuel vehicles is available for business or personal vehicles, except EVs eligible for the federal EV tax credit. The deduction is not amortized and must be taken in the year the vehicle is acquired.

The following is a summary of information provided by the Internal Revenue service website regarding federal tax deductions for clean fuel vehicles. We make no guarantees as to the accuracy of this information. In order to determine you potential specific tax benefit of this incentive, please consult with a tax professional. Further information can be found at the following websites:

<http://www.irs.gov/formspubs/page/0,,id%3D104102,00.html>
<http://www.irs.gov/formspubs/page/0,,id%3D12063,00.html>

The following chart details the maximum federal tax deduction as determined by the GVW of the vehicle and the year it was purchased. There are currently no federal tax deductions for alternative fuel vehicles for purchases made after December 31, 2006.

Available Tax Deduction				
GVW	<2004	2004	2005	2006
<10,000 lbs.	\$2,000	\$2,000	\$2,000	\$500
10,000-26,000 lbs.	\$5,000	\$5,000	\$5,000	\$1,250
26,001+ lbs.	\$50,000	\$50,000	\$50,000	\$12,500

❖ **Federal Tax Deduction for Alternative Fuel and Electric Recharging Infrastructure**

Program Description: A tax deduction of up to \$100,000 per location is available for qualified clean fuel refueling property or recharging property for EVs. Clean-burning fuels include: natural gas, liquefied natural gas, liquefied petroleum gas, hydrogen, electricity, and any other fuel that is at least 85% alcohol or ether. Clean-fuel vehicle refueling property is defined as any property (other than a building or its structural components) used to store or dispense a clean-burning fuel into the fuel tank or to recharge motor vehicles propelled by electricity. The deduction cannot be claimed by tax-exempt organization or government agencies, or if the property is predominantly to furnish lodging. Furthermore, the deduction is only allowed in the tax year that the property is placed into service.

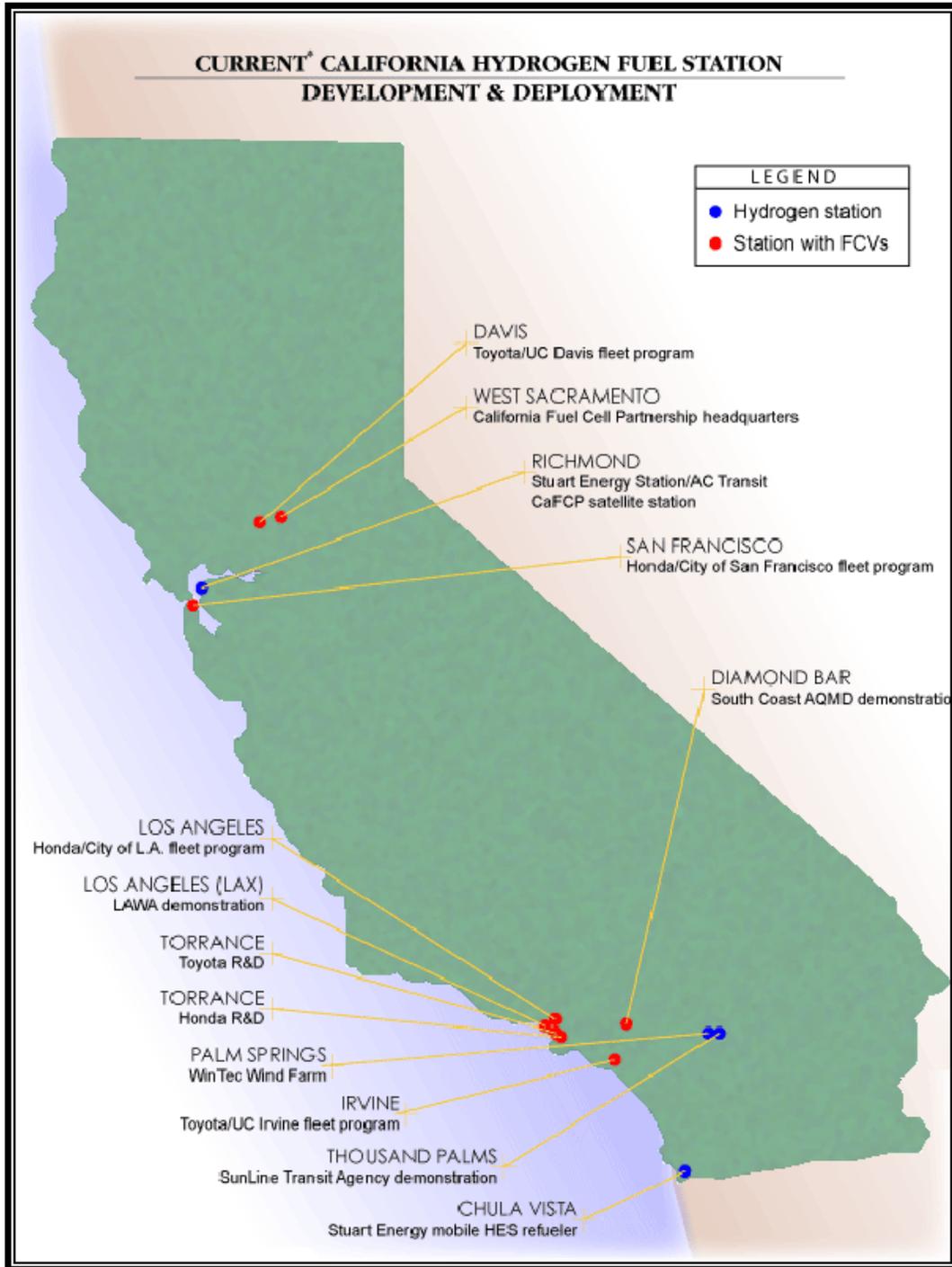
State and Local Tax Incentives

❖ **Operation Clean Air**

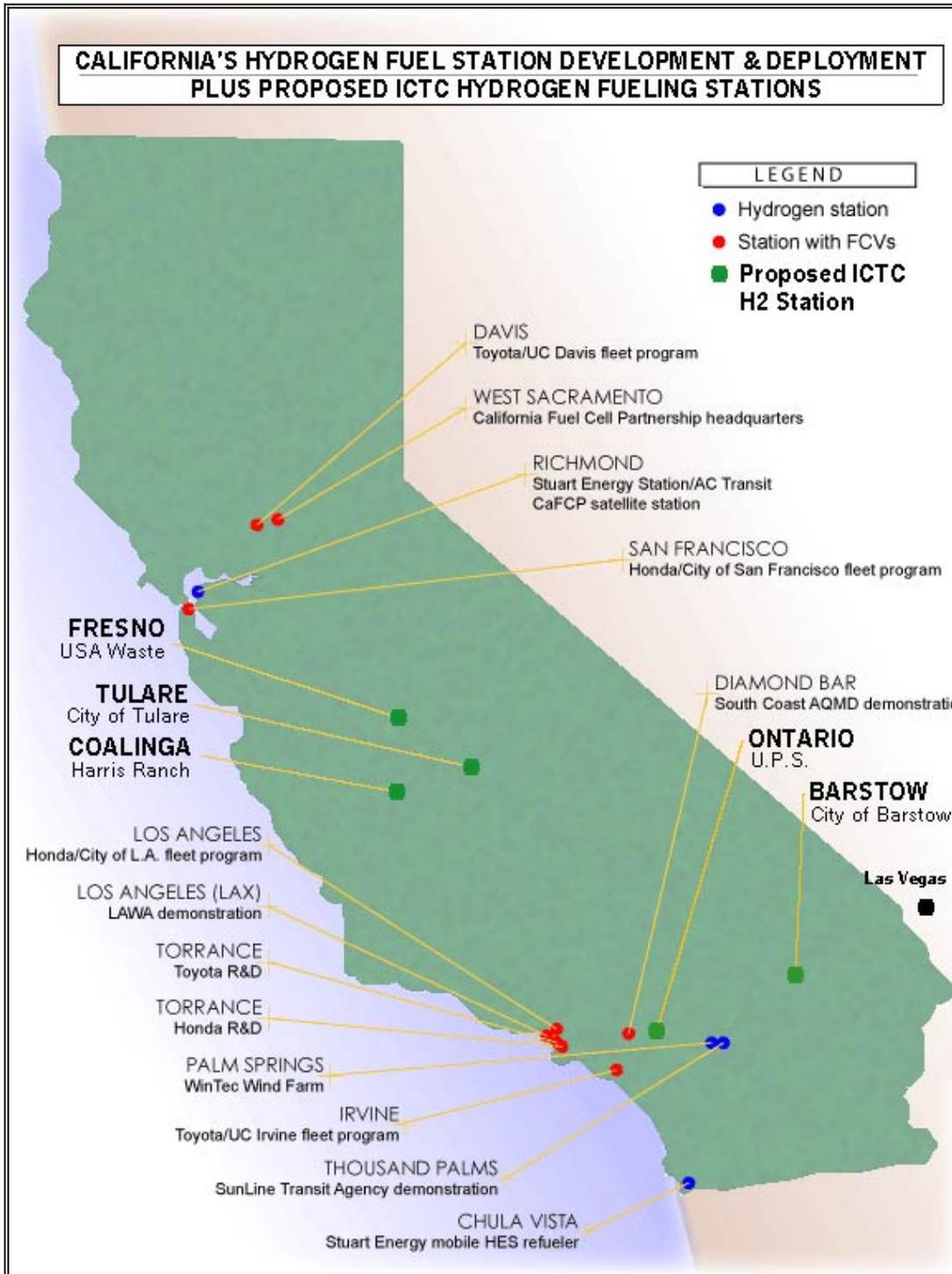
Program Description: Operation Clean Air, a coalition led by governments and industry, is working to secure \$50 million in federal funding for the San Joaquin Valley under a proposed new and innovative Air Quality Empowerment Zone. This creative use of tax credits will provide incentives to clean the air.

Level of Funding: Potentially \$50 million

Appendix C – California Fuel Cell Partnership Map of Current Hydrogen Vehicle & Station Development Projects



Appendix D – Map of Current Hydrogen Vehicle & Station Development Projects with Proposed ICTC Hydrogen Demonstration Projects Added



REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) September 2005		2. REPORT TYPE Subcontractor Report		3. DATES COVERED (From - To) 4/22/04 - 08/31/05		
4. TITLE AND SUBTITLE Strategy for the Integration of Hydrogen as a Vehicle Fuel into the Existing Natural Gas Vehicle Fueling Infrastructure of the Interstate Clean Transportation Corridor Project: April 22, 2004–August 31, 2005			5a. CONTRACT NUMBER DE-AC36-99-GO10337			
			5b. GRANT NUMBER			
			5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S) Gladstein, Neandross & Associates			5d. PROJECT NUMBER NREL/SR-540-38720			
			5e. TASK NUMBER FC05.9000			
			5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Gladstein, Neandross & Associates 3015 Main St., Suite 300 Santa Monica, CA 90405				8. PERFORMING ORGANIZATION REPORT NUMBER LCM-4-44175-01		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				10. SPONSOR/MONITOR'S ACRONYM(S) NREL		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/SR-540-38720		
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES NREL Technical Monitor: Richard Parish						
14. ABSTRACT (Maximum 200 Words) An evaluation of opportunities to integrate hydrogen into the natural gas vehicles and fueling stations of the Interstate Clean Transportation Corridor--an existing network of over 600 heavy-duty trucks and 20 fueling stations in California and Nevada fueled by liquefied natural gas.						
15. SUBJECT TERMS hydrogen highway; Interstate Clean Transportation Corridor; ICTC; natural gas fueling infrastructure; transition from natural gas to hydrogen						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18