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The National Hydrogen Association's

8th Annual U.S. Hydrogen Meeting

Proceedings

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HYDROGEN PARTNERSHIPS for the FUTURE

11-13 March 1997
Alexandria, Virginia, U.S.A.

Prepared By:
National Hydrogen Association
1800 M Street, N.W., Suite 300
Washington, DC 20036-5802, U.S.A.

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8th Annual U.S. Hydrogen Meeting

Hydrogen Partnerships for the Future

11-13 March 1997

TABLE OF CONTENTS

GENERAL SESSION III
Entering the Market: Partnerships in Transportation

INTRODUCTION

Edison once said the "necessity is the mother of invention". If that is true, then man is creating the necessity to invent solution that controls CO_2 emissions. International agreements with limits on "greenhouse gas emission" in the near future, coupled with recent studies by Dr. Robert Williams at Princeton concluding that hydrogen is the least expensive way to provide a CO_2 free energy system, make the case for accelerating the demonstration and commercialization of hydrogen technologies. The need to develop and apply a hydrogen solution to the issue is consistent with the direction of the NHA, the intent of its annual meeting and this year's theme: "Hydrogen Partnership for the Future."

In order to develop a hydrogen future, the hydrogen community needs partners. This theme was sounded at the first meeting presentation by Sen. Harry Reid of Nevada when he discussed the partnering in the state of Nevada among the Federal Government, State Institutions, and private industry in renewables and hydrogen. Out of this dialog emerged a view expressed by the new NHA Chairman, Dr. Venki Raman, that defined the roles for federal government and industry. The federal government's role is to create knowledge, develop technologies, demonstrate those technologies, and facilitate their introduction. Industry's role is to develop technology into products that respond to the needs of the marketplace. Local government's role is to develop of infrastructure and to create environments that are conducive to the deployment of these technologies. The partnership theme and each respective role was repeated in presentations throughout the conference.

The partnership theme is also represented in the NHA's Hydrogen Commercialization Plan, which was presented by the outgoing chairman to the meeting attendees in the first general session. This Plan was adopted by a vote of the membership during the Annual Membership meeting. The goals of the Hydrogen Commercialization Plan represent a beacon with many paths to it. The implementation plan will lay out the next few steps along the paths toward achieving the goals in the Hydrogen Commercialization Plan. Issues in each market, such as whether to store hydrogen as a liquid or gas and how to store it, are just a few of the forks in the road. The hydrogen community must assure itself that the path taken at each fork in the road is shorter and safer path to widespread hydrogen use.

Of the three markets identified in the Plan (transportation, power production and village power), sessions were built around the transportation and power production. Production of CO_2 gases in the United States is divided between power generation, transportation, and industries and all other sources, with about 1/3 produced by each. Hydrogen offers the opportunity to greatly reduce CO_2 use in the power production and transportation sectors.

Three parts of the transportation market were covered; cars, trucks and buses. Rapid progress was reported in both fuel cell and ICE vehicle propulsion systems. Serious study of the hydrogen corridor concept is being conducted to provide infrastructure to fuel hydrogen vehicles. The meeting pointed out the need to intensify the dialog on some of the most important issues facing the hydrogen community. For transportation alone, these issues include:

hydrogen as a liquid or a gas
media for on-board hydrogen storage
vehicle propulsion: ICE versus fuel cell
odorant versus hydrogen sensors
on-board fuel reforming versus on-board hydrogen.

The presentation on the utility market included a discussion on restructuring with Dave Freeman who is changing the electric future in which we will be living . It shaped the discussion about the role of renewables in new power markets and the needs to lower the cost of renewables. Restructuring may open up economic niche markets for hydrogen and other renewables.

Another important conference theme was safety. This issue, more than any other, is on the public's mind. It is only through public demonstrations that familiarity with hydrogen can bring about the same level of acceptance as exists with gasoline. A dialog with both the financial community and the insurance company is needed to develop the most appropriate standards and practices for achieving this goal.

The global challenge of climate change is increasing. Discussions are underway among the nations of the world on the framework for a climate change agreement. In the balance is a decision about whether or not a meaningful agreement can be achieved by the "Conference of the Parties" in Kyoto, this December. Regardless of the results from this year's meeting, at some point in the near future an agreement will be a reality. The emerging linkage between the DOE Hydrogen Program and Global Climate Change initiatives presents the entire hydrogen community with an opportunity to move the hydrogen agenda into the energy mainstream. The NHA Commercialization Plan will guide our activities toward implementing the Plan's goals. But the NHA can not implement the Commercialization Plan alone. It is through the unification of all members of the hydrogen community, support from the partnerships, and outreach that a hydrogen future can be established.

Review Draft

Strategic Planning for the Hydrogen Economy:
The Hydrogen Commercialization Plan

November 1996

National Hydrogen Association
1800 M Street, N.W., Suite 300
Washington, DC 20036-5802

Dr. Keith Prater, NHA Chairman, presented The Hydrogen Commercialization Plan at the 8th Annual U.S. Hydrogen Meeting. The Commercialization Plan was adopted by the NHA membership and it is recognized as a living document that is subject to change. A copy of this plan accompanies these proceedings.

GENERAL SESSION I:

Government's Partnership Role for Hydrogen Technology Development

Support of a Pathway to a Hydrogen Future

Presented by:

Dr. Allan R. Hoffman
U.S. Department of Energy
Acting Deputy Assistant Secretary
Office of Utility Technologies

Presented to:

National Hydrogen Association

March 12, 1996

Hydrogen R&D Program Vision

(Consensus of the Hydrogen Technical Advisory Panel)

- Hydrogen will join electricity in the 21st century as the primary energy carriers in the Nation's sustainable energy future.
- Hydrogen and electricity will ultimately come from renewable energy sources, although fossil fuels will provide a long-term transitional resource.
- Future hydrogen suppliers will deliver a significant portion of America's energy for transportation and other applications.
- For these applications, hydrogen offers a non-polluting, inexhaustible, efficient, and potentially cost-effective energy system derived entirely from domestic energy sources.

Electricity Industry Restructuring: Opportunities and Challenges for Hydrogen

Opportunities

- Potentially larger market for distributed resources
- Greater use of real time pricing
  - Larger peak/off peak price differential favors hydrogen storage opportunities
- Non-Federal public purpose programs
- Customer choice for "green" technologies
- Global climate change emissions

Electricity Industry Restructuring: Opportunities and Challenges for Hydrogen

Challenges

- Increased competition makes longer term, higher-risk technologies harder to sell
- Unbundled transmission pricing
- Utilities focus on near-term, less likely to support R&D projects with longer-term payoffs

Transportation Sector: Opportunities and Challenges for Hydrogen

Opportunities

- ZEV and near-ZEV vehicle markets
- Hydrogen can extend the range of electric vehicles
- Customer choice for "green" technologies
- Methane to hydrogen conversion with CO_2 sequestration may emerge as a "clean" transitional strategy

Transportation Sector: Opportunities and Challenges for Hydrogen

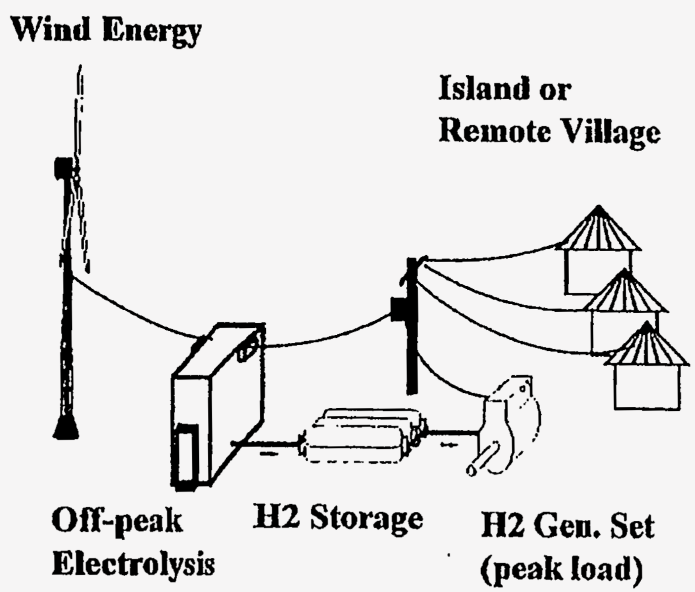
Challenges

- Hydrogen production, transmission, and distribution infrastructure is not in place for transportation applications
- Hydrogen-fueled vehicles are not currently available in the marketplace
- Perceived safety and liability issues
- Hydrogen storage on-board vehicle limits range

Near-term Opportunities for Hydrogen

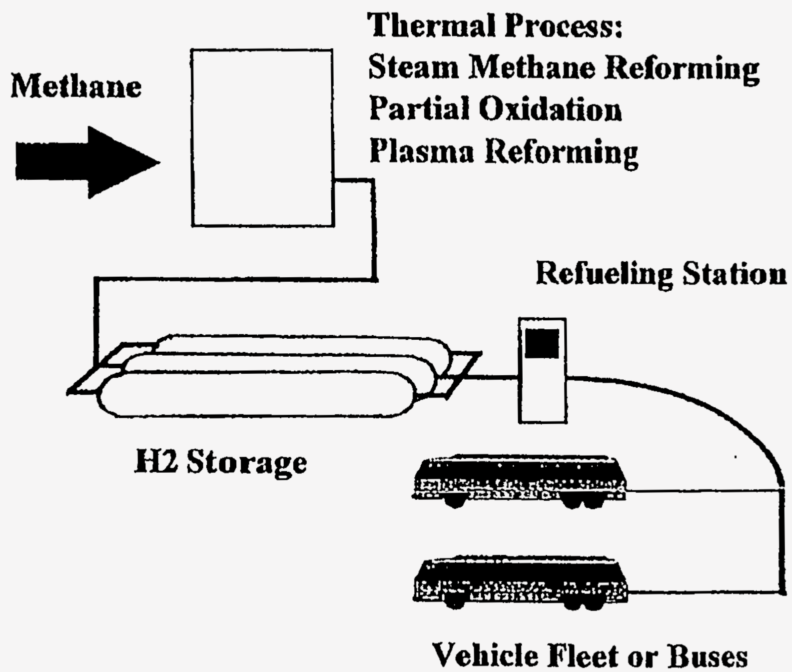
Utility Sector

(Remote Village Technology Validation)



Transportation Sector

(Distributed Fueling Station Technology Validation)



Mid-term Hydrogen Scenario
(Representative)

Windmills, Hydro and Biomass Reactors

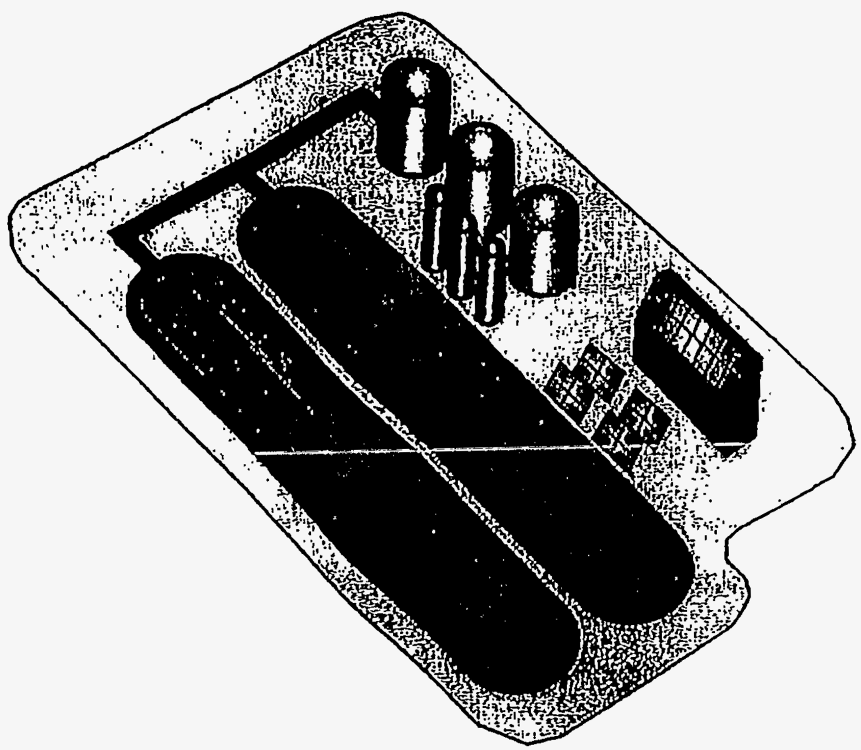
Phase 1: Wind, Hydro, and Biomass resources are converted to conventional energy carriers (i.e., electricity and bio-crude oil are transported to end-use markets).

Hydrogen is produced at the point-of-use.

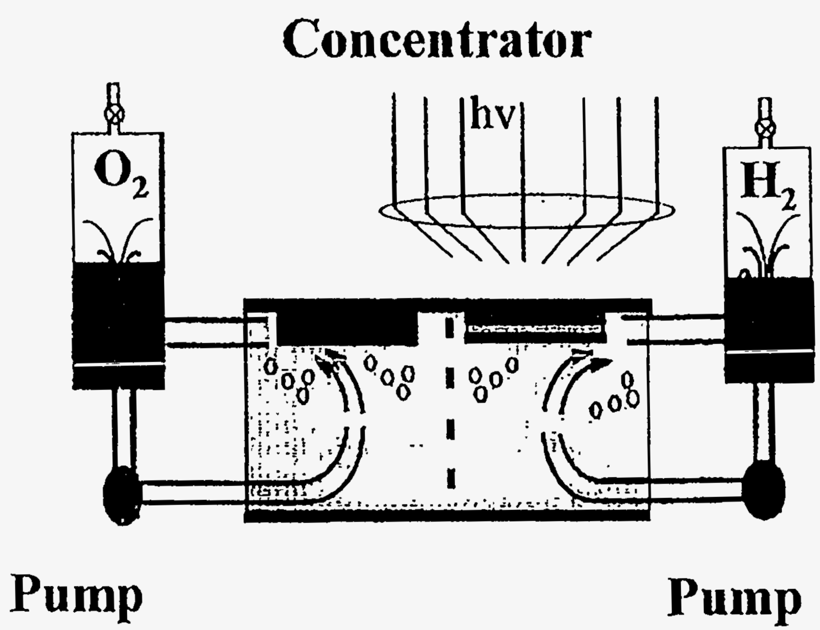
Phase 2: As hydrogen infrastructure develops Wind, Hydro, and Biomass resources are converted to hydrogen at the point of energy production and transported to end-use hydrogen markets.

Hydrogen Production Technologies from Water (Long-term)

Photobiological reactors (NREL)



Photoelectric cells (Hawaii)



Summary

- Many opportunities exist in utility and transportation sectors for hydrogen energy systems in the near-, mid-, and long-term
- Research, development, and validation activities will help to achieve hydrogen price goals make hydrogen technologies competitive in the marketplace
- Global Climate Change is a potential significant driver for the development of hydrogen systems
- A full transition toward a hydrogen economy can begin in the next decade.

