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A Compendium

Hydrogen-Blend and Hydrogen Fueled Internal Combustion Engine Activities



Fall 2006
Early Version

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13. ABSTRACT (Maximum 200 words) **This report provides information on activities related to hydrogen internal combustion engines (HICE) and hydrogen-blend gaseous fueled internal combustion engines (HBICE). Hydrogen is an attractive fuel for vehicle power and other applications because it produces an exhaust that is nothing but water vapor, with other emissions controllable to near zero levels eliminating air pollution and no carbon dioxide to exacerbate climate change. Hydrogen can be burned in a more-or-less standard internal combustion engine but applicable technology for improvement of performance, thermal efficiency and emissions are available in the near term. This compendium documents a number of heavy duty drivetrain developments. This document provides some visibility into pertinent activities being performed at U.S. federal government agencies that relate to technology developments for internal combustion engines fueled by hydrogen or hydrogen-blends. Important activities are also being performed at the state and local levels and in the private sector. Some automobile manufacturers are pursuing HICE production vehicles research. Likewise, some private concerns aspire to enter smaller niche markets such as off-road vehicles on airports or stationary power generation.**

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Forward

This report represents one part of an effort to provide information to the U.S. transit authorities on activities related to hydrogen internal combustion engines (HICE) and hydrogen-blend gaseous fueled internal combustion engines (HBICE). Scientists are focusing on the use of hydrogen as a source of energy. Hydrogen is an attractive fuel for automotive power and other applications because it produces an exhaust that is nothing but water vapor, with other emissions controllable to near zero levels eliminating air pollution and no carbon dioxide to exacerbate global warming. Hydrogen can be burned in a more-or-less standard internal combustion engine but applicable technology for improvement of performance, thermal efficiency and emissions are near term.

Unfortunately, pure hydrogen extracted from natural gas has an inevitable by-product of the process -- carbon dioxide -- the very thing that the use of hydrogen is intended to eliminate. The industry and scientists are looking at a host of alternatives for production on an industrial scale from renewable sources of hydrogen to capturing vented hydrogen from manufacturing processes.

This document is prepared with the support and guidance of the FTA, some original equipment manufacturers, and some vehicle manufacturers as part of a program designed to also assist the public with readily-available, pertinent information about engines for use in HICE vehicle implementations. This information can aid in conceptual decision-making and communication to the community about features that may offer a path forward to hydrogen as a transportation fuel and encourage the use of hydrogen for cleaner, lower-emission vehicles. The report is to serve as a discussion paper for industry dialogue and may be updated from time-to-time.

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Preface

This report was prepared by WestStart-CALSTART. WestStart-CALSTART is a non-profit organization that works with the public and private sectors to develop advanced transportation technologies and foster companies that will help clean the air, lessen our dependence on foreign oil, reduce global warming, and create jobs. CALSTART, Inc. is the California operating division of WestStart-CALSTART. The data contained in this report includes public information and/or information provided by other organizations. Contact information where available is provided with each description as a source of more detailed information.

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The Federal Transit Administration (FTA) sponsored the effort to compile data for this report. CALSTART would like to acknowledge the contributions of time and data from various staff representing government organizations including the Department of Energy, Department of Defense, the FTA, the Environmental Protection Agency, the National Science Foundation, and national laboratories, Idaho National Lab, and Argonne National Lab. This also includes the South Coast Air Quality Management District and some original equipment manufacturers and suppliers through participation at a symposium on this general subject. These contributions in information and data resulted from a one day symposium called “Bridging the Transition...Hydrogen Internal Combustion Engines” held in Mission Bay, California on February 22, 2006. Other public references such as downloads from websites and reports also were a source of data for this report as cited in footnotes.

Table of Contents

FORWARD	I
NOTICE.....	I
PREFACE.....	II
ACKNOWLEDGEMENTS.....	II
LIST OF TABLES.....	V
1.0 INTRODUCTION	1
1.1 PURPOSE OF THE COMPENDIUM	1
1.2 ORGANIZATION OF THE DOCUMENT.....	2
2.0 OVERVIEW OF HICE PROGRAMS	3
2.1 PROGRAMS OVERVIEW	4
2.2 TEST AND INFRASTRUCTURE PROGRAMS.....	4
2.2.1 DOE AVTA Ford F-150 HCNG ICE.....	4
2.2.2 SunLine Transit Agency and FTA Operations.....	5
2.2.3 IWHUP and Westport Innovations.....	5
2.2.4 SunLine ISE HHICE Bus.....	6
2.3 ENGINE DEVELOPMENT PROGRAMS	6
2.3.1 BMW V-12 7 Series.....	6
2.3.2 Ford H ₂ ICE Shuttle Bus.....	8
2.3.3 Westport Innovations H ₂ Injectors.....	9
2.3.4 Quantum Technologies Hydrogen Conversions.....	9
2.3.5 City Engines	10
2.3.6 Hydrogen Engine Center.....	10
2.3.7 MAN Nutzfahrzeuge and EU HyFleet.....	10
2.3.8 Mazda RX-8 Hydrogen Rotary Engine-2004.....	10
2.3.9 Volvo Multi-Fuel Prototype.....	11
2.3.10 Pivotal Engineering Hydrogen Engine.....	12
3.0 DOE HYDROGEN, FUEL CELLS & INFRASTRUCTURE TECHNOLOGIES PROGRAM... 13	
3.1 DEVELOPMENT OF A TURNKEY H ₂ FUELING STATION (RTDD)	15
3.2 HYDROGEN REFUELING TECHNOLOGY (RTDD).....	16
3.3 RESEARCH AND DEVELOPMENT OF A PEM FUEL CELL, HYDROGEN REFORMER, AND VEHICLE REFUELING FACILITY (RTDD)	17
3.4 PRAXAIR HYDROGEN FUELING STATION AT LAX – SMALL-FOOTPRINT H ₂ CAPABILITY AT THE CORNER FILLING STATION (RTDD)	18
3.5 HYDROGEN FUEL PROJECT - H ₂ FUEL (RTDD).....	19
3.6 CALIFORNIA HYDROGEN INFRASTRUCTURE PROJECT (RTDD).....	20
3.7 CONTROLLED HYDROGEN FLEET AND INFRASTRUCTURE DEMONSTRATION AND VALIDATION PROJECT (VDP).....	21
3.8 HYDROGEN AND NATURAL GAS BLENDS - CONVERTING LIGHT AND HEAVY DUTY VEHICLES.....	21
3.9 GLOBAL ASSESSMENT OF HYDROGEN BASED TECHNOLOGIES	22
3.10 ALTERNATIVE HYDROGEN PRODUCTION PATHWAY AND HYDROGEN UTILIZATION.....	23
4.0 DEPARTMENT OF DEFENSE (DOD) PROGRAMS	25
4.1 CONCEPTUAL PLANS FOR NEW MEXICO HYDROGEN PRODUCTION AND DISPENSING DEMONSTRATION	25
5.0 DEPARTMENT OF TRANSPORTATION/FEDERAL TRANSIT ADMINISTRATION (DOT/FTA) PROGRAMS	27
5.1 SUNLINE PROJECT HICE TRANSIT BUS	27

5.2 HYDROGEN BUS TECHNOLOGY VALIDATION PROGRAM	28
5.3 DEVELOPMENT AND DEMONSTRATION OF HD HCNG ENGINE MEETING FUTURE EMISSION STANDARDS	30
5.4 NEW HAVEN ADVANCED TRANSPORTATION SYSTEM DEVELOPMENT PROGRAM	31
6.0 NATIONAL SCIENCE FOUNDATION (NSF) EFFORTS.....	32
7.0 NATIONAL LABORATORY ROLES	33
7.1 ARGONNE NATIONAL LABORATORY	33
7.2 SANDIA NATIONAL LABORATORIES	34
7.3 IDAHO NATIONAL LABORATORY - ADVANCED VEHICLE TESTING AND EVALUATION	35
8.0 STATE AND LOCAL AGENCY PROGRAMS	37
8.1 FLORIDA HYDROGEN INFRASTRUCTURE PROGRAM	37
8.2 MID-WEST HYDROGEN H	38
8.3 CALIFORNIA - SOUTH COAST AQMD PROGRAMS.....	39
8.3.1 Five-City Hydrogen ICE Vehicle and Fueling Infrastructure.....	39
8.3.2 Hydrogen ICE Shuttle	40
8.3.3 Hydrogen CNG Engine	40
8.3.4 Hydrogen CNG Engine LACMTA.....	40
8.4 CALIFORNIA HYDROGEN HIGHWAY NETWORK	41
9.0 ORIGINAL EQUIPMENT MANUFACTURER PROGRAMS.....	42
9.1 FORD HYDROGEN ICE VEHICLES	42
9.1.1 Ford Model U – 2003.....	42
9.1.2 Ford H2RV - 2003	43
9.1.3 Ford FOCUS C-MAX H ₂ ICE – 2004	44
9.1.4 Ford H ₂ ICE Shuttle Bus.....	45
9.1.5 Ford Tug Florida H ₂ Tow tractor	46
9.2 ISE CORPORATION HHICE BUS	46
9.3 MAZDA RX-8 HYDROGEN ROTARY ENGINE-2004	47
9.4 QUANTUM FUEL SYSTEMS TECHNOLOGIES WORLDWIDE CONVERSION VEHICLES	48
9.4.1 Hydrogen Toyota Prius Conversion.....	48
9.4.2 Ford Hybrid Escape Conversion	49
9.5 VOLVO MULTI-FUEL CONCEPT CAR	50
9.6 HYDROGEN ENGINE CENTER.....	52
9.7 CITY ENGINES	52
9.8 WESTPORT INNOVATIONS	52
10.0 NON-U.S. PROGRAMS	54
10.1 PRINCE EDWARD ISLAND WIND-HYDROGEN VILLAGE PROJECT	54
10.2 HyICE - OPTIMIZING HYDROGEN ENGINES, EUROPEAN COMMISSION.....	55
10.3 INTEGRATED WASTE HYDROGEN UTILIZATION PROJECT - VANCOUVER, BC	56
APPENDIX A GLOSSARY OF ACRONYMS.....	58

Table of Figures

Figure 1: Transit bus with HCNG	5
Figure 2: IWHUP project.....	5
Figure 3: SunLine HHICE bus	6
Figure 4: BMW's 7 Series HICE	7
Figure 5: Ford's H2ICE Shuttle Bus	8
Figure 6: Injector	9
Figure 7: Quantum's Prius convert	9
Figure 8: The Mazda RENESIS	11
Figure 9: Volvo Multi-Fuel Prototype	11
Figure 10: Overview of DOE Hydrogen Programs.....	14
Figure 11: CRF's DI-HICE prototype	34
Figure 12: Ford's E450 Shuttle Van.....	40
Figure 13: SunLine's HCNG bus	40
Figure 14: Ford Model U	42
Figure 15: Ford H2RV	43
Figure 16: Ford C-Max H ₂ ICE.....	44
Figure 17: Ford HICE shuttle bus.....	45
Figure 18: Ford's TUG M1.....	46
Figure 19: HICE hybrid-electric transit bus	46
Figure 20: RENESIS Hydrogen RE.....	47
Figure 21: Ford Hybrid Escape	50
Figure 22: Volvo Multi-Fuel Concept Car diagram.....	51
Figure 23: The Volvo Multi-Fuel Concept Car	51
Figure 24: HyICE	55

List of Tables

Table 1: Infrastructure and Test Demonstration Projects.....	15
Table 2: Model U specs.....	43
Table 3: Prius Emissions Comparison Table.....	49

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1.0 Introduction

One of the many paths being explored in moving towards a hydrogen economy is the development of internal combustion engines fueled by hydrogen or hydrogen-blends. This compendium is intended as a communication tool to identify significant activities relating to such hydrogen internal combustion engine (HICE) development in the U.S. that are sponsored by the federal government, state agencies, local entities, and private enterprise. An anticipated benefit of spotlighting these development efforts is a hastening of the technology growth for heavy duty vehicles – in particular, public transit buses.

1.1 Purpose of the Compendium

WestStart-CALSTART, under contract to the Federal Transit Administration, is assisting the FTA with interagency coordination of HICE activities through an Interagency Hydrogen Task Force which supports both the White House Office of Science and Technology Policy and the Department of Energy. The intent of the coordination effort is to assure a strong linkage to heavy-duty vehicle and transit bus applications that can reduce the risks associated with a new fuel.

This compendium documents a number of heavy duty drivetrain developments that may eventually be commercialized for use in the transit bus or other heavy vehicle markets in the future. But there are also development activities identified for light-duty applications because, in the past, proven control systems and sensors used for the light-duty industry have been applied to heavy-duty engines (e.g. current lean burn, cooled exhaust gas recirculation, etc.).

Specifically, the document identifies pertinent activities being performed at U.S. federal government agencies that relate to technology developments for internal combustion engines fueled by hydrogen or hydrogen-blends. The intent of this compendium is to report the available, public research surrounding the development of HICE or blend-fueled vehicles and infrastructure technologies that might help reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice. The aim is to assure that strong links exist to the public transit buses and heavy duty vehicles that can reduce the risks associated with a new fuel for transit and improve the business case for such fuels.

Important activities are also being performed at the state and local levels and even in the private sector. Some automobile manufacturers are pursuing HICE production vehicles and research in fuel cell centered research. Likewise, some private concerns aspire to enter smaller niche markets such as off-road vehicles on airports or stationary power generation. This document provides some visibility into those activities and facilitates the flow of information to those organizations and the federal programs

1.2 Organization of the Document

The first section is a summary overview that identifies some of the currently known HICE government or public agency activities at the various levels, as well as the private sector programs. The remainder of the document consists of chapters that outline federally sponsored projects, including those of the Department of Energy (DOE), Department of Defense (DOD), and the Department of Transportation/Federal Transit Administration (DOT/FTA). Presently, the Environmental Protection Agency (EPA) does not have active HICE programs but is very interested in tracking the technology. The National Science Foundation (NSF) provides databases and simulation assets to researchers in both the public and private sector and the next chapter is meant to highlight that resource. Chapter 7 spotlights some programs within the National Laboratories. The next Chapter 8 delineates some state and local programs that involve the technology or HICE/HBICE vehicles. Chapter 9 adds information about some automotive OEM programs and some private sector companies with programs involving HICE or HBICE. The final chapter highlights a few programs beyond the U.S. borders. Since this is the first report compilation, it may not be as comprehensive as intended; not all known programs or projects may have been identified and information provided. Likewise, the depth of information on all programs is not consistent. Future updates are planned and we will seek to enhance the publication.

2.0 Overview of HICE Programs

This section provides a summary overview of the notable HICE and hydrogen blend-fueled ICE projects. More details can be found in the appropriate succeeding chapters of this document. Significant activities surrounding hydrogen internal combustion engines (HICE) are being performed within the U.S., some sponsored by federal agencies and some sponsored by public and private organizations. But fuel cells and hydrogen infrastructure, not HICE, are the focus of America's vision for transition to a hydrogen economy and naturally receive the media attention. There is a small and growing sense within the industry that HICE, in selected vocations, may offer an excellent opportunity to hasten the deployment of hydrogen infrastructure and the transition to hydrogen.

It is thought that the hydrogen economy will ultimately include hydrogen fuel cells as one of the sources of primary motive power for vehicles and stationary power generation. A potential evolutionary approach to reach the hydrogen economy may well involve a transition strategy using internal combustion engines. This approach for vehicles and powertrains consists of moving from existing ICEs operating on conventional fuels; to engines operating on hydrogen (HICE) and hydrogen blends (HBICE); to hybrid electric vehicles using hydrogen-fueled internal combustion engines; and, ultimately, to a portfolio of fuels and advanced powertrains that include hydrogen fuel cells.

The technical community is aware of the HICE potential emission advantages and performance issues relative to existing ICE engines. For transit applications, the critical issue is the development of a hydrogen engine with comparable or better performance than its diesel counterpart. Some important work to date has been conducted as retrofits to internal combustion engines and a few original equipment manufacturers (OEMs) have HICE programs. Typical results in retrofit situations are lower power output or reduced range when compared to the engines they replace. Some OEMs, such as BMW, which is pursuing a re-design approach and tailoring the ICE for hydrogen, have produced very good results that suggest a nearer term commercial path for a hydrogen transportation solution than via fuel cells.

Important activities in the development of hydrogen and hydrogen-blend fueled internal combustion engines are being performed in programs managed by various U.S. government, state, and local agencies. DOE has programs for demonstration, validation, and infrastructure that are targeted towards fuel cells but currently involve HICE light and heavy duty vehicles. The National Science Foundation (NSF) has combustion research programs useful for analyses and for performance improvement in HICE powertrains. The EPA has expertise that can be useful for emissions control and a willingness to share that information with industry (although there are no active HICE programs within the EPA). DOD, although not as focused on hydrogen directly as a transportation fuel, has some projects in the proposal stage.

2.1 Programs Overview

A projects review of agency programs at the federal, state, and local levels revealed that many projects had multiple areas of focus and usually were collaborative in nature. In fact, many projects that involved work on HICE also had multiple sources of funds from multiple sponsors. Thus, instead of identifying projects by individual agency or organization, it is more practical to report on specific HICE activities. For example, a number of funded projects in DOE are focused on hydrogen infrastructure for fuel cell vehicles, but hydrogen or hydrogen-blend fuel is also used for internal combustion engine vehicles. As a result, presenting a clear picture of this kind of HICE project information can be better accomplished by describing the results identified in reports by the test agency or demonstration site for the section, “Test and Infrastructure Programs.”

In other cases, there were clear thrusts by manufacturers or suppliers that were doing engine or engine technology development. Identifying such OEMs, suppliers, or centers of expertise for the section “Engine Developments,” no matter the funding source or “customer,” provides another convenient category to summarize the technology.

2.2 Test and Infrastructure Programs

Several projects have focused on using hydrogen or hydrogen/methane (HCNG) blends as a substitute fuel for gasoline or compressed natural gas (CNG). The results of these experiments have been variable but generally positive, depending upon the care that was taken in modifying the engine for the hydrogen or blended fuel.

2.2.1 DOE AVTA Ford F-150 HCNG ICE

Idaho National Laboratory (INL), under funding from DOE through the Advanced Vehicle Testing Activity (AVTA), has been investigating the use of hydrogen and HCNG blends as a substitute fuel in several different vehicles converted to run on gaseous fuels. Its activities have demonstrated that simple fuel substitution, with no special engine modifications, can result in an improvement in most criteria emissions, except for NO_x, which can increase substantially. Other fuel substitution projects at INL have utilized third-party aftermarket engine modifications on GM and Ford pickups to assess performance using various blends of HCNG and also 100% hydrogen fuel.

For example, a fleet pick-up with a factory Ford F-150 CNG 5.4L V-8 was modified by adding supercharging, ignition timing modifications and exhaust gas recirculation. The emissions improvements relative to CNG fuel with 15% and 30% HCNG blends yielded modest improvements in CO and CO₂ but an increase in NO_x. Time-to-60 mph tested at 10.12 sec for CNG but for the two blended fuels, the time was 10.97 and 12.68 seconds, respectively. The range was also decreased with the fuel blends. These experiments provide interesting benchmarks of what is possible using current technology in a retrofit approach rather than an engine with its design and calibration optimized for hydrogen or

HCNG such as the SunLine example next which can reflect comparable or improved performance.

2.2.2 SunLine Transit Agency and FTA Operations

SunLine Transit Agency, under sponsorship of FTA, DOE, South Coast Air Quality Management District (SCAQMD), and others, has evaluated a variety of alternative fuels for transit vehicles over a number of years. One project involved the operation of 40-foot transit buses on 20% HCNG. The company worked with Westport Innovations to modify and test a Cummins Westport (CWI) B GasPlus, 5.9L, spark-ignited, natural gas engine to operate on HCNG.¹ A variety of HCNG blend levels were assessed during engine testing to determine the optimal mix for this application. After the engine testing and re-calibration, it was determined that the optimal blend was 20% HCNG with the only modification necessary to the engine being a higher volume mass flow sensor due to the characteristics of the hydrogen in the fuel.



Figure 1: Transit bus with HCNG

The results of the vehicle chassis testing at SunLine indicated a 55% reduction in NO_x for HCNG compared to the natural gas engine. Other criteria emissions remained low due to the oxidation catalysts used with both HCNG and CNG engines. Fuel consumption did increase by 12% due to the lower energy density of the hydrogen, but it is projected that more detailed calibration of the engine could improve upon that number. This project demonstrated that conventional,

heavy-duty CNG engines could be modified to operate on HCNG with relatively few hardware changes. Two of the buses operated in revenue service during 2002-2004 and logged over 65,000 vehicle miles. Additional projects are being planned with transit authorities. This success provides a stepping stone for a transition to greater use of hydrogen by incorporating it into the CNG fuel that many transit or refuse fleets are already using.

2.2.3 IWHUP and Westport Innovations



Figure 2: IWHUP project

Under a collaborative project of the Integrated Waste Hydrogen Utilization Project (IWHUP), waste hydrogen from a sodium chlorate plant will be captured. The hydrogen will then be conditioned and transported to a fueling station in Vancouver, Canada. For transit operations, the hydrogen will be blended with compressed natural gas (HCNG). Westport Innovations will be modifying its CWI 8.3 liter C Gas Plus engines to operate on HCNG for installation in four transit buses

¹ National Renewable Energy Laboratory, "Development and Demonstration of Hydrogen and Compressed Natural Gas (H/CNG) Blend Transit Buses", NREL/TP-540-38707, November 2005. Available in PDF at <http://www.nrel.gov/vehiclesandfuels/ngvtf/pdfs/38707.pdf>

that BC Transit will operate in the Vancouver area. Lessons learned from the SunLine project will be incorporated into this more recent project. This project has significant funding from the Canadian government.

2.2.4 SunLine ISE HHICE Bus



Figure 3: SunLine HHICE bus

combustion engine.² Testing at SunLine, in Palm Springs, CA and in Winnipeg, Canada has demonstrated the ability of the system to operate in environmental extremes while providing 2 to 6 miles/kg of fuel economy, which is comparable to conventional natural gas buses being operated at SunLine.³ No significant problems, other than some fueling issues in extremely cold weather, have been identified.

Another project based at SunLine that provides a stepping stone in the transition is the test and evaluation of a hybrid-electric hydrogen internal combustion engine (HHICE) drive system in a 40-foot New Flyer bus. The bus uses an ISE ThunderVolt® hybrid-electric drive system that generates power with a Ford hydrogen-burning, V-10, turbocharged, intercooled internal

2.3 Engine Development Programs

The previously-described projects focus on retrofitting existing engines to operate on hydrogen or hydrogen blends, usually under a third-party (not the original equipment supplier) subcontracted effort. Such projects are typically the quickest way to get a HICE or HBICE vehicle into operation, but generally do not allow for optimal design and calibration of the modified engines. The following projects are representative of activities that focus on specific engine design changes by auto makers or OEMs to enable the most efficient use of hydrogen as a fuel.

2.3.1 BMW V-12 7 Series

The BMW vision for future powertrains differs from most other auto manufacturers. Most competitors acknowledge that hydrogen-powered internal combustion engines are a step on the ladder, but fuel cells are the future. BMW is not so sure.

Professor Raymond Freymann, the managing director of BMW's Research and Technology Division, states: "We think the future is not so radical. All of our consideration is on internal combustion engines. We're not sure fuel cells will happen —

² ISE website, "ISE Delivers First Hybrid Hydrogen Internal Combustion Engine Bus to SunLine Transit", December 2004, http://www.isecorp.com/ise_news/ev_bulletins/dec-04-hhice-rollout-sunline-transit.php

³ See Section A7.3 "ISE Corporation HHICE Bus" for more information.

other than as the power source for everything driven electronically, such as air conditioning, in-car entertainment, lights, etc. For this application, the fuel cell makes perfect sense. But as the power source for driving the car? That is a huge step.”

"Rather, we think the internal combustion engine, fueled by liquid hydrogen is perfect. The technology exists. The internal combustion engine also offers much better power density and efficiency than fuel cells. Fuel cells have such a long way to go. I'm not sure anyone would be able to pay the bills."⁴



Figure 4: BMW's 7 Series HICE

BMW will sell a bi-fuel-powered (gasoline and hydrogen) V-12 7 Series within two years. A similar engine recently powered the BMW H2R racer (created by California-based Designworks) to nine hydrogen speed records at the Miramas proving ground in France. The records include a standing quarter-mile in 14.9 seconds.

"Within two years, Germany will have a 'hydrogen highway' linking major towns, and Governor Schwarzenegger has announced a similar initiative in California. When there is no liquefied hydrogen for refueling, you just use normal gasoline. The engine cannot be tuned as efficiently as we would like, but the hydrogen performance is still very good."⁵

"Hydrogen will work best in direct-injection engines with supercharging," Freymann notes. "The thermal efficiency of a hydrogen internal combustion engine will be more than 50 percent. Gasoline engines currently operate below 40 percent and diesels just above 40 percent. The hydrogen engine will have more power and more torque and no pollution." Liquid hydrogen tanks will likely be carbon reinforced. Hydrogen is much lighter than gasoline or diesel, although it does need more storage space.⁶

The motivation behind this innovative new concept is clear: hydrogen is the fuel of the future. It reduces dependence on other natural resources and eliminates CO₂ emissions, which are responsible for the greenhouse effect. And if renewable energy is used to generate hydrogen for use in cars, the entire cycle is environmentally friendly.

“BMW has created an engine which uses hydrogen as its source of energy and which is as dynamic and agile as every other BMW powerplant.” The 2001 BMW 745h had a bivalent 4.4 liter, V-8 engine which ran on either hydrogen or petrol (gasoline), with 182hp (135 kW) of power and a top speed of 134 mph (215 km/h). The range was ~ 185 miles (300 km) on a full tank of hydrogen, plus ~ 400 miles (650 km) on gasoline.

⁴ Interview with BMW Raymond Freymann on the BMW Website
Source: <http://www.edmunds.com/insideline/do/Features/articleId=105640#2>

⁵ Ibid

⁶ Ibid

The twelve-cylinder engine in the BMW 7 Series now represents the technological benchmark in this market segment. It incorporates Valvetronic, a system that variably controls the lift motion of twenty-four intake valves. This controls the flow of combustion air into the engine with supreme accuracy thereby reducing both fuel consumption and exhaust emissions significantly.⁷

BMW plans to introduce this hydrogen-powered 7 Series luxury sedan in the 2010 timeframe. The engine will be bi-fuel, able to operate on either hydrogen or gasoline. BMW's Group spokesperson, Bill Scully, has been quoted as stating, "BMW has been developing hydrogen-fueled internal combustion engine vehicles for nearly 25 years. We have researched other hydrogen technologies extensively and have a commitment to the hydrogen combustion engine."

2.3.2 Ford H₂ ICE Shuttle Bus

Ford's vision is to take HICE technology from research to commercial trial. This will provide insight into acceptance of hydrogen as a fuel. Success in the technology may provide a bridge from gasoline engines to fuel cell vehicles while offering many of the FCV benefits at a lower cost. These vehicles will support hydrogen as a renewable fuel and reduce dependence on imported oil.



2006 – H₂ICE Demo/Fleet

Figure 5: Ford's H₂ICE Shuttle Bus

The company announced in June 2006 that it plans to place eight E-450 shuttle vehicles into service at tourist destinations in Florida. The vehicle uses a Ford E-450 chassis with a 6.8L inter-cooled, super-charged ICE and a shuttle bus body. Engine performance is expected to provide a peak torque of 340 ft-lb at 2500 RPM with a peak power of 225 hp at 4000 RPM. The hydrogen Fuel System & Management System includes a separate

hydrogen enclosure at the rear of the vehicle with six fuel tanks that provide a vehicle range of 150 miles. Ford's HICE shuttle bus vehicles will be available in late 2006. The vehicle is compliant to Canadian and Federal motor vehicle standards. Additional information can be found in Chapter 9.

Two of these hydrogen-powered shuttle buses will pull into the Lehigh Valley early next year, staying for a two-year test that should give many residents their first view of a hydrogen-powered vehicle. One bus will be used for campus transportation at the Trexlertown headquarters of Air Products and Chemicals Inc., the world's largest supplier of hydrogen. The other bus will be based at the Da Vinci Discovery Center of Science and Technology in South Whitehall Township, where it will be used for trips to schools and other educational efforts.

⁷ BMW Website – technology.

Both buses will fill up at a specialized fuel station at Air Products' Trexlertown campus. The Valley will be one of the very few regions of its size to host a hydrogen vehicle test. Thus far, most of the pilot programs have taken place in major cities such as Los Angeles, Chicago and Sacramento, California and Penn State University also has a hydrogen fueling station provided by Air Products which will support hydrogen and hythane demonstrations.⁸

2.3.3 Westport Innovations H₂ Injectors



Figure 6: Injector

Westport Innovations is working with both Ford and BMW to develop hydrogen direct injectors for their engines. This direct injection of hydrogen into the combustion cylinder, instead of port injection, is now being investigated in more detail and promises a significant increase in the performance of the HICE. Compared to port-injected hydrogen, direct injection – along with other engine modifications – can increase power density and thermal efficiency. It can also improve tailpipe emissions when combined with aftertreatment under various load conditions.

2.3.4 Quantum Technologies Hydrogen Conversions



Figure 7: Quantum's Prius convert

Quantum Technologies has developed a conversion for the Toyota Prius that permits operation on hydrogen instead of gasoline. Deliveries of these vehicles to various customers have begun including 36 HHICE Prius vehicles to cities in the South Coast Air Basin in southern California for test and evaluation under Air District sponsorship. The SCAQMD vehicles are expected to have the equivalent fuel efficiency of their fuel cell

counterparts at a fraction of the system cost. The Prius is modified to include multi-port hydrogen fuel injection, turbocharging with an intercooler, and compressed hydrogen storage. Emission test results show SULEV performance and have indicated significant CO and CO₂ emission reductions compared to a conventional Prius. The range has been demonstrated to be approximately 90 miles, limited by the capacity (1.6 to 2.4 kg of compressed hydrogen) of the 5,000 psi on-board storage tanks. Its performance is reported to be comparable to that of the gasoline Prius with a small increase in fuel economy.

⁸ Hydrogen Powered Buses Come to Lehigh Valley, The Morning Call, 6 August 2005.

2.3.5 City Engines

City Engines has licensed technology from Collier Technologies, Inc. (CTI) to produce heavy-duty hydrogen fueled engines for the transit industry. City Engines plans to fabricate and demonstrate an 11 liter engine for Pennsylvania State University and deliver four engines for test to the Los Angeles County Metropolitan Transportation Authority. Two engines in the LACMTA program will run on CNG and another two will run on hydrogen-CNG blends. Partial funding is provided by the South Coast Air Quality Management District. City Engines is also looking at the manufacture of an 8 liter engine as well.

2.3.6 Hydrogen Engine Center

The Hydrogen Engine Center is launching operations in December 2005 to re-manufacture Ford in-line six engines to run on hydrogen, hydrogen blends, and natural gas fuel for commercial sale in non-road applications

2.3.7 MAN Nutzfahrzeuge and EU HyFleet

In Europe, MAN Nutzfahrzeuge AG and NEOMAN Bus GmbH are participating in the European Union Hydrogen Fleet (EU HyFLEET), an outgrowth of the Clean Urban Transport for Europe (CUTE) fuel cell project. The MAN team will be delivering 14 HICE buses to the Berlin transport authority. The engines are based on the MAN natural gas engine and will include four naturally aspirated as well as ten supercharged turbo-engines in the fleet. MAN is also proposing to provide 20 HICE buses to Rotterdam, Holland to become part of a project with Shell Hydrogen BV that is being advertised as the world's largest hydrogen-fueled public transport system.

2.3.8 Mazda RX-8 Hydrogen Rotary Engine-2004

Mazda introduced the RX-8 Hydrogen Rotary Engine (RE) concept at the North American International Auto Show in 2004. The RX-8 Hydrogen RE was shown in a hydrogen-powered version of RENESIS, Mazda's next generation rotary engine that was introduced in 2003 in the RX-8.⁹

⁹ Ford, George Davis, Low Emissions IC Engine Development at Ford Motor Company, June 2005



2004 – H2ICE Rotary

Figure 8: The Mazda RENESIS

The RENESIS Hydrogen RE allows the RX-8 concept to run on either hydrogen fuel or gasoline by adding a high pressure hydrogen tank as part of the fuel system. It also capitalizes upon a key advantage of the rotary, separate intake and combustion chambers, to assure RX-8's ease-of-operation and reliability. The RENESIS Hydrogen RE incorporates an electronically-controlled hydrogen injector system, with the hydrogen injected in a gaseous state. The system draws air from the side port during the intake cycle and uses dual hydrogen injectors in each of the engine's twin rotor housings to directly inject hydrogen into the intake chambers.

Because it offers separate chambers for intake and combustion, the rotary engine is ideal for burning hydrogen without the backfiring that can occur in a traditional piston engine. The separate induction chamber also provides a safer temperature for fitting the dual hydrogen injectors with their rubber seals, which are susceptible to the high temperatures encountered in a conventional reciprocating piston engine.

Also helping to maximize the benefits of the rotary engine in hydrogen combustion mode, the RENESIS Hydrogen RE features adequate space for the installation of two injectors per intake chamber. Because hydrogen has an extremely low density, a much greater injection volume is required when compared with gasoline, thus demanding the use of more than one injector. Typically, this can be difficult to achieve with a conventional reciprocating piston engine because of the structural constraints that prevent mounting injectors in the combustion chamber. However, with its twin hydrogen injectors, the RENESIS Hydrogen RE is both practical and able to deliver sufficient power.

In addition to the revolutionary hydrogen-powered RENESIS rotary engine, the Mazda RX-8 Hydrogen RE concept benefits from improved aerodynamics and optimized tires and weight-saving measures. A fast-fill tandem master cylinder reduces brake drag and friction hub carriers help cut power losses.¹⁰

2.3.9 Volvo Multi-Fuel Prototype



Figure 9: Volvo Multi-Fuel Prototype

Volvo announced the development of a multi-fuel vehicle at the 2006 Michelin Bibendum Challenge. This prototype vehicle has been developed to operate on five different fuels which include gasoline, E85 (Ethanol 85, a blend of 85% ethanol and 15% gasoline), natural gas, bio-methane, and a 10% HCNG blend. Volvo developed a unique catalyst system to achieve a PZEV/SULEV

¹⁰ Ford News Release, Mazda RX 8 HICE Rotary, 2004.

emission rating for the U.S. market. High temperature materials in the exhaust manifold and turbo allow the exhaust gas temperatures to be extremely high, enabling the vehicle to run cleaner, accelerate quicker, and operate smoother at higher speed.

2.3.10 Pivotal Engineering Hydrogen Engine

Pivotal Engineering is developing a unique engine that can operate on a variety of fuels. The engine is a redesign of the conventional two-stroke engine and proposes to significantly reduce emissions usually associated with this engine type, while maintaining a high power density. Using direct injection of the fuel without poppet valves enables the engine to operate on hydrogen at a combustion condition closer to stoichiometric than conventional 4-stroke engines, thereby increasing power and efficiency. This approach represents new thinking that may be appropriate in order to take full advantage of the characteristics of hydrogen as a fuel.

3.0 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program

In January 2002, the U.S. Secretary of Energy, along with executives of the U.S. automobile industry, announced a new cooperative automotive research partnership between the DOE and the auto industry's U.S. Council for Automotive Research (USCAR). This government-industry partnership, designated "FreedomCAR" (in which CAR stands for "Cooperative Automotive Research") supersedes and builds upon the successes of the previous partnership (The Partnership for a New Generation of Vehicles, or PNGV). In September of 2003, the FreedomCAR Partnership was expanded to include five major energy companies to address issues related to the supporting fuel infrastructure. It was renamed the FreedomCAR and Fuel Partnership. The FreedomCAR and Fuel Partnership depart from the family sedan vehicle focus of PNGV to address the development of advanced technologies suitable for all light-duty passenger vehicles (i.e., cars, SUVs, pickups, minivans). Additionally, compared with PNGV, the government's role in the FreedomCAR and Fuel Partnership has shifted to focus on more fundamental, longer-range, higher-risk technology research. The long-term goal of the FreedomCAR and Fuel Partnership is to enable the full spectrum of light-duty passenger vehicle classes to operate completely free of petroleum and free of harmful emissions while sustaining the driving public's freedom of mobility and freedom of vehicle choice.

In November 2002, the Secretary of Energy announced the rejuvenation of the government-industry 21st Century Truck Partnership (21st CTP) to address the research and development needs of commercial vehicles. The 21st CTP is a partnership between the U.S. truck and bus industry, its supporting industries, and the federal government. Its ultimate goal is to dramatically improve the energy efficiency and safety of trucks and buses while maintaining a dedicated concern for the environment. The FCVT Program addresses research and development through the 21st CTP on commercially viable technologies that will dramatically cut the fuel use and emissions of commercial trucks and buses while enhancing their safety and affordability. This is also a multi-year plan through an important supportive industry partnership.

Then in February 2003, President Bush announced the FreedomCAR and Hydrogen Fuel Initiative. Within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), the FCVT Program and the Hydrogen, Fuel Cells, and Infrastructure Technologies (HFCIT) Program have been assigned the responsibility for implementing the FreedomCAR and Hydrogen Fuel parts of the initiative, respectively. The FCVT and the HFCIT Programs are working together closely to implement the initiative, and the interdependency of the two programs is depicted in Figure 1. The expansion of the FreedomCAR and Fuel Partnership to include the energy sector also supports the achievement of the goal of the FreedomCAR and Hydrogen Fuel Initiative. The HFCIT program that supports the hydrogen fuel initiative is outlined in the HFCIT Multi-Year Research, Development, and Demonstration Plan.

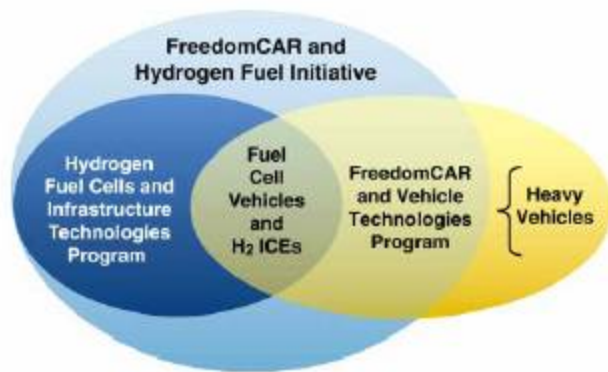


Figure 10: Overview of DOE Hydrogen Programs

Since the internal combustion engine (ICE) focus in this document describes government projects that are funded by both the HFCIT Program and the FCVT Program, it should be noted that projects in both can result in the accomplishment of specific development work, testing, and data capture on ICE vehicles that are either fueled by hydrogen or hydrogen-blends. However, in researching each agency's

activities to create this document, a lot of collaboration was found among the projects. As mentioned previously, the result is that the combination of multiple agencies and multiple sources of funds makes it difficult to organize the information by principal agency for projects that involve government funding.

Likewise, entities at the state and local levels, such as air quality districts and economic development agencies, have created initiatives and programs that are responding in various ways to provide a path to a hydrogen economy. These organizations are also in collaboration with the federal projects involving HICE vehicles. Specific vehicle original equipment manufacturers and private sector companies are also pursuing hydrogen internal combustion engine technology.

The EERE's Hydrogen, Fuel Cells & Infrastructure Technologies Program is implementing the technology development efforts needed to realize the vision of a hydrogen economy.¹¹ In collaboration with DOT and EPA, DOE plans to conduct hydrogen infrastructure and fuel cell vehicle demonstration projects to validate technology status and refocus RD&D in two areas:

- Hydrogen fueling station safety, operations, reliability, and vehicle interface/fuel dispenser systems
- Vehicle performance and reliability under real operating and climate conditions.¹²

The following section identifies DOE programs (by title) that contain an element involving HICE, or HCNG-ICE vehicles, or stationary applications. Programs summarized here are from one of two areas under technology validation: 1) Refueling Technology Development and Demonstrations (RTDD) or Vehicle Demonstration Projects (VDP). Each project is identified by a title with either RTDD or VD in parenthesis to relate back to the two summary areas for the purpose of this early draft of the HICE Compendium. More pertinent details are planned for future revisions to fulfill

¹¹ Source: Intro DOE Multi-Year Development Plan

¹² Source hydrogen_posture_plan.pdf in DOE Programs folder

this purpose. Some of these projects in 2004 reported significant accomplishments and may even be completed but are identified here because future objectives indicate an intention to include HICE or HCNG-ICE demonstrations, development work, or testing that may relate to the purpose of this document. Examples include refueling demonstrations that have left refueling stations available for continued operations. The summary table below provides an overview of the programs. The following subsections provide more details.

Table 1: Infrastructure and Test Demonstration Projects	
Project Title / Key Contact	HICE Vehicles
D. Refueling Technology Development and Demonstration (RTDD)	
Development of a Turnkey Hydrogen Fueling Station, David Guro, Air Products	Conversion Buses [CATA/Penn State] and utility vans to run on H2 and H2-Blends
Hydrogen Refueling Technology, Michele Davies, Hydradix/SunLine	Plan to use with 3 FCBs, FCV, street sweepers and SunLine Transit CNG buses converted to run on hydrogen blend NG
R&D of a PEM Fuel Cell, Hydrogen Reformer, and Vehicle Refueling Facility, Mark Wait, Air Products	Las Vegas paratransit bus and LD vehicle plus six converted CNG transit buses
Praxair Hydrogen Fueling Station at LAX - Small Footprint H2 Capability at the Corner Filling Station, Aaron Rachlin, Praxair	LAX station to serve HICE Prius?
Hydrogen Fuel Project - H2Fuel, Derick Morse, RTC of Washoe Co	RTC Reno NV plans acquisition of HICE and H2-CNG Blend ICE transit buses for validation of Fuel station
Florida Hydrogen Initiative, Inc. (New Project), Stephen Adams, Florida Department of Environmental Protection	Potential for H2 Vehicles
E. Vehicle Demonstration Projects (VDP)	
Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project (New Project), Sig Gronich and John Garbak, DOE	Fuel Cell Vehicles, however, BMW is part of Air Products Led Demo
Hydrogen and Natural Gas Blends - Converting Light and Heavy Duty Vehicles Kirk Collier, Collier Techs	Test Ford F150/H2Blend and 8.9LHD Engine; converting 9 Ford F150s for City of Las Vegas – now licensing “City Engines”
Global Assessment of Hydrogen Based Technologies Fouad Fouad, U. of Alabama	H2 and H2-Blends in Ford F150s emissions and performance testing Congress directed project

3.1 Development of a Turnkey H₂ Fueling Station (RTDD)

Key Objectives To demonstrate the potential for an economically viable stand-alone, fully integrated hydrogen fueling station and demonstrate the station at Penn State University Phase 3 Scale up for Operations Testing

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Subcontractors: H2Gen Innovations, Inc. – Alexandria, VA; Pennsylvania State University – University Park, PA; QuestAir Technologies Inc. – Burnaby, BC, Canada

Technology Of critical importance to the success of this project is the availability of vehicles at the PSU site to validate the performance of the installed fueling station. It is recognized by PSU, Air Products, and its partners, that fuel cell buses will not be available by January 2004. Since this was the targeted commissioning date for the hydrogen fueling station, a team was established to synthesize a plan for the station and for making vehicles available. The team meets regularly and consists of representatives from Air Products, the PSU Hydrogen Institute, DOE (Philadelphia Regional Office), State of Pennsylvania Department of Environmental Protection, Centre Area Transit Authority (CATA), Penn State University, Pennsylvania Transportation Institute (PSU PTI), and Penn State University, Office of Physical Plant (PSU OPP).

Project Status The PSU Hydrogen Institute has taken the lead in developing a follow-on project to:

- (1) Convert several CATA CNG buses to run on a H₂/CNG blend,
- (2) Convert several PSU OPP utility vans to use a H₂/CNG blend,
- (3) Purchase for PSU OPP one hydrogen utility van (with internal combustion engine),
- (4) Upgrade the CATA and PSU facilities for operation with a H₂/CNG blend, including required training, and
- (5) Operate and maintain the fueling station for a period of 3 years. Penn State PTI has secured funding from two Pennsylvania State agencies for the first year of its project.¹³

3.2 Hydrogen Refueling Technology (RTDD)

Key Objectives The objective of this project was to develop and demonstrate a hydrogen-refueling station that combines HyRadix's on-site hydrogen generation technology with compression, storage and dispensing facilities designed by SunLine Services Group. The refueling station will also provide hydrogen that will be blended

¹³ DOE FY 2004 Progress Report p. 681 (V.D.1 Development of a Turnkey Hydrogen Fueling Station)

with compressed natural gas (CNG) to form HCNG and used in SunLine's fleet of converted CNG buses.

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SunLine Services Group, Thousand Palms, CA

Technology Demonstrate and develop on-site autothermal reforming of natural gas for a hydrogen fueling station, plus evaluation of fuel cell (FC) vehicle refueling under real-world conditions.

Project Status DOE funded installation and initial operational period (30 days demo – DOE; AQMD-added an additional 12 months of operational funding). This project is turned over to SunLine for continued operations to provide hydrogen and hydrogen-CNG fuel for operation of SunLine's vehicle fleet.¹⁴

3.3 Research and Development of a PEM Fuel Cell, Hydrogen Reformer, and Vehicle Refueling Facility (RTDD)

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Plug Power Inc., Latham, NY and City of Las Vegas

Key Objectives The objective of this project is to demonstrate the technology of an Energy Station that can dispense blends of hydrogen and compressed natural gas (CNG) and pure hydrogen to vehicles, and the co-production of electricity from a stationary fuel cell.

¹⁴ DOE FY 2004 Progress Report p. 681 (V.D.4 Hydrogen Refueling Technology)

Technology On-site hydrogen generation and a liquid hydrogen supply system was installed to satisfy initial demand for hydrogen at the refueling station, and to provide back-up hydrogen supply for additional system reliability. The hydrogen compression, storage, blending, and dispensing systems are capable of supplying pre-determined blends of H₂ and CNG to be dispensed to trucks and buses with internal combustion engines (ICEs) converted to run on H₂/CNG mixtures. The station will also be able to dispense pure hydrogen to vehicles.

Project Status As of 2004, there was one light-duty vehicle (LDV) and one para-transit bus fueled with the H₂/CNG blend. The project is complete as originally funded but the facilities may be used for vehicles for the City of Las Vegas.¹⁵

3.4 Praxair Hydrogen Fueling Station at LAX – Small-Footprint H₂ Capability at the Corner Filling Station (RTDD)

Key Objectives Fabricate one of the first publicly accessible hydrogen fueling stations within the South Coast Air Basin and develop a small-footprint template (including rooftop hydrogen storage) that will be compatible with the needs of conventional commercial retail fueling station facilities. The initial capability of the station will be fast-fill refueling of up to three light-duty hydrogen-powered vehicles in succession, with future expansion plans allowing for the slow (overnight) refueling of buses via a manifold on the compressor skid that will allow tube trailer hydrogen to augment the production capacity of the station's on-site electrolysis unit. Additional future goals will be to provide high-pressure hydrogen refueling at 10,000 psig for the next generation of vehicles requiring greater driving range between refueling events.

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BP, Inc., Naperville, IL

Technology The Praxair-BP hydrogen fueling station at the Los Angeles International Airport (LAX) will serve as a demonstration hydrogen fueling station for a fleet of hydrogen-powered vehicles to be placed at LAX and vicinity within the next several years.¹⁶

¹⁵ DOE FY 2004 Progress Report p. 681 (V.D.5 R&D of a PEM Fuel Cell, H₂ Reformer and Vehicle Refueling Facility)

¹⁶ DOE FY 2004 Progress Report p. 681 (V.D.6 Praxair Hydrogen Fueling Station at LAX – Small-Footprint H₂ Capability at the Corner Filling Station)

Project Status

Facilities are still in-place and are planned for use in the SCAQMD Five Cities program (see Chapter 8).

3.5 Hydrogen Fuel Project - H2Fuel (RTDD)

Key Objectives This project will construct, integrate, and operate a geothermal electrical generation facility to power a hydrogen fuel production facility utilizing electrolysis technology. The project will also construct, integrate, and operate facilities for gas storage, transmission, distribution, dispensing fuel, and maintaining hydrogen powered vehicles. A number of transit vehicles using various types of hydrogen powered propulsion systems will be operated and maintained under real world conditions.

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Regional Transportation Commission of Washoe County Reno, NV
Oromat

Technology The project will acquire a number of hydrogen and hydrogen/compressed natural gas (HCNG) powered transit vehicles and construct a hydrogen/HCNG fuel dispensing station concurrent with the design and construction of the geothermal power and the primary fuel production facilities. Until the primary geothermal powered fuel production facility is on-stream, hydrogen will be generated from electrolysis units operating on grid power.

Project Status This New Project is congressionally-directed¹⁷ and the Regional Transportation Commission of Washoe County is continuing on a path to convert their entire fleet to hydrogen-blend fuels or hydrogen as the vehicle technology becomes available.

¹⁷ DOE FY 2004 Progress Report p. 681 (V.D.8 Hydrogen Fuel Project - H2Fuel)

3.6 California Hydrogen Infrastructure Project (RTDD)

Key Objectives The focus of this project is on the supply of hydrogen to demonstrate a cost effective infrastructure model in the state of California for nationwide implementation. The project will implement a variety of flexible infrastructure concepts within selected regions to demonstrate “real world” infrastructure including potential pathways to a fully developed hydrogen economy. In the longer-term time frame, the project will include demonstration of several delivered hydrogen modes, hydrogen production from waste energy sources, renewable sources, and on-site generation modes. Gathering infrastructure and fueling experience data will make information available to make future infrastructure recommendations.¹⁸ The team includes BMW, which has announced its intention to make hydrogen ICE dual fuel vehicles available to the public. The motivation for adding this project to the list is the possibility of capturing data on such hydrogen-fuel ICEs through future project tasks.

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Air Products – Team Lead
Honda, Toyota, Nissan, BMW, GM, DaimlerChrysler, Fuel Cell Energy
SCAQMD, ConocoPhillips, Shell Hydrogen UC Irvine

Technology The team will deploy and demonstrate multi-purpose, multifunctional assets capable of relocation, while advancing the state-of-the art in fueling. Infrastructure stations included:

- Pipeline Station
- Mobile Hydrogen Fuelers
- Hydrogen Fueling Units with Novel Delivery Concept
- 700 bar Station Dispensing Upgrades
- Liquid Hydrogen Dispensing Upgrade
- Enhance High pressure Distribution Capabilities
- Electronic Remote Access Monitoring System

Project Status Program kickoff was June 2005.

¹⁸ 2005 DOE Hydrogen Program California Hydrogen Infrastructure Project, Mark Pedersen, Air Products and Chemicals, Future Energy Solutions Group, Project TV8 Pedersen, May 25, 2005

3.7 Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project (VDP)

Key Objectives This is a new project with five separate teams focused on controlled fleet demonstrations of fuel cell vehicles. The negotiations for one team are still underway but it involves BMW, an automobile OEM that plans to produce HICE powered vehicles. Consequently, although no details are summarized here at this time, the team is noted for future inclusion.¹⁹

3.8 Hydrogen and Natural Gas Blends - Converting Light and Heavy Duty Vehicles

Key Objectives Develop and demonstrate the viability of hydrogen compressed natural gas mixtures (HCNG) as a means of providing a transition strategy to hydrogen fuel cells. The goals also are to demonstrate vehicle reliability when fueled and operating on HCNG. Another goal is to demonstrate reduced vehicle emissions. The final objective is to develop commercial products that will utilize major advantages of HCNG.

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Collier Technologies, Inc.

Technology Collier used cooled exhaust gas recirculation (EGR) with the addition of a supercharger for light-duty vehicles. Lean burn with increased engine displacement and higher turbocharger boost pressures was used for heavy-duty vehicles. Collier also successfully developed a “kit” that is user installable for the light duty vehicles demonstrating 50,000 miles of trouble free operation. Tests also demonstrated NOx reductions from 24 to 96%, depending on test and application. Ford F150 pick-up trucks were tested with various hydrogen-CNG blend fuels. Also, a heavy duty 8.9L engine was tested on HCNG blends.

Project Status The recently completed project has resulted in a follow-on request to convert nine additional light-duty vehicles (Ford F-150s) for the City of Las Vegas.

¹⁹ DOE FY 2004 Progress Report p. 716 (V.E.1 Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project)

A follow-on effort will update control strategies for buses using engines modified by Collier Technologies, Inc. (CTI).²⁰

3.9 Global Assessment of Hydrogen Based Technologies

Key Objectives This project plans to capture and compare the state-of-practice for four potential hydrogen-based technologies: 1) hydrogen-natural gas blends ICE, 2) hydrogen ICE, 3) hybrid-electric vehicles (HEV) and fuel cell vehicles (FCV). Comparisons include performance, emissions, and fueling characteristics of the four technologies. The potential for full-scale deployment of the four vehicle classes will also be contrasted. Assessment also includes hydrogen infrastructure needs to support deployment (at local and regional levels). Results will be offered for education and training programs to increase the knowledge of the new technologies. Other outreach will increase the awareness of the new technologies through various mechanisms, such as promotional materials for public media, a web-site, college programs, and a hydrogen fair in the southeast to demonstrate the various vehicle technologies, pumping stations, hydrogen storage, safety issues, etc.

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University of Alabama at Birmingham - Virginia Sisiopiku, Robert Peters, Steven Jones, Danilo Santini, Andrew Sullivan
Argonne National Laboratory, Argonne, Illinois

Technology The team plans to measure performance and emission characteristics of the four hydrogen vehicle technologies: hythane-fueled (hythane is a 20% by volume blend of hydrogen and CNG) ICE vehicles, hydrogen-fueled ICE vehicles, hydrogen-fueled hybrid-electric vehicles, and hydrogen fuel cell vehicles. Research will include the infrastructure for large scale vehicle deployment, based on the results from vehicle research, to provide estimates of the hydrogen demand and the cost of the additional infrastructure required to meet this demand that demand.

Project Status Ford F-150s have been tested on the Argonne National Laboratory dynamometer in their Transportation Technology R&D Center. Emission characteristics for carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbons (THC), and nitrous oxides (NO_x), and fuel efficiency (equivalent miles per gallon of gasoline) were

²⁰ DOE FY 2004 Progress Report p. 719 (V.E.2 Hydrogen and Natural Gas Blends - Converting Light and Heavy Duty Vehicles Project Status)

performed using different blends of compressed hydrogen (H₂) and compressed natural gas (CNG) employing several different driving cycles. Tests were also performed for a Ford F-150 operating solely on compressed hydrogen (100% H₂).

The UAB study team has used Argonne's PSAT (Partnership for a new generation of vehicles Systems Analysis Toolkit) vehicle simulation software to model the performance, efficiency, and emissions of several prototype vehicles powered by hydrogen fueled internal combustion engines. The team will simulate and compare hydrogen fueled vehicles to conventional ICEs in terms of performance and emissions. Results of vehicle tests and simulations will be used to evaluate potential impacts of a hydrogen vehicle deployment on regional air quality.

The team plans to investigate infrastructure requirements for a southeast regional hydrogen vehicle deployment, including potential hydrogen producers and transport mechanisms. The work will include investigation of codes and standards related to hydrogen fueling stations.²¹

3.10 Alternative Hydrogen Production Pathway and Hydrogen Utilization

Key Objectives In FY 2004, DOE's Office of Fossil Energy (FE) initiated the Hydrogen from Coal Research, Development, and Demonstration (RD&D) plan to support the President's Hydrogen Fuel Initiative, the Hydrogen Posture Plan, and the FutureGen project. FutureGen is a \$1 billion government-industry initiative to design, build, and operate an advanced coal-based power plant to co-produce electricity and hydrogen while achieving near-zero emissions and geological sequestration of carbon dioxide. The Hydrogen from Coal Program outlines a plan to commercially produce hydrogen and electric power from coal in decentralized and central settings by 2011 and 2015 respectively.

An RFP was released in March 2006 that was dubbed the "Alternative Hydrogen Production Pathway and Hydrogen Utilization" (81.089). The Utilization component seeks to demonstrate hydrogen and/or hydrogen-natural gas mixture fuel protocol and reciprocating internal-combustion engine (ICE) modifications for advanced engine systems. Such systems would be needed to achieve optimum performance and lowest emissions by the end of 2015.

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Project Team TBD

²¹ DOE FY 2004 Progress Report p. 725 (Global Assessment of Hydrogen-Based Technologies)

Technology Several programs are currently underway to define baseline emissions and operational ranges for hydrogen and hydrogen-methane mixtures. Examples of these types of programs are studies being conducted by DOE-NETL's Office of Science and Engineering Research (OSER) on lubricant life in hydrogen ICEs, injector performance, and ignition systems. All of these programs focus on performance issues – that is, short term test data with regards to emissions. To date, power and long-term operational issues have not been verified. Some examples of these long-term operational issues include:

- Low power density linked to the low volumetric energy density and combustion properties of hydrogen.
- Little if any durability data are available, particularly for 100% hydrogen-fueled ICEs.
- Ignition System Life and associated alternatives.

Other lifetime issues could include the interactions of the fuel with the engine lubricant, the interaction of the fuel with the engine materials, and the interaction of the combustion products with the engine lubricant system. These are multifaceted issues that may incorporate a number of modes for failure.

The proposed research shall include efforts which address each of the above long-term operational issues and shall be structured in two primary areas: (1) lab-scale operational performance for ICEs under varying load conditions (preferably for 100% hydrogen fueled applications); and (2) comparative performance and economic evaluation of a baseline ICE and/or vehicle and modified ICE and/or vehicle. Data for a minimum of 1,000 hrs of operation is required (preferably more). The proposed efforts should include at least one engine manufacturer's involvement.

Project Status Two to four awards are expected later in 2006 in the range of \$1,000,000 to \$3,000,000 in DOE funding plus a minimum of 30% cost share. This is planned as a three year program.²²

²² US Department of Energy, National Energy Technology Laboratory, Funding Opportunity Number: DE-PS26-06NT42801, CFDA Number: 81.089 Fossil Energy Research and Development, Issued Mar 02, 2006

4.0 Department of Defense (DOD) Programs

Currently, the DOD does not have HICE or HCNG-ICE projects underway. Some projects are proposed and the National Automotive Command is working with national laboratories and the Defense Logistics Agency on a Request for Information. One project that has been explored for sometime is planned for New Mexico. Although not underway, this potential project concept will provide some insight into the plans and will be another project to follow for potential HICE applications.

4.1 *Conceptual Plans for New Mexico Hydrogen Production and Dispensing Demonstration*

Key Objectives In Phase I of the proposed demonstration project, the concept is to build a hydrogen production plant on a plot of land located north of the parking structure at Albuquerque International Sunport, a location where a compressed natural gas (CNG) facility fuels rental car shuttle bus services. It will provide easy access to supporting fleets as well as public access for airport fleet and shuttle bus services. The project team concept includes building a hydrogen production unit capable of providing enough hydrogen to fuel (either with hydrogen or HCNG) three internal combustion engine vehicles with the ability to expand production in future phases. Facilities for reforming, storing, blending, and fuel dispensing of hydrogen and natural gas blends are proposed.

The vehicle demonstration concept during Phase I is proposed to test hydrogen and a variety of HCNG blends in a test fleet. The proposed initial test fleet is light-duty internal combustion engine vehicles from neighboring federal and local fleets. Other vehicle types may include shuttle buses or a passenger car with a hybrid electric powertrain calibrated to burn hydrogen in the Phase I.

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Project Team The six proposed project team leaders include New Mexico Hydrogen Technology Partnership (HyTeP), the National Automotive Center (NAC) of the U.S. Department of Defense-Army, the City of Albuquerque-International Sunport, Kirtland AFB; the New Mexico Energy, Minerals and Natural Resources Department; and the New Mexico Economic Development Department.

Technology The City of Albuquerque-International Sunport currently operates a CNG refueling station at the Albuquerque airport. Sunport will provide access to this natural gas and the land needed to house the equipment needed to produce, store and use hydrogen and HCNG blends. Sunport will promote public education about hydrogen

technologies throughout the Albuquerque area. Kirtland Air Force Base, complying with the federal Energy Policy Act of 1992, will be responsible for testing a small fleet of vehicles including vehicle monitoring, maintenance and reporting.

Project Status This project is not underway at this time but the team is working towards formal project initiation.²³

²³ Draft System Specification, US Army, National Automotive Command, January 2005

5.0 Department of Transportation/Federal Transit Administration (DOT/FTA) Programs

The critical issues important to the FTA are developing a hydrogen engine with comparable or better performance and emissions than its transit bus counterpart. Storing sufficient hydrogen on board the vehicle to provide the range desired by consumers is an identical issue for hydrogen ICE and fuel cell vehicles. Much of the work to date has been conducted as retro-fits rather than by original equipment manufacturers.

The FTA is following a three-pronged path toward hydrogen as a transit fuel and one pathway may help to advance the early deployment and evaluation of hydrogen infrastructure. A hydrogen internal combustion engine in a hybrid electric configuration offers very low emissions and enhanced fuel efficiency as compared to current diesel or natural gas buses. Although not the zero emission vehicle that is a hydrogen fuel cell bus, this vehicle system offers the lowest vehicle cost for a transit operator to gain valuable experience in the establishment of a safe hydrogen infrastructure and in the operation of a hydrogen-fueled vehicle. This can offer an advantage since HICE can mitigate the “chicken and egg” problem facing hydrogen and fuel cell vehicles.

5.1 SunLine Project HICE Transit Bus

Key Objectives FTA is supporting the demonstration of such a bus at SunLine Transit. The roll-out occurred in December 2004 with extremely positive results to date. This Hydrogen Hybrid Internal Combustion Engine bus is getting about 8 miles to a gallon diesel equivalent. The goal is to integrate and demonstrate a hydrogen ICE hybrid bus at SunLine Transit and also simulate revenue service at Chula Vista Transit for one month. The bus was tested in a high temperature environment at SunLine transit in Palm Desert, California and in shipped to Canada for cold weather testing in Winnipeg, Manitoba. Emissions tests are planned for the ARB chassis dynamometer in Los Angeles to determine the actual emissions under various standard bus cycles (CBD, FDDS, and Orange County cycles).

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Project Team FTA – lead funding partner, South Coast Air Quality Management District (SCAQMD) – Southern California funding partner
ISE Corporation – Vehicle system Integrator

Ford Motor Company – initial vehicle tests
SunLine Transit Agency, Palm Desert – Vehicle operations and
maintenance, warm weather test
New Flyer – Transit bus chassis
Winnipeg Transit in Manitoba, Canada – Cold weather test

Technology ISE Research developed a hydrogen-ICE hybrid-electric transit bus using deep-cycle batteries in a series hybrid configuration and a variant of Ford Motor Company's (Ford) V10 Triton gasoline engine, which has been used successfully in a gasoline-ICE hybrid-electric bus. ISE Research assembled and installed the hydrogen fuel hybrid-drive system into a New Flyer transit bus chassis. After the initial testing by ISE Research and Ford, the bus was demonstrated and tested at various transit districts, including Chula Vista, Winnipeg, and SunLine Transit. CARB will test the bus on the chassis dynamometer to determine the actual emissions under various standard bus cycles. Subsequent to the various demonstrations, the bus will be operated at SunLine Transit.

Project Status The HHICE transit bus has been operated over the past year by SunLine Transit as well as completing cold weather operations tests in Winnipeg. The HHICE engine is run at ultra-lean conditions, 0.4 of stoichiometric, and has no other provisions for emissions control. The lean operation – and hence very cool burn – keeps NO_x production at minimal levels, at or below 20-25 ppm. As there is no carbon in the fuel, HC and CO are below normal ability to be detected.

The program described herein provides early evidence that the tailpipe NO_x can be brought much lower by use of catalytic absorber material substituted for the muffler now used on the engine. A portable engine dynamometer was developed to evaluate exhaust gas treatment using a similar (V10, 6.8 liter) hydrogen engine. Initial testing to evaluate the operation of this engine and to get baseline emission and operational data is described. NO_x absorber equipment was added and initial absorption testing showed NO_x at below ppm levels, showing a reduction of well over a factor of ten.

5.2 Hydrogen Bus Technology Validation Program

Key Objectives This project plans development and demonstration of hydrogen and natural gas blend buses with the University of California at Davis through the campus transit agency, Unitrans. The goal of the program is to demonstrate the feasibility of operating buses on blends of hydrogen in converted compressed natural gas engines through extensive engine testing and in future transit service operations.

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Project Team FTA (federal funding partner)

California Air Resources Board, CalEPA (ICAT funds)
UC Davis, Institute of Transportation Studies – Engine tests, simulations
City Engines – Engine retrofit
Unitrans – Vehicle operations
Air Products and Chemicals Inc – Infrastructure

Technology

Collier Technologies modified a John Deere 8.1 liter natural gas transit bus engine to operate on a blend of hydrogen and natural gas. The engine modifications included enhanced air flow by replacing the stock turbocharger and changes to the engine timing using a modified engine controller. Initial work on the John Deere engine resulted in improved emissions but significantly lowered power output. Follow-on work demonstrated the efficacy of further extending the lean burn limit as a method to reduce NO_x emissions and enhancing air flow to the engine to increase engine output power relative to the base engine operating on natural gas alone. The Phase II work resulted in an engine that meets the CARB standards for NO_x and has improved power relative to the Phase I engine. The power is still somewhat reduced from the stock CNG engine.

The work on the Phase II portion of the bus program allowed Collier Technologies to develop a commercialization plan based on a Phase III engine. Phase III will focus on achieving technology that is suitable for implementation in transit buses throughout the United States. The goal is to achieve hardware that can be designated as U.S. manufacture through selective outsourcing of the components specifically designed for U.S. heavy duty vehicle integration with the HCNG fuel.

Collier Technologies has chosen the Daewoo 11.0 liter CNG engine to use as their commercial HCNG engine platform. The Daewoo engine is rated at 286 hp at 2200 rpm and 831 ft-lbs at 1320 rpm. That engine will be used in Phase III of the bus program. Modifications to the engine included engine timing adjustments, enhanced air flow capability, and operating at an equivalence ratio of roughly 0.53. Collier Technologies has tested the modified engine on their dynamometer.²⁴

Project Status Substantial test data is available along with simulation data for transit bus application. HCNG engines are installed in two buses but the project is awaiting fueling infrastructure at the current CNG facility for Unitrans to begin bus service operations. The commercial readiness is close at hand. This project demonstrated that changing fuels and the computer algorithms of the engine controller do not achieve the ultimate emissions results that the technology is capable of attaining. First, the engine air system can be modified to deliver significantly more air through use of special turbochargers or superchargers. Second, the engine can be oversized then de-rated for power. Collier Technologies developed their present commercial prototype based on the information gained from an ICAT funded program. The commercial prototype uses a larger engine

²⁴ “Hydrogen Bus Technology Validation Program”, Andy Burke, Zach McCaffrey, Marshall Miller Institute of Transportation Studies, UC Davis, May 12, 2005

(Daewoo 11 liter) with enhanced air flow capability and is now licensed to City Engines. City Engines is pursuing engine certification.

5.3 Development and Demonstration of HD HCNG Engine Meeting Future Emission Standards

Key Objectives The Los Angeles County Metropolitan Transit Authority (MTA) has over 2,300 transit buses that operate on CNG. MTA is interested in evaluating various technologies that will help in complying with future CARB and U.S. EPA requirements, including the Zero Emission Bus program required under CARB Transit Bus Regulations. The MTA is currently evaluating a variety of technologies and strongly believes that HCNG fueled ICEs with NO_x aftertreatment will provide a bus with near-zero emissions, qualifying as a Zero-Emission Bus. MTA believes that this may be the one of the most cost-effective zero emission propulsion systems available in the near future.

Key Contact Adi Areili
Consultant to LACMTA

Project Team Los Angeles County Metropolitan Transportation Authority
Areili and Associates
City Engines
Trillium Fuel Systems
Federal Transit Administration
South Coast Air Quality Management District

Technology MTA will contract with City Engines in Reno, Nevada to modify an existing 11.0L Doosan engine to operate on a mixture of 30% hydrogen blended into natural gas, and demonstrate two 40' transit buses on CNG and two 40' transit buses on HCNG for a period of six months to evaluate the technology as well as quantify the emission benefits of the HCNG mixture. City Engines will also seek emissions certification for this HCNG ICE for transit bus use. Additionally, Trillium Fuel Systems, MTA's primary CNG supplier, will modify one of MTA's refueling facilities to allow for fueling the four buses with the HCNG mixture. Hydrogen will be supplied using a tube trailer. City Engines plans to commercialize the engine based on the success of the program. City Engines plans to develop, demonstrate, and certify a heavy-duty HCNG engine meeting the federal 2010 standards.²⁵

Project Status The project was approved by SCAQMD in March 2006 and contracting is underway to go forward with this project.

²⁵ Agenda Item 7, AQMD Board Meeting Minutes DATE: March 3, 2006

5.4 New Haven Advanced Transportation System Development Program

Key Objectives The project is part of the FTA National Hydrogen Initiative. Greater New Haven Transit District (GNHTD) is expanding and diversifying energy technology to reduce its reliance on fossil fuels through hydrogen-powered transit operations. Their Advanced Transportation System is based on two hydrogen fueled battery dominant, hybrid-electric transit vehicles, the first of which will be powered by a fuel cell, the second by an internal combustion engine. The vehicles in this program will be supported by two state-of-the-art hydrogen generation and fueling systems, one utilizing a natural gas-based reformation technique and one a compressor-less electrolysis technology.

Key Contact Team Leader -Lou Lautman
Gas Technology Institute

Project Team Donna Carter, Executive Director of GNHTD
Integrated Product Development (IPD) Team led by the Gas Technology Institute (GTI) of Des Plaines, IL.
Gas Technology Institute - Lead
Gas Technology Institute - Hydrogen reformation system developer,
MES (with Sabre Engineering and CompositeTek) - Vehicle developer/builder
Hydrogenics - Fuel cell supplier,
Avâence (Connecticut-based) - Electrolytic hydrogen system developer
- Installer of the renewable power supply
Innovation Drive - Marketing, public awareness, team coordination, reporting and commercialization aspects of the program.

Technology The Advanced Transportation System is based on two hydrogen fueled battery dominant, hybrid-electric transit vehicles, the first of which will be powered by a fuel cell, the second by an internal combustion engine.

Project Status Phase I, awarded September 2005, is part of a projected multi-year program, which aims to simultaneously design and deliver two hydrogen fueled hybrid-electric transit vehicles, and two on-site hydrogen production, storage, and dispensing systems, as well as the design and implementation of innovative diagnostic, maintenance, and training platforms for the vehicles and fueling systems. Ultimately the project will also encompass the design and construction of a new state-of-the-art transit facility for GNHTD.²⁶

²⁶Fuel Cell Website – September 6, 2005
<http://www.fuelcelltoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/NewsDisplayArticle/0,1602,6425,00.html>

6.0 National Science Foundation (NSF) Efforts

As described in its strategic plan, NSF is the only federal agency whose mission includes support for all fields of fundamental science and engineering, except for medical sciences. They are tasked with keeping the United States at the leading edge of discovery in areas from astronomy to geology to zoology. So, in addition to funding research in the traditional academic areas, the agency also supports "high-risk, high pay-off" ideas, novel collaborations and numerous projects that may seem like science fiction today, but which we'll take for granted tomorrow. And in every case, NSF ensures that research is fully integrated with education so that today's revolutionary work will also be training tomorrow's top scientists and engineers.²⁷

The key assets within NSF that support HICE are combustion simulations that can be used by industry to design and analyze new engine configurations. They offer direct numerical simulation, large eddy simulation, and Reynolds averages Navier Stokes simulations. In addition, they have a broad portfolio of combustion and flame simulation tools.

A vision called for in the Atkins report by a blue ribbon panel chaired by Daniel E. Atkins, suggests the creation of a national level, integrated system of hardware, software, and data resources and services within NSF. This new infrastructure would open the door to new types of scientific/engineering research and education, and could well benefit engine designers. Plus, a process information model (PrIMe) offers a new paradigm for generation of predictive kinetic models, i.e. models with quantified uncertainty for dynamic generation of predictive models based on available data sets.

Finally, pertinent projects are doing relevant engine analysis and optical studies of combustion processes. These are available to the industry and are suggested for possible incorporation in new projects going forward.

²⁷ Source: <http://www.nsf.gov/about/>

7.0 National Laboratory Roles

The Advanced Vehicle Testing Activity (AVTA) is conducted jointly by the [Idaho National Laboratory](#) (INL) and the [National Renewable Energy Laboratory](#) (NREL). The AVTA is part of the Department of Energy's [FreedomCAR & Vehicle Technologies Program](#). The primary goal of AVTA is to provide benchmark data for technology modeling, and research and development programs, by benchmarking and validating the performance of light-, medium-, and heavy-duty vehicles that feature one or more advanced technologies, including:

- Internal combustion engines burning advanced fuels, such as 100% hydrogen and hydrogen/compressed natural gas-blended fuels
- Hybrid electric, pure electric, and hydraulic drive systems
- Advanced batteries and engines
- Advanced climate control, power electronic, and other ancillary systems.

By benchmarking the performance and capabilities of advanced technologies, the AVTA supports the development of industry and DOE technology targets. The testing results are also leveraged as input to component, system, and vehicle models, as well as hardware-in-the-loop testing.

The AVTA develops vehicle test procedures with input from industry and other stakeholders to accurately measure real-world vehicle performance. These test procedures are then used to test production and pre-production advanced technology vehicles on dynamometers and closed test tracks as well as in government, commercial, utility, and industry fleets. The AVTA tests produce unbiased information about vehicles with advanced transportation technologies, which reduces the U.S. dependence on foreign oil, while improving the nation's air quality.

The AVTA also produces information resources that support the decisions fleet managers and the public make when acquiring advanced technology vehicles. The testing results are presented in easy-to-understand formats that allow users to compare the performance of different types of vehicles.²⁸

7.1 Argonne National Laboratory

Argonne's Center for Transportation Research (CTR)

While economic and environmental modeling served as the CTR's foundation, engineering and technology development has gained increasing importance in providing solutions to transportation energy and environmental problems. The EERE sponsors many CTR initiatives through the FreedomCAR and Vehicle Technologies and

²⁸ <http://avt.inel.gov/>

Hydrogen, Fuel Cells, and Infrastructure Technologies programs. The CTR plays a prominent role in the national laboratories' research and development for the FreedomCAR Partnership.

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Thomas Wallner, Ph.D.
Hydrogen Research Specialist
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7.2 Sandia National Laboratories

Combustion Research Facility

Researchers in the Combustion Research Facility HICE laboratory are initially focusing on the measurement and analysis of in-cylinder hydrogen mixing processes in a direct injection (DI) HICE. The laboratory houses an automotive-sized single-cylinder engine (~0.6 liters/cylinder) that provides extensive optical access for application of advanced laser-based optical diagnostics to study fundamental in-cylinder engine phenomena.



Figure 11: CRF's DI-HICE prototype

Transition strategy using HICE may serve to promote the H₂ infrastructure and pave the way for Fuel Cell Vehicles. Work in optimizing a production ICE for maximum efficiency and minimum emissions has demonstrated levels of NMHC at 0.0076 g/m; CO at 0.0082 g/m; CO₂ at 1.4 g/m and NO_x levels of 0.74 g/mi (engine-out without a catalyst)²⁹

DOE H₂ program supported research at UC Riverside CE-CERT yielded tailpipe-out NO_x measured at 57 ppb (dry) -- corrected for water yields ~40 ppb; ambient NO_x was measured at 50 ppb.

Supported by the EERE's Office of FreedomCAR and Vehicle Technologies Program, CRF researchers Christopher White and Joseph Oefelein are collaborating on a combined experimental and numerical investigation of the fundamental in-cylinder engine processes that occur in a direct-injection hydrogen-fueled internal combustion engine

²⁹ Ford Research, SAE 2002-01-0243

(DI-HICE). The DI-HICE can potentially avoid many of the problems at high engine loads exhibited by conventional HICEs such as pre-ignition and backflash. Unlike a port-fuel-injection (PFI) system, a DI-HICE avoids the power density loss associated with the displacement of air by lighter hydrogen since fuel in a DI-HICE is injected after the intake valve has closed.

Generally, a PFI HICE can provide 15–40% less horsepower than an identical gasoline engine, but a DI-HICE provides 15% more horsepower than the gasoline engine. However, efficient in-cylinder injection in a DI-HICE requires that hydrogen and air mix in a very short time (i.e., approximately 4 ms at 5000 rpm). Since mixture formation at the initiation of combustion is critical to engine performance and emissions, a fundamental understanding of the effects and optimization of in-cylinder hydrogen–air mixture formation is necessary before commercialization is possible.

The Advanced Hydrogen Engine Laboratory at the CRF studies fundamental in-cylinder engine processes in a DI-HICE. The facility possesses an optically accessible, automotive-sized single-cylinder engine. Experimental results acquired by White are complemented by Oefelein’s closely coupled set of numerical calculations using the “Large Eddy Simulation” (LES) technique. Oefelein’s simulations use a highly specialized, massively parallel flow solver designed to treat the turbulent reacting flow processes typically encountered in ICEs.

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7.3 Idaho National Laboratory - Advanced Vehicle Testing and Evaluation

Key Objectives In May 2006, DOE announced a number of “Industry Partnership Projects to Increase Fuel Efficiency”. One project, in collaboration with industry, focuses on the testing and evaluation of commercially available and pre-production light-, medium-, and heavy-duty advanced technology vehicles using advanced energy storage technologies (such as batteries, ultra-capacitors, and high-pressure, high-volume hydrogen storage tanks); advanced drive trains; internal combustion engines burning advanced fuels (such as 100 percent hydrogen and hydrogen enriched natural gas blended fuels); advanced climate control, power electronic, and other ancillary systems; and combinations of advanced onboard engine technologies (hybrids). Activities also include evaluations of the necessary infrastructure required to fuel advanced technology vehicles.

Clarity Group, Inc. in Phoenix, AZ will conduct field performance evaluations including baseline performance, accelerated reliability, and fleet testing of state-of-the-art light-, medium-, and heavy-duty advanced technology vehicles equipped with one or more

advanced technologies. Evaluations will also be conducted on the required vehicle-to-infrastructure interface required for fueling the advanced technology vehicles.³⁰

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Idaho National Laboratory
Clarity Group

Technology The team plans to measure performance and emission characteristics of the vehicles selected by INEL at some time in the future. This is planned as a five year program.

³⁰ DOE Press Release, DOE Announces \$14 Million Industry Partnership Projects to Increase Fuel Efficiency, May 26, 2006

8.0 State and Local Agency Programs

8.1 Florida Hydrogen Infrastructure Program

Florida is pioneering the widespread use of hydrogen to diversify its energy portfolio, grow its economy, lessen the nation's dependence on foreign fuels, and keep the state's air clean. In 2003, Governor Jeb Bush launched "H2 Florida" in partnership with leading technology companies to cultivate Florida's business climate for hydrogen technologies. Today, Florida is a national leader in the development of hydrogen energy, with 28 mobile and stationary hydrogen demonstration projects under way, in development, or in the planning stage. Combined with eight universities conducting over 100 research projects on hydrogen, Florida is aggressively demonstrating that hydrogen is "the fuel of the future."

Florida's 2005 accomplishments include:

- Delta Airlines, Ford Motor Company, and TUG Technologies will demonstrate hydrogen fueled tow tractors at Orlando International Airport;
- The State of Florida purchased eight of the world's first commercially available hydrogen shuttle buses for use in the greater Orlando Area in a joint venture with Ford Motor Company, ChevronTexaco, and Progress Energy;
- Ford Motor Company and BP America will demonstrate fuel cell cars in partnership with the State of Florida and Progress Energy;
- The State of Florida teamed with Progress Energy Florida, Florida Power & Light, Plug Power, and Hydrogenics to install two fuel cells at Homosassa Springs Wildlife State Park and Hugh Taylor Birch State Park;
- The Florida Department of Environmental Protection will soon begin installing fuel cell back-up power systems at its 12 district and branch offices around the state;
- In March, the State of Florida and 25 technology companies released Florida's Accelerated Commercialization Strategy for Hydrogen Energy Technologies, the state's hydrogen highway "roadmap;"
- In the first of several training sessions, Florida recently trained over 100 of its fire marshals on hydrogen safety;
- North Port High School became the first school in the nation to teach students about hydrogen technologies using an on-site Plug Power fuel cell, together with a hydrogen science curriculum; and
- Governor Bush's proposed Florida Hydrogen Energy Technologies Act unanimously passed the Florida House of Representatives, with strong industry support. It did not reach the Senate floor in the closing days of the legislative session. The proposed legislation would have provided significant tax credits and financial incentives to manufacturers and end users of hydrogen technologies. Florida state government will move forward by administratively implementing components of the proposed legislation, including financial incentives, targeted

grants, and uniform statewide siting standards for hydrogen technology. Florida's hydrogen program has blossomed during the last two years and will continue to grow this year as the legislation for the 2006 session of the Florida legislature is prepared.

Key Contact Details of "H2 Florida" can be found at www.FloridaHydrogen.org.³¹

8.2 Mid-West Hydrogen H

The Northern H represents Upper Mid-West Hydrogen Initiative signature infrastructure project. This is in part because it prepares the region to participate in the eventual introduction of hydrogen vehicles, but also because it provides a potential organizing framework for complementary, but independent hydrogen projects along each corridor of the "H."

As proposed, the Northern H involves implementing 1-3 stations in each jurisdiction, with each station approximately 125 miles (200 km) apart. At this distance, a hydrogen vehicle could easily travel and refuel across the entire network. It is worth noting that every proposed host city across the network also has at least one institution of higher learning with which to partner, making these early stations excellent research platforms and educational tools.

UMHI has proposed a deliberate, multi-fuel approach to developing the Northern H based on the premise that a shift to clean hydrogen and biofuels requires transition infrastructure that accommodates a wide range of vehicle platforms and fuels as markets for both evolve. While hydrogen and fuel cells are promising, their future is not guaranteed. A prudent approach requires pursuing more than one fueling option simultaneously.

To take full advantage of biofuels in the short-term, the Northern H stations would ideally be equipped with programmable pump capability to enable the user to dispense ethanol-blended gasoline and biodiesel-blended diesel in any desired proportion. Gaseous hydrogen dispensing would be visible and available as part of the same energy station, although hydrogen users would be limited initially to dedicated on- or off-road fleets. An important potential benefit of this approach is that consumers filling up with gasoline, diesel or biofuels would be able to see hydrogen used as a transportation fuel long before using it themselves.

A multi-fuel strategy may not be practical in every location, and will likely raise the initial cost of the stations. But the aim of offering hydrogen alongside gasoline, diesel, ethanol and biodiesel blends is to make these early stations more practical and financially viable while hydrogen use is low. This allows more conventional fuels to, in effect, subsidize the introduction of hydrogen.

³¹ http://www.usfcc.com/resources/Catalyst_Spring2005.pdf

There are also technical reasons for considering a multi-fuel approach. For example, over the past few years ethanol has emerged as a potentially attractive feedstock for hydrogen production and is already widely distributed. In addition, the co-location of fuels invites the potential for fuel blending as a transition step.

This “no regrets” multi-fuel approach to building out hydrogen infrastructure means that if, for whatever reason, hydrogen fails to commercialize as a transportation fuel — either as quickly as expected, or at all — the Northern H investment will not be wasted since it will have successfully diversified domestic fuel options and helped to expand a biofuels refueling backbone.³²

8.3 California - South Coast AQMD Programs

The South Coast Air Quality Management District (AQMD) plays a role in Hydrogen & Fuel Cell Technology for Transportation by relying on automakers for vehicle technology development. However, the AQMD is a partner on at least two DOE Hydrogen Fleet and Infrastructure Demonstration & Validation teams learning demonstration teams. While the focus of AQMD resources is on Basin-wide local fueling infrastructure development, there is purposing this as a fueling network for hydrogen internal combustion engine vehicles by funding a Five-City Demonstration and a HCNG Engine Development.

The SCAQMD Board has awarded Hydrogen Fueling Projects to provide hydrogen at the following locations in the district: LAX Airport, UCLA, Huntington Beach, Irvine, SunLine Transit, Coachella Valley, Torrance, AQMD Headquarters and California State University Los Angeles. The intent is to provide for basin-wide coverage for commuting at strategic locations with easy access. A diversity of hydrogen production technology is being installed through fuel partnerships.

8.3.1 Five-City Hydrogen ICE Vehicle and Fueling Infrastructure

The AQMD has partnered with five cities in the district: Burbank, Ontario, Riverside, Santa Ana and Santa Monica. The intent is install public hydrogen fueling stations at different cities through Air Products. Funds are also awarded for development and demonstration of hydrogen internal combustion engine (ICE) vehicles. The vehicle conversions were awarded to Quantum Technologies and 30 vehicles have been delivered.

Quantum developed and converted Toyota Priuses to hydrogen ICE vehicles. The conversion vehicles have a range slightly less than 100 miles but driving characteristics are similar to the gasoline fueled Prius. The vehicles will be operated under a five year CARB Experimental Permit but the emissions meet SULEV for NO_x, CO, HC, and CO₂

³² The Northern H: Developing the First Canada-U.S. Hydrogen Refueling Network, R. Nordstrom, R. Parsons, Director, Upper Midwest Hydrogen Initiative, NHA 2006.

and could qualify for AT-PZEV. More information on the vehicles can be found under Quantum discussion.

8.3.2 Hydrogen ICE Shuttle



Figure 12: Ford's E450 Shuttle Van

The AQMD has found strong interest in southern California for a Ford Motor Company –E450 Shuttle 12 Passenger Shuttle Van equipped to run on hydrogen using a proven 6.8L V-10 Triton Engine. There is a possible partnership with Ford and local fleets. Additional information about the shuttle and the hydrogen ICE can be found under the vehicle description for Ford projects.

8.3.3 Hydrogen CNG Engine



Figure 13: SunLine's HCNG bus

Although this program is completed successfully, the test reports and information reflects recent Hydrogen-CNG ICE development. Westport Innovations for the SunLine Transit Agency converted a CWI 230HP, 5.9L spark-ignited lean-burn B Gas Plus natural gas engine modified to operate on an optimized HCNG [80%/20%) fuel blend. Tests showed up to 50% NO_x reduction and an increase in engine efficiency. Two buses operated in revenue service during 2002-2004,

logging over 65,000 vehicle miles. Additional projects are being planned with transit authorities.

8.3.4 Hydrogen CNG Engine LACMTA

The Los Angeles County Metropolitan Transportation Authority operates one of the largest fleets of CNG fueled transit buses. A project that is about to start is a conversion of four 40-foot buses which will operate on two CNG and two HCNG engines for demonstration at LACMTA. This City Engines project is expected to use a lean-burn engine with EGR. Transit Authorities see potential to comply with future engine emission standards for NO_x reduction.

8.4 California Hydrogen Highway Network

The California Hydrogen Highway Network was launched by California Governor Schwarzenegger through Executive Order signed April 20, 2004. Through a volunteer stakeholder supported and state led effort a Blueprint Plan has been adopted. Phase I could provide for up to 50 stations supplied hydrogen through reformation, electrolysis, or pipeline. The network is expected to service up to 2,000 vehicles powered by fuel cells and ICEs.

9.0 Original Equipment Manufacturer Programs

9.1 Ford Hydrogen ICE Vehicles

Ford Motor Company is dedicated to the realization of fuel cell powertrains in mass produced consumer vehicles. But fuel cell powertrains are not ready for mass production in the near term. HICE is regarded as a transition or “bridging” strategy to stimulate the hydrogen infrastructure, and related hydrogen technologies which includes on-board hydrogen fuel storage, hydrogen fuel dispensing, and hydrogen safety sensors. Recently, Ford’s efforts on its Model U concept vehicle have developed an advanced hydrogen ICE engine based on its 2.3-liter I-4 engine used in the Ford Ranger, the European Ford Mondeo, and a number of Mazda vehicles. The engine is optimized to burn hydrogen with 12.2:1 high-compression pistons, fuel injectors designed to handle hydrogen gas, a coil-on-plug ignition system, an electronic throttle, and new engine management software.

9.1.1 Ford Model U – 2003



2003 – NAIAS Model U

Figure 14: Ford Model U

The Model U incorporates a 2.3-liter, four-cylinder supercharged, intercooled hydrogen internal combustion engine, coupled with a hybrid electric transmission result in a HICE hybrid vehicle. This HICE hybrid offers enhanced fuel economy - the equivalent of 45 miles per gallon and about 300 miles of range - plus near-zero regulated emissions and a 99-percent reduction in carbon dioxide. The powertrain also features Ford's advanced Modular Hybrid Transmission System, a way to simplify hybrid electric vehicle (HEV)

technology in manufacturing, while contributing to significant fuel economy improvements. This vehicle can meet PZEV emissions.

The Model U internal combustion engine is optimized to run on hydrogen. The engine is supercharged and intercooled for maximum efficiency, power, and range. Its emission of all pollutants, including carbon dioxide, is nearly zero, and the engine is up to 25 percent more fuel-efficient than gasoline engines. A hybrid-electric transmission system further improves efficiency.

Because hydrogen has a very wide combustion range (from 4 to 75 percent), hydrogen-fueled engines are able to use a wider range of air/fuel mixtures than gasoline engines, and can be run in the fuel-efficient "lean" regime without the complications of pre-

ignition or "knock." Much like a diesel engine, the hydrogen ICE runs unthrottled while under way, with air/fuel mixtures as lean as 86:1 during highway cruise, compared to the 14.7:1 of gasoline-powered vehicles. It can reach an overall efficiency of 38 percent, which is approximately 25 percent better than a gasoline engine.

Because there are no carbon atoms in the fuel, combustion of hydrogen produces no hydrocarbon or carbon-dioxide emissions. Even without aftertreatment, oxides of nitrogen (NO_x) are very low, and catalyst research may soon reduce tailpipe output of potentially smog-forming emission to below ambient conditions in many cities. Designing a gasoline engine to burn hydrogen fuel has typically resulted in significantly lower power output - until now. Ford researchers have shown that with supercharging, the hydrogen ICE can deliver the same power as its gasoline counterpart and still provide near-zero-emissions performance and high fuel economy. The centrifugal-type supercharger provides nearly 15 pounds per square inch (psi) of boost on demand.

Also, Model U uses a novel dual-stage intercooling process. After leaving the supercharger, the intake air passes through a conventional air-to-air intercooler, then through an air conditioning-to-air intercooler for a further reduction in temperature. This patent-pending solution further improves the performance of the engine.

Table 2: Model U specs

Powertrain	
Hydrogen 2.3-liter ICE with supercharging and dual-stage intercooling	
Module Hybrid Transmission System	
Performance	
Engine Horsepower	118 hp (88 kW) at 4,500 rpm
MHTS assist	33 hp (25 kW) continuous / 46 hp (35 kW) peak
Total combined horsepower	151 hp (113 kW) at 4,500 rpm
Torque	154 foot-pounds (210 Nm) at 4,000 rpm
Estimated fuel economy	45 miles per kilogram hydrogen (equivalent to 45 mpg)
Emissions	PZEV or better
Fuel capacity (kg)	7.0
Fuel type	Hydrogen

9.1.2 Ford H2RV - 2003



2003 – Centennial H2RV

Figure 15: Ford H2RV

Earlier versions of a HICE engine have been tested in Ford Focus wagons dubbed Hydrogen Hybrid Research Vehicles, or H2RVs. The Focus wagons include a battery pack that powers an electric motor, creating a hydrogen-electric hybrid engine. The H2RVs were tested in southeast Michigan. Ford said fuel efficiency improves by 25 percent with hydrogen and up to 50 percent with a hybrid hydrogen engine.

9.1.3 Ford FOCUS C-MAX H₂ICE – 2004

Ford engineers equipped the Ford Focus C-MAX with a prototype hydrogen internal combustion engine (H₂ICE). The vehicle was unveiled July 2004 at the Research Conference of the German Car Manufacturer Association (VDA) in Stuttgart, which was attended by the German Chancellor Gerhard Schröder and other important political figures.



2004 – H₂ICE C-Max

Figure 16: Ford C-Max H₂ICE

to establish a commercial demand for hydrogen fuel. This will help to establish a hydrogen fuelling infrastructure and, as more vehicles need hydrogen, so this network of fuelling stations will grow. The gasoline internal combustion engine has been developed over a period of more than 100 years and can offer very mature technology.

This does not mean that the modifications required to produce the prototype hydrogen internal combustion engine are trivial. The base engine is a 2.3 liter four-cylinder gasoline engine producing 110 hp (82kW). The Ford Focus C-MAX with H₂ICE differs from the base vehicle mainly in the packaging of the engine. Also, the battery has been moved from the engine compartment to underneath the back seat; additionally, there are special safety systems and sensors to suit the different fuel tank technology. The H₂ICE power train also requires some additional electronic systems and components such as two intercoolers.

The test vehicle uses compressed gaseous hydrogen stored at 350 bar in three tanks. Two are located in the trunk and the third one is installed under the floor. Two pressure regulators reduce the gas pressure down to 5.5 bar at the engine manifold. Altogether the three tanks accommodate a capacity of 119 liters, which equates to 2.75 kg of hydrogen and provides a range of about 200 km.

A supercharger enables the Ford Focus C-MAX H₂ICE to have similar performance to the corresponding gasoline engine. By compressing the intake air, the supercharger increases the mass of the fuel mixture in the combustion chamber. During compression the air is heated and it is then cooled by the two intercoolers, of which one is located behind the front bumper and the other in the middle of the engine compartment. The

The Ford Research Center at Aachen developed this technology demonstrator to analyze its technical and environmental potential. On the way towards achieving sustainable mobility, Ford regards the hydrogen internal combustion engine as an important step towards a hydrogen-fueled future where fuel cells, delivering clean electric power, are the ultimate goal.

Before the technical and economical maturity of fuel cell vehicles is achieved, it is important

cooled and compressed air is fed to the combustion engine to combine with the hydrogen in the cylinders.

The hydrogen/air-ratio of the Ford Focus C-MAX H₂ ICE can be adjusted in a wide range since the ignitability of hydrogen in air varies from four to 70 per cent by volume. This means that both very lean and very rich hydrogen/air mixtures are possible, which enables the optimal control of fuel consumption and NO_x emissions to be achieved.³³

9.1.4 Ford H₂ ICE Shuttle Bus



2006 – H₂ICE Demo/Fleet

Figure 17: Ford HICE shuttle bus

Ford's HICE shuttle bus vehicles will be available in late 2006. Their vision is that they will take HICE technology from the research lab to the commercial trial. This will provide insight into acceptance of hydrogen as a fuel. Success in the technology may provide a bridge from gasoline engines to Fuel Cell Vehicles while offering many of the FCV benefits now at less cost. These vehicles will

support hydrogen as a renewable fuel reducing dependence on imported oil.

The vehicle is a Ford E-450 chassis with 6.8L inter-cooled, supercharged ICE with a shuttle bus body. Engine performance is expected to provide a peak torque of 340 ft-lb at 2500 RPM with a peak power of 225 hp at 4000 RPM. The hydrogen Fuel System & Management System includes a separate hydrogen enclosure at rear of vehicle with six fuel tanks providing a vehicle range of 150 miles. The vehicle complies with Canadian and Federal motor vehicle standards.

Two hydrogen-powered shuttle buses will pull into the Lehigh Valley early next year, staying for a two-year test that should give many Valley residents their first view of a hydrogen-powered vehicle.

One bus will be used for campus transportation at the Trexlertown headquarters of Air Products and Chemicals Inc., the world's largest supplier of hydrogen. The other bus will be based at the Da Vinci Discovery Center of Science and Technology in South Whitehall Township, where it will be used for trips to schools and other educational efforts.

Both buses will fill up at a specialized fuel station at Air Products' Trexlertown campus. The Valley will be one of very few regions its size to host a hydrogen vehicle test. Most

³³ Ford Motor Company website

pilot programs so far have taken place in major cities such as Los Angeles, Chicago and Sacramento, Calif.³⁴

9.1.5 Ford Tug Florida H2 Tow tractor

Ford Motor Company, the Florida Department of Environmental Protection (DEP), TUG Technologies Corporation, Delta Airlines and the Greater Orlando Aviation Authority (GOAA) have showcased a hydrogen fueled tow tractor outside of City Hall in downtown Tallahassee, Florida. Project partners have teamed to create a one-of-a-kind product to benefit the local environment and economy. Two TUG M1 tow tractors will be placed into service with Delta Airlines as baggage carriers at the Orlando International Airport later this summer.



Figure 18: Ford's TUG M1

They will be powered by a Ford 4.2-liter, V-6 industrial engine converted and calibrated to operate on gaseous hydrogen. The proof-of-concept hydrogen fueled engines will create approximately 80 horsepower at 3600 RPM - naturally aspirated. The tow tractors emit near zero tailpipe emissions, without utilizing an exhaust after-treatment system, making them an ideal solution for the airport environment where emissions levels are strictly regulated., The engine also delivers up to a 99.7 percent reduction in carbon dioxide, with the main by-product being water.³⁵

9.2 ISE Corporation HHICE Bus



2004 – H2ICE Hybrid Bus (ISE)

Figure 19: HICE hybrid-electric transit bus

ISE Research will develop a hydrogen-ICE hybrid-electric transit bus using deep-cycle batteries in a series hybrid configuration and a variant of Ford Motor Company's V10 Triton gasoline engine. ISE Research will assemble and install the hybrid-drive system into a New Flyer transit bus chassis. After the initial testing

by ISE Research and Ford, the bus will be demonstrated and tested at various transit

³⁴ Hydrogen Powered Buses Come to Lehigh Valley, The Morning Call, 6 August 2005.

³⁵ Press Release from Ford, Apr 28, 2005

districts, including Chula Vista, Winnipeg, and SunLine Transit. CARB will test the bus on the chassis dynamometer to determine the actual emissions under various standard bus cycles. Subsequent to the various demonstrations, the bus will be operated at SunLine Transit.

9.3 Mazda RX-8 Hydrogen Rotary Engine-2004



2004 – H2ICE Rotary

Figure 20: RENESIS Hydrogen RE

The RENESIS Hydrogen RE allows the RX-8 concept to run on either hydrogen fuel or gasoline by adding a high pressure hydrogen tank as part of the fuel system. It also capitalizes upon a key advantage of the rotary, separate intake and combustion chambers, to assure RX-8's ease-of-operation and reliability. The RENESIS Hydrogen RE incorporates an electronically controlled hydrogen injector system, with the hydrogen injected in a gaseous state. The system draws air from the side port during the intake cycle and uses dual hydrogen injectors in each of the engine's twin rotor housings to directly inject hydrogen into the intake chambers.

Because it offers separate chambers for intake and combustion, the rotary engine is ideal for burning hydrogen without the backfiring that can occur in a traditional piston engine. The separate induction chamber also provides a safer temperature for fitting the dual hydrogen injectors with their rubber seals, which are susceptible to the high temperatures encountered in a conventional reciprocating piston engine.

Also helping to maximize the benefits of the rotary engine in hydrogen combustion mode, the RENESIS Hydrogen RE features adequate space for the installation of two injectors per intake chamber. Because hydrogen has an extremely low density, a much greater injection volume is required compared with gasoline, thus demanding the use of more than one injector. Typically, this can be difficult to achieve with a conventional reciprocating piston engine because of the structural constraints that prevent mounting injectors in the combustion chamber. However, with its twin hydrogen injectors, the RENESIS Hydrogen RE is both practical and able to deliver sufficient power.

In addition to the revolutionary hydrogen-powered RENESIS rotary engine, the Mazda RX-8 Hydrogen RE concept benefits from improved aerodynamics and optimized tires

³⁶ Ford, George Davis, Low Emissions IC Engine Development at Ford Motor Company, June 2005

and weight-saving measures. A fast-fill tandem master cylinder reduces brake drag and friction hub carriers help cut power losses.³⁷

9.4 Quantum Fuel Systems Technologies Worldwide Conversion Vehicles

9.4.1 Hydrogen Toyota Prius Conversion

Quantum Fuel Systems Technologies Worldwide, Inc., was awarded a contract by California's South Coast Air Quality Management District (AQMD) to provide the engineering, design and development of advanced hydrogen fuel systems for a fleet of 30 Toyota Prius Hybrid Electric Vehicles.

Quantum developed the complete OEM-level hydrogen internal combustion engine fuel system, including both the injection system and hydrogen storage system. Included in the fuel systems are the company's patented fuel injectors, fuel rails, electronic control system and software, hydrogen storage and a customized turbocharger. Quantum integrated these hydrogen fuel systems into the vehicles and performed complete validation including crash testing, engine and vehicle durability, and emissions testing to verify emissions levels (see below).

Quantum can offer the vehicles with two hydrogen storage configurations: Quantum's TriShield® compressed hydrogen storage system or an optional metal hydride storage system. Quantum plans to make Texaco Ovonics metal hydride storage also available for evaluation. Quantum previously worked with Texaco Ovonics to develop a hydrogen-powered concept vehicle using a model year 2002 Toyota Prius Hybrid Electric Vehicle. The interest generated by the concept vehicle developed by Quantum for Texaco Ovonics contributed to establishing the foundation for this program.

The AQMD test fleet program entailed Quantum performing all of the necessary engineering, safety testing, interface with licensing agencies and validation of the model year 2004 Toyota Prius providing a turnkey conversion that meets performance specifications and in-use conditions determined by the AQMD. In addition to performing in specified starting conditions and meeting certain drivability specifications, the vehicle also needed to achieve SULEV (Super Ultra Low Emissions Vehicle) emissions levels. Quantum with their experience in a ECD Ovonics program with a 2002 and 2004 hydrogen Prius conversion using a Metal Hydride Storage System knew that the vehicles provided a very energy efficient platform capable of SULEV emissions.

The AQMD has identified the use of alternative clean fuels in mobile sources as a key air quality attainment strategy. Hydrogen fuel cell vehicles are near zero-emission vehicles but currently have limited availability, high costs and short warranty periods. In order to stimulate the demand for hydrogen, expedite the development of infrastructure, and

³⁷ Ford News Release, Mazda RX 8 HICE Rotary, 2004.

provide a bridge to fuel cell vehicles, the AQMD has initiated an effort to establish a network of hydrogen fueling stations and deploy a small fleet of hydrogen powered ICEs.

The converted H₂ hybrid Toyota Prius has an ICE with electronic multi-port hydrogen fuel injection system, turbocharged and inter-cooled for increased performance and efficiency. Performance comparable to gasoline version with slightly increased fuel economy. With the H₂ compressed hydrogen fuel system, the four vehicles were tested to FMVSS 303

The engine horsepower is 70 HP at 4,000 rpm with torque at 85 lb-ft at 3,200 rpm. Fuel consumption rating is 56-60 mpKg City (FTP 75) and 50-52 mpKg Highway (HFET). Fuel capacity is 1.6 to 2.4 kg at 5,000 psig with compressed hydrogen storage and approximately 4.0 kg at 1,500 psig with a metal hydride storage system.³⁸

Table 3: Prius Emissions Comparison Table

System	Emissions			
	NMOG	CO	NOX	CO ₂
California Air Resources Board SULEV standard (gm/mile)	0.010	1.000	0.020	Not applicable
California Air Resources Board SULEV standard (gm/km)	0.006	0.625	0.013	Not applicable
Gasoline Prius - baseline measurement (gm/mile)	0.010	0.386	0.004	222.800
Gasoline Prius - baseline measurement (gm/km)	0.006	0.241	0.003	139.250
Hydrogen Prius - Tailpipe out (with catalytic converter) (gm/mile)	0.000	0.002	0.008	0.683
Hydrogen Prius - Tailpipe out (with catalytic converter) (gm/km)	0.000	0.001	0.005	0.427

9.4.2 Ford Hybrid Escape Conversion

U.S. Army National Automotive Center (NAC) awarded a contract to develop a hydrogen-fueled Ford Escape Hybrid vehicle for the U.S. Army to Quantum Fuel Systems Technologies Worldwide, Inc. Under the contract, Quantum will evaluate different hydrogen fuel system configurations, considering the feasibility of bi-fuel and dedicated hydrogen systems. Quantum will develop an advanced hydrogen storage system, fuel injection system, and electronic controls required for the Hydrogen Escape Hybrid. The work will be conducted by Quantum at its Advanced Vehicle Concept Center in Lake Forest, CA.³⁹

³⁸ Quantum Presentation to Hydrogen Internal Combustion Engine Symposium, WestStart-CALSTART, 22 February 2006.

³⁹ Ibid.



Figure 21: Ford Hybrid Escape

This Hydrogen Escape Hybrid contract complements the Mobile Hydrogen Infrastructure (MHI) program, which is funded in the FY 06 Department of Defense budget. The overall objective of the MHI program is to demonstrate the capability of Quantum's HyHauler Plus transportable hydrogen refueling stations to meet emerging hydrogen fuel demand as hydrogen and fuel cell technologies are deployed throughout the military as part of the 21st Century Base

initiative. The demonstration program includes supporting the deployment of hydrogen internal combustion engine administrative vehicles, including the Hydrogen Escape Hybrid, as well as fuel cell vehicles.⁴⁰

9.5 Volvo Multi-Fuel Concept Car

Volvo has introduced its Multi Fuel Concept Car at the Michelin Challenge Bibendum 2006. The five-cylinder, 2.0-litre prototype car (200 bhp) runs on five different fuels: hythane (a blend of 10% hydrogen and 90% methane), biomethane, natural gas (CNG), bioethanol E85 (85% bioethanol and 15% gasoline) and gasoline. The turbo-charged engine delivers 200hp (149 kW) of power, accelerating from 0 to 100 km/h in 8.7 seconds. Volvo considers the Multi-Fuel concept car a first step towards a hydrogen powered society. Combustion of pure renewable fuels like hydrogen, biomethane and bioethanol gives negligible net contribution of fossil carbon dioxide.

The Multi-Fuel vehicle meets the emission standards for Euro 4 and the proposed levels for Euro 5. The vehicle has two catalysts, one close-coupled to the engine that lowers initial start emissions, and one under the floor for reduced high-speed emissions. High-temperature materials in the exhaust manifold and turbo allow extremely high exhaust gas temperatures of up to 1,050 °C. This enables the car to run cleaner, accelerate quicker and operate more smoothly at higher speed. An alternative catalyst system has also been developed to meet the extremely low tailpipe emissions for PZEV/SULEV in the U.S. market.

The car contains one large and two smaller tanks totaling 98 liters for gaseous fuels (hythane, biomethane, and CNG), and one 29-litre tank for liquid fuels (bioethanol E85 and petrol). The small gaseous fuel tanks are made of steel, whereas the large tank has a durable, gas tight aluminum liner, reinforced with high performance carbon fiber composite and an exterior layer of hardened fiber-glass composite.

⁴⁰ Quantum to Build Hydrogen-Fueled Escape Hybrid for US Army, Green Car Congress, 15 Feb. 2006.

Multi-Fuel System for Hythane, Biomethane, CNG, Bioethanol E85 and Petrol

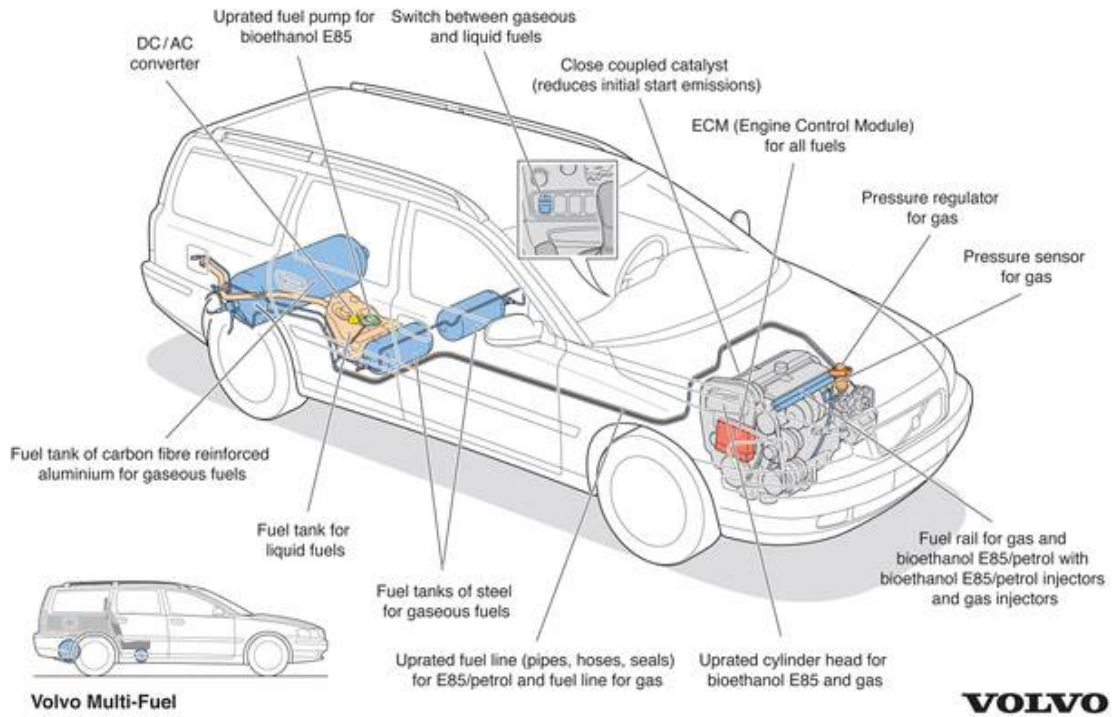


Figure 22: Volvo Multi-Fuel Concept Car diagram



Figure 23: The Volvo Multi-Fuel Concept Car

The fuel tanks are fitted neatly under the luggage compartment floor, which means that full loading capacity is preserved. Two fuel fillers are used to fill up all five fuel types, one for gaseous and one for liquid fuels. The engine automatically adjusts itself to the right blend of gaseous or liquid fuels. To switch between fuel types, the driver simply presses a button.⁴¹

9.6 Hydrogen Engine Center

The Hydrogen Engine Center launched operations in December 2005 to re-manufacture Ford in-line six engines that run on hydrogen, hydrogen blends, and natural gas fuel for commercial sale in non-road applications.

9.7 City Engines

City Engines has licensed technology from Collier Technologies, Inc. to produce heavy-duty hydrogen fueled engines for the transit industry. City Engines plans to fabricate and demonstrate an 11 L engine for Penn State University and deliver a number for test to the LACMTA. Engines will run on hydrogen-CNG blends. Partial funding is provided by the SCAQMD. City Engines is also looking manufacture of an 8 liter engine as well.

9.8 Westport Innovations

Westport Innovations Inc. (TSX:WPT) announced today that it has received a purchase order from BMW AG of Munich, Germany to support BMW Group Research and Technology on hydrogen internal combustion engine development. The commitment is expected to cover work through September 2005.

Westport will provide fuel injection hardware and engineering support, including sets of Westport's prototype hydrogen fuel injectors for testing at BMW Group facilities. Westport retains the intellectual property and ownership rights for the injectors. The advanced hydrogen injector design incorporates Westport's patented and proprietary high pressure direct injection technology.

"Our new agreement with BMW Group is another demonstration of Westport's gaseous-fueled engine technology leadership," said Michael Gallagher, Westport's Chief Operating Officer. "We are proud to be selected by BMW, one of the world's leaders in high-performance engine design and development. Although hydrogen as a fuel for mass-produced vehicles remains some time away, it's clear that the combination of low-cost internal combustion engines with the environmental benefits of hydrogen could be an important step towards sustainable mobility."

⁴¹ Volvo to Preview Five-Fuel Vehicle; Includes Hythane, Green Car Congress, 7 June 2006.

BMW Group is one of the leading automotive partners in the European Integrated Hydrogen Project Phase II (EIHP2) and has been conducting trials with hydrogen-powered vehicles for decades. More information about BMW Group's hydrogen program is available on the Internet at www.bmwgroup.com/cleanenergy.

Westport Innovations Inc. is the leading developer of gaseous fuel engine technologies. It develops, manufactures and sells a wide range of engines for commercial transportation applications such as trucks and buses through Cummins Westport Inc., its joint venture with Cummins Inc. Technology development alliances are in place with a number of other leading engine manufacturers, including Ford, MAN, Isuzu, and BMW to develop engines that operate using cleaner-burning fuels such as natural gas, propane, hydrogen, and blended fuels such as HCNG.⁴²

⁴² Westport Receives Purchase Order from BMW Group on Hydrogen Engine Development Program, Autochannel News, 22 March 2004

10.0 Non-U.S. Programs

10.1 Prince Edward Island Wind-Hydrogen Village Project

Key Objectives The Prince Edward Island Wind-Hydrogen Village will demonstrate how wind energy and hydrogen technologies work together to offer clean and sustainable energy solutions in our daily lives. Wind energy will be the primary energy source. The wind turbines at North Cape will be used directly to meet ongoing electricity needs and to provide power to electrolysis equipment that makes hydrogen from water. The hydrogen will then be used in fuel cell systems or hydrogen internal combustion engines to provide backup and primary electricity, as well as transportation fuel, for industrial, farm, and household needs.

Phase One of the project will see the installation of a hydrogen energy station, a hydrogen storage depot, and a wind-hydrogen and wind-diesel integrated control system to power the North Cape Interpretive Centre Complex, the Atlantic Wind Test Site, as well as other homes and office buildings in the North Cape area.

Phase Two is expected to include up to three full-service hydrogen shuttle buses to be used in Charlottetown and the Charlottetown-North Cape corridor, a hydrogen refueling station, additional fuel cell utility vehicles, and the expansion of the wind-hydrogen village to provide energy for additional buildings and facilities, including at least one farm operation and the Seacow Pond Wharf.

Phase Three Plans involve the introduction of a hydrogen-powered tour boat to operate out of Seacow Pond Wharf. The boat will be retrofitted with an engine that has the ability to run on pure hydrogen, with a diesel fall-back system.

Project Team The project leaders are Hydrogenics Corporation and the Prince Edward Island Energy Corporation. Hydrogenics is a leading global developer of clean energy solutions, advancing the Hydrogen Economy by commercializing hydrogen generation and fuel cell products. The PEI Energy Corporation is a Crown Corporation which owns and operates the North Cape Wind Farm and is involved in the development of other renewable energy initiatives in Prince Edward Island.

Other participants are:

- Atlantic Orient Corporation, a global leader in small wind turbine power systems for remote communities
- Dynetek Corporation, a leader in compressed-gas hydrogen storage systems
- Frontier Power Systems, a PEI-based engineering company which specializes in the design, construction and installation of control systems to enable renewable energy-based technologies to be integrated into conventional electrical systems
- Holland College, the primary technical training institute in Prince Edward Island

- Maritime Electric Company Limited, the primary electrical utility in Prince Edward Island
- Saskatchewan Research Council will provide the engines for the pickup trucks and boats as well as integration expertise, and will assist in technology transfer
- Saint Mary's University
- University of New Brunswick
- University of Prince Edward Island
- Vestas Canada, the world's largest wind turbine company

Project Status Industry Canada has announced that the \$10.3-million project will receive an investment of \$5.1 million through the Hydrogen Early Adopters (h2EA) program of Technology Partnerships Canada. The other major financial contributor is the Government of Prince Edward Island which will invest \$2.5 million in earnings from the North Cape Wind Farm and \$425,000 from Prince Edward Island Business Development.⁴³

10.2 HyICE - Optimizing Hydrogen Engines, European Commission



Figure 24: HyICE

Key Objectives HyICE (Hydrogen Internal Combustion Engine), launched in January 2004, is a three-year European initiative aimed at contributing to the development of a clean and economical hydrogen fueled automobile engine. The is coordinated by BMW Group Research and Technology Its press relations officer, Claudia Scheiderer, says, “A significant amount of research and development remains to be carried out before the hydrogen economy can become a reality. The conventional internal combustion engine, even after more than 100 years of service, has not necessarily outlived its usefulness.”

Indeed, she says, the internal combustion engine (ICE) is particularly well suited not only as a transition technology, featuring high power density, and relatively low cost, but also as a future energy concept using alternative fuels such as hydrogen.

“It is our objective, says Sheiderer, “to combine both customer demand regarding performance and efficiency with reasonable product cost. We believe that the direct conversion of chemical bound energy, in the form of hydrogen, to mechanical propulsion energy, using the well-established ICE, has the real potential for a rapid integration into mass market vehicles, considering time, cost and available know-how, because the ICE is able to use different fuels.”

In order to adapt the internal combustion engine to the use of hydrogen, components capable of handling the new fuel, with its specific characteristics, have to be developed.

⁴³ Source: <http://www.gov.pe.ca/news/getrelease.php3?number=4080>

In addition to the components, BMW is putting a strong emphasis on the development of suitable concepts for mixture formation and combustion. “One of the main benefits of our EC-funded HyICE project is that the tools developed for later engine optimization are publicly available,” says Scheiderer.

As the first logical step, the project is focusing on the development of new components such as injectors and an ignition system as well as the preparation of computational fluid dynamics (CFD) tools for optimization of the process of mixture formation and combustion. By bringing together representatives of the automobile industry and researchers from Europe and the USA, the project is ensuring the dissemination and exchange of important and valuable know-how. The results of the project, together with supporting components, are expected to form the prerequisites for the development of an optimized propulsion system.⁴⁴

10.3 Integrated Waste Hydrogen Utilization Project - Vancouver, BC

Key Objectives Demonstrate clean energy solutions that make use of an existing but currently untapped source of hydrogen fuel – hydrogen emitted as the by-product of a sodium chlorate manufacturing plant in the North Vancouver area. The purified hydrogen could be used to continually fuel a fleet of up to 20,000 hydrogen-powered vehicles in the Vancouver area, greatly reducing greenhouse gas emissions, local air pollutants, and the use of fossil fuels.

Key Contact Sacre-Davey Innovations Inc.
North Vancouver

Project Team

Hydrogen Early Adopters (h2EA) program - \$6 million
Government of Canada, Sustainable Development Technology Canada - \$5.9 million
Natural Resources Canada's Canadian Transportation Fuel Cell Alliance - \$273,000
Westport-Innovations and Other Industry Partners - \$6.1 million
Total project value - \$18.3 million.

Technology The demonstration will initially involve the operation of eight light-duty trucks running on hydrogen; a fuel cell system operating on hydrogen and providing electrical power and heat to a car wash, and four public transit buses converted by Westport for Vancouver's TransLink fleet to run on a blend of hydrogen and compressed natural gas (HCNG).

⁴⁴ World Wide Web

http://europa.eu.int/comm/research/transport/news/article_2796_en.html

Project Status A Westport Innovations release notes that this is a three-year Integrated Waste Hydrogen Utilization Project (IWHUP), which is beginning in late 2006.⁴⁵

⁴⁵ CALSTART Daily Newsnotes, Oct 14 2005 – web link
http://www.calstart.org/dailynewsnotes/daily_nns_detail.php?id=7774

Appendix A Glossary of Acronyms

Acronym	Meaning
AVTA	U.S. Department of Energy's Advanced Vehicle Testing Activity
CUTE	Clean Urban Transport for Europe
CWI	Cummins Westport, Inc.
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EERE	U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
FTA	U.S. Federal Transit Administration
HBICE	Hydrogen blend internal combustion engine
HCNG	Hydrogen-blended compressed natural gas
HHICE	Hybrid-electric hydrogen internal combustion engine
HICE	Hydrogen internal combustion engine
ICE	Internal combustion engine
INL	Idaho National Laboratory
IWHUP	Integrated Waste Hydrogen Utilization Project
NAIAS	North American International Auto Show
NSF	National Science Foundation
OEM	Original equipment manufacturer
RE	Rotary Engine
RTDD	Refueling Technology Development and Demonstrations
VDP	Vehicle Demonstration Project