Fuel Cells for Future Transportation: The Department of Energy OTT/OUT Partnership

Pandit Patil, Director
Office of Advanced Automotive Technologies, OTT

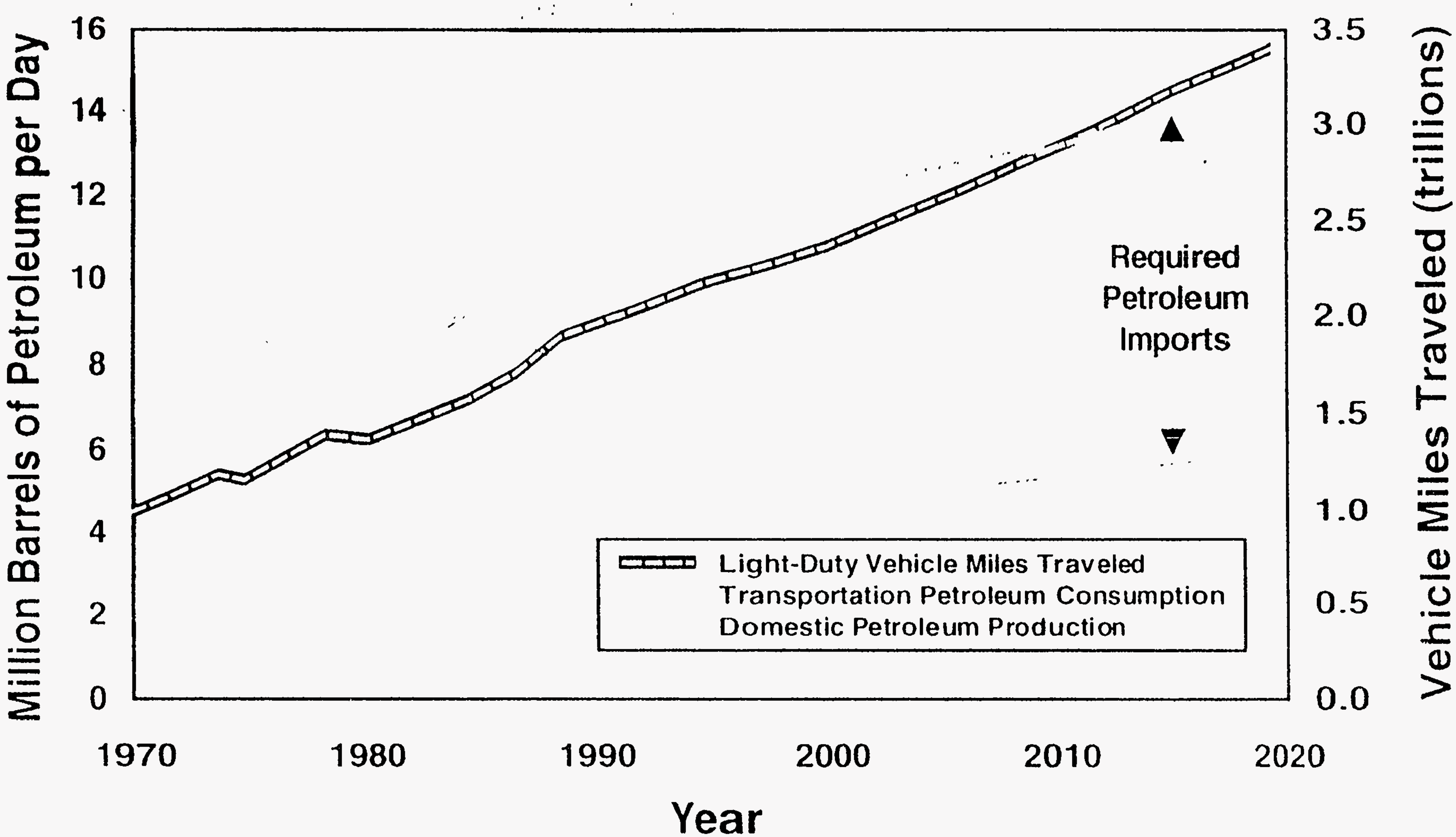
Sig Gronich, Team Leader
Hydrogen Program, OUT

JoAnn Milliken
Fuel Cell Systems R&D

Jim Ohi
National Renewable Energy Laboratory

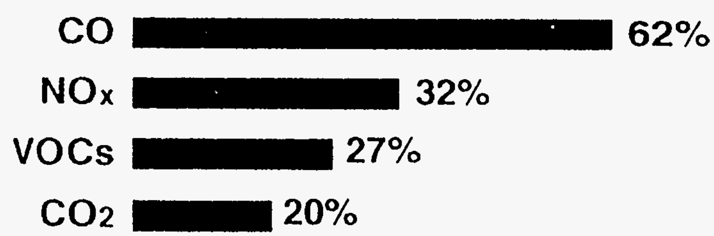
8th Annual U.S. Hydrogen Meeting, Alexandria, VA
March 12, 1997

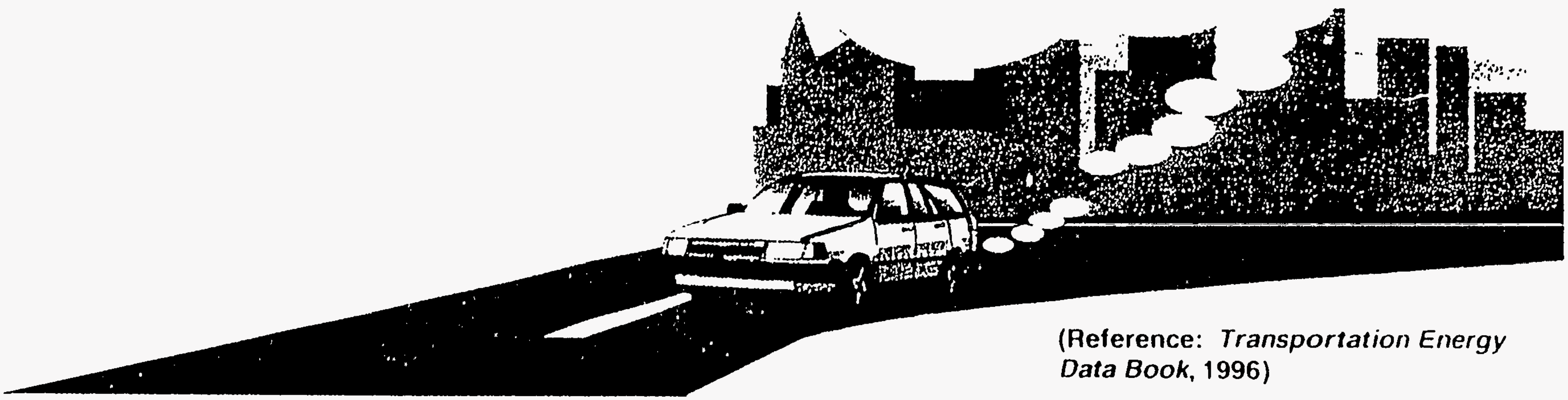
U.S. Dependence on Imported Oil is Growing



Highway Vehicles are a Major Source of Air Pollution

Highway Vehicle's Share of Emissions





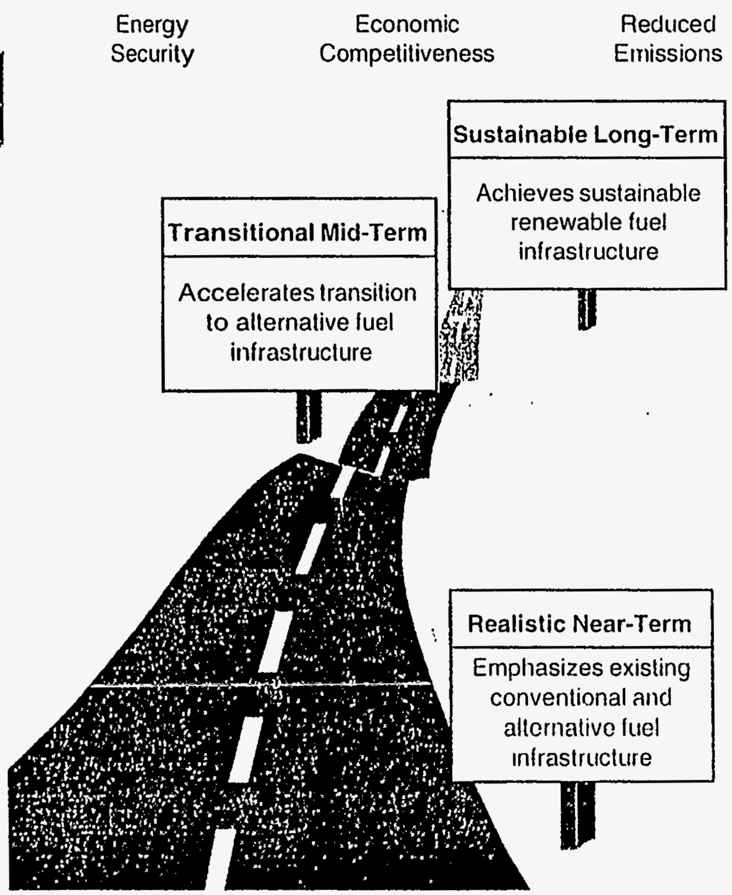
(Reference: *Transportation Energy Data Book*, 1996)

SOURCE. Abacus Technology Corporation

Fuel Cells for Transportation Program Goals

- By 2000, validate automotive fuel cell power systems that are:
  - >51% energy efficient @ 40kW max power
  - >100 times cleaner than EPA Tier II standards
  - fuel-flexible (conventional and alternative)
- By 2004, validate systems that are:
  - cost-competitive with ICEs
  - equivalent in range, safety, and reliability

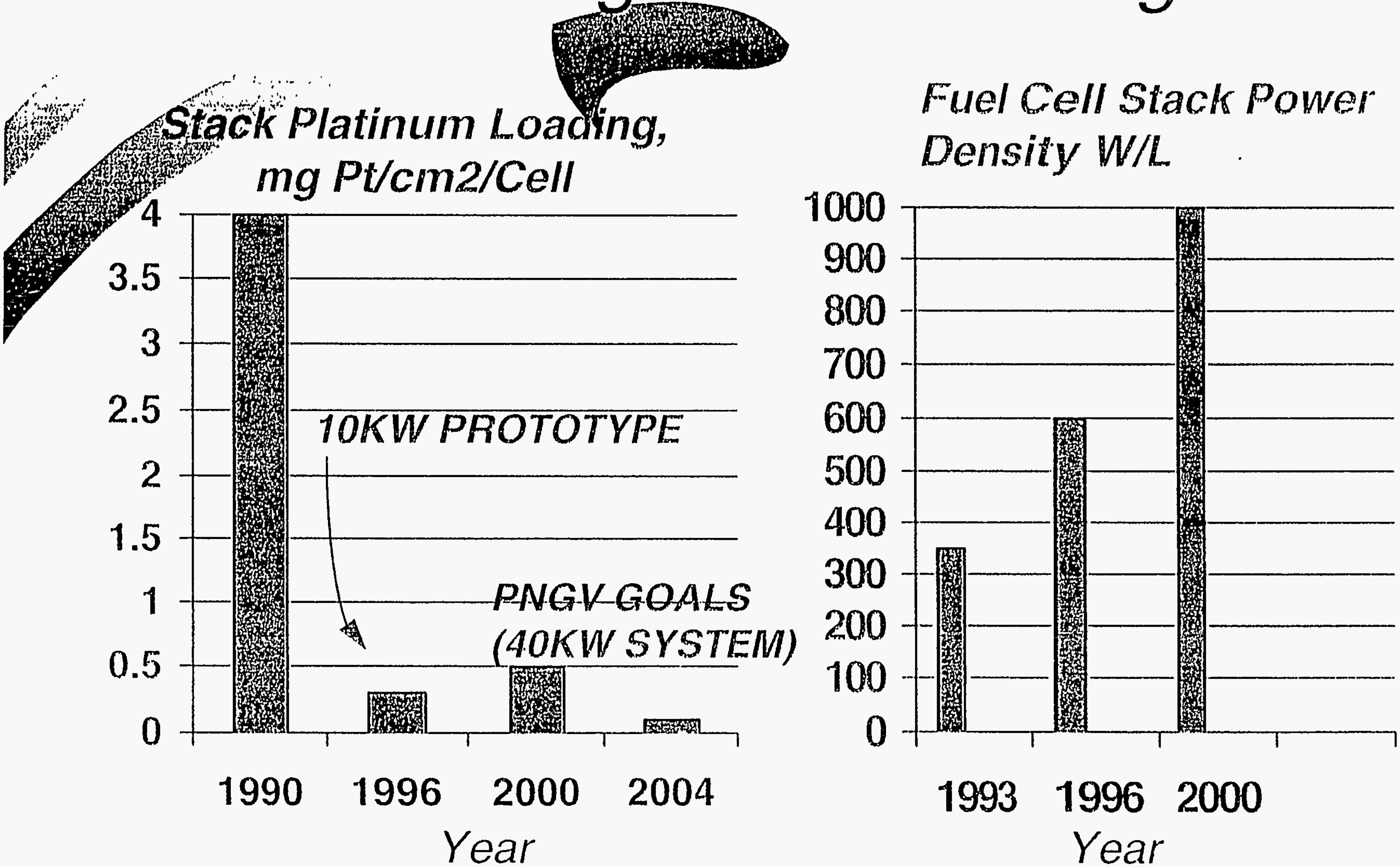
OTT Fuel Strategy



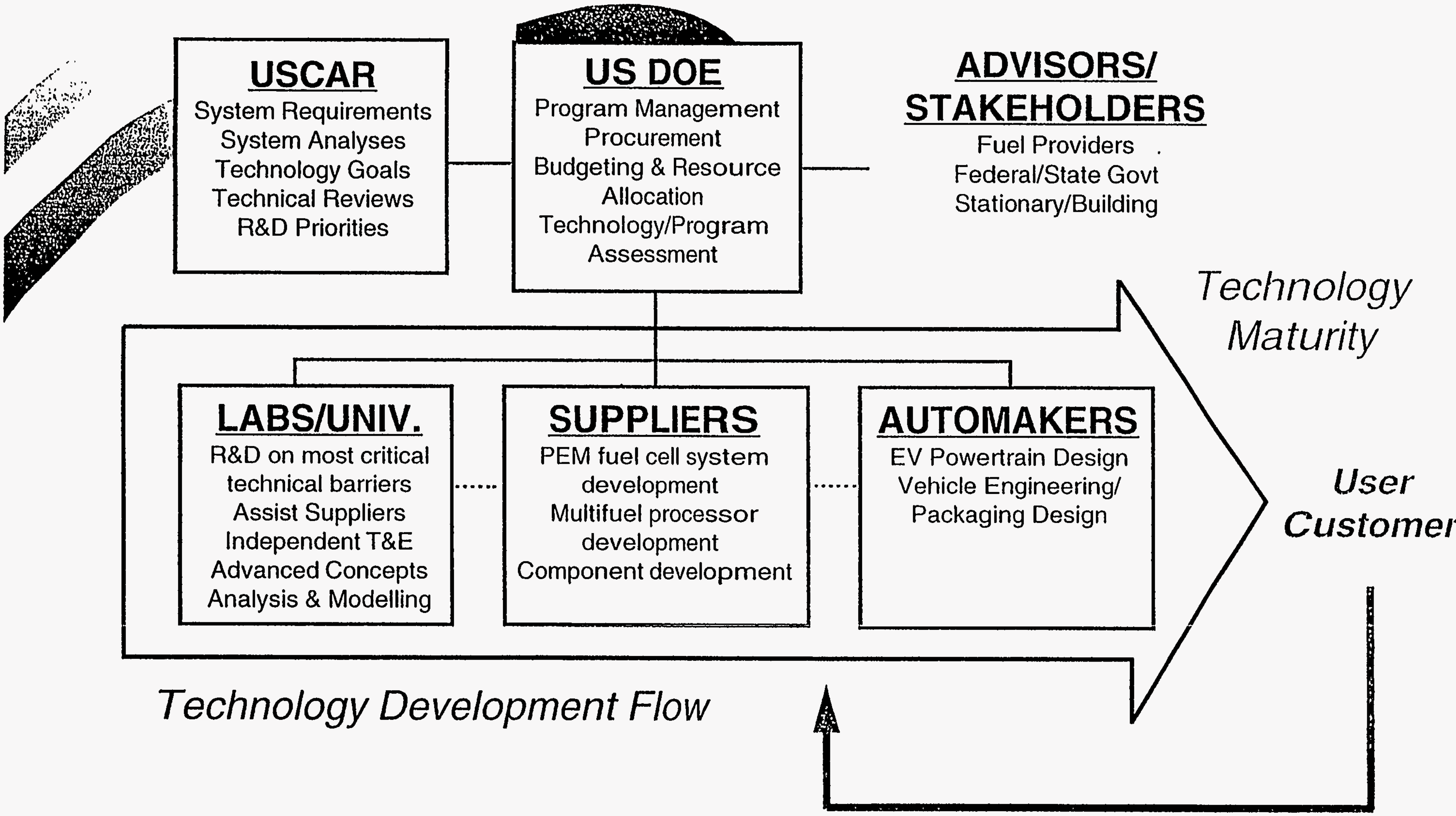
SOURCE: Abacus Techology Corporation

- *Fuel-flexible fuel processor*
- *Near-term: existing fuel infrastructure*
- *Mid-term: alternative fuel infrastructure*
- *Long-term: renewable fuel infrastructure*

Rapid Progress is Being Made in Achieving Technical Targets



Fuel Cell Program Implementation Strategy
National Fuel Cell Alliance



OTT/Ford Project

Direct Hydrogen Fuel Cell

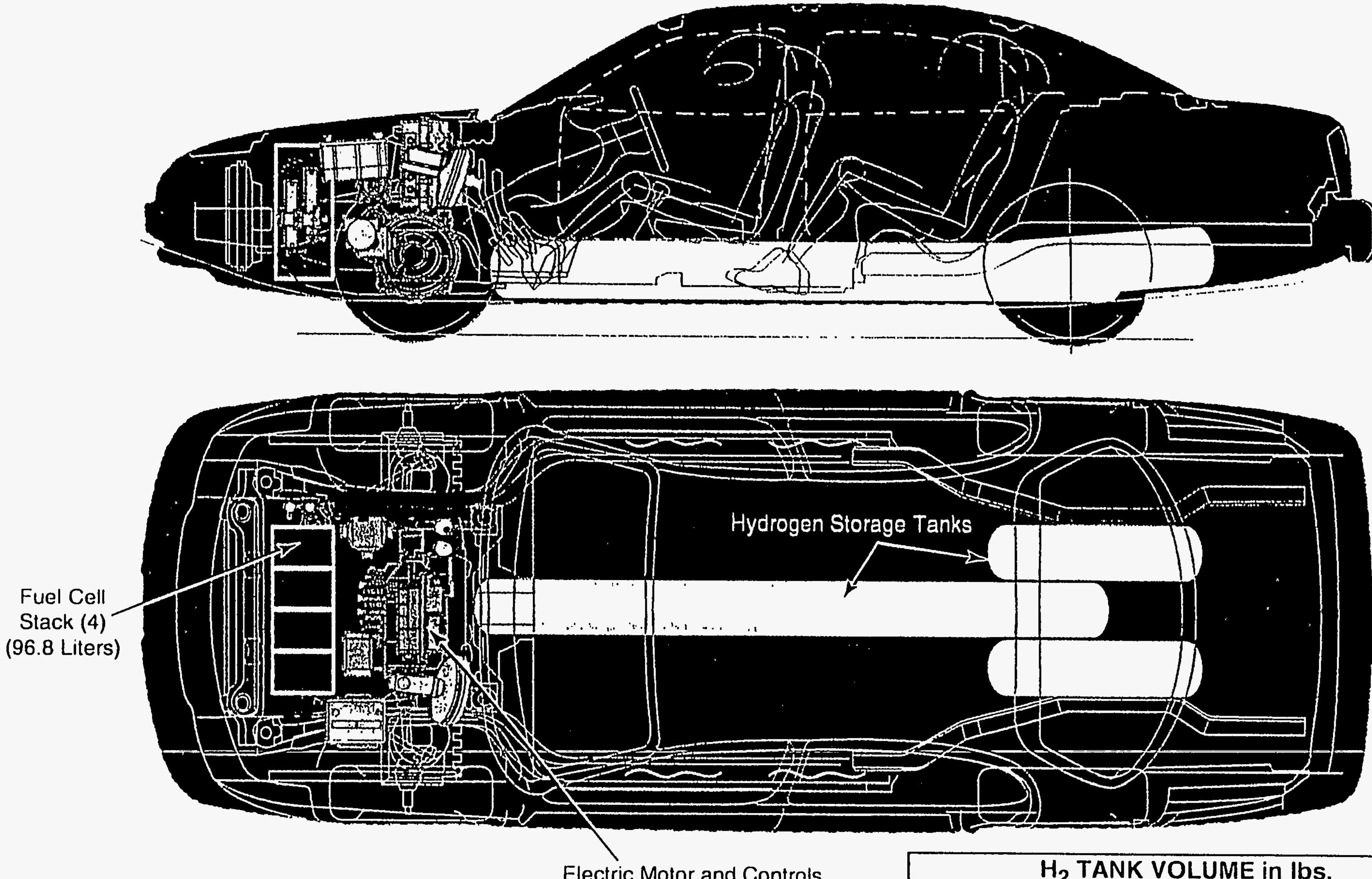
✦ FY96 Accomplishments

- Preliminary conceptual design report
- Fabricated prototype hydrogen tanks
- Tested 10kW stacks
- Hydrogen vehicle safety report (DTI)

✦ FY97 Plans

- Conceptual design report for battery-augmented FCV
- Develop two 50kW stack systems (IFC, MTI)
- Test stack systems under automotive drive cycles

GROUND UP ZEV FUEL CELL VEHICLE
(Gaseous H_2 Tanks)



H_2 TANK VOLUME in lbs.		
	Per	Total
9.0" x 105" Long	4.9	4.9
9.0" x 35" Long	1.5	4.5
		9.4

Ford FUEL CELL PROGRAM

Powering the New Generation Vehicle - *Today*

Using the Department of Energy's reformer technology developed at A.D. Little, fuel cell vehicles can run on a variety of fuels, including ethanol, methanol, gasoline and natural gas.

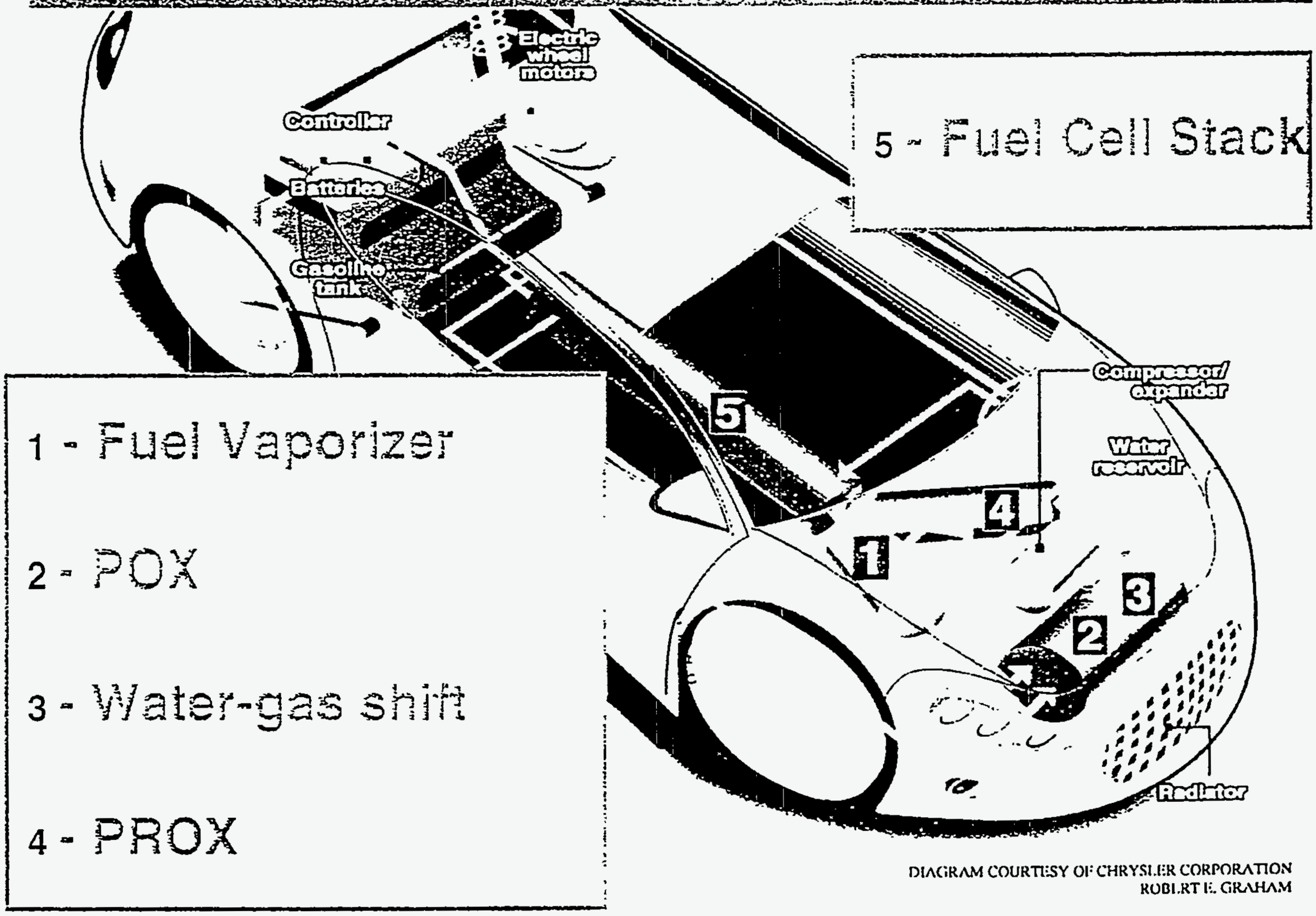


DIAGRAM COURTESY OF CHRYSLER CORPORATION
ROBERT E. GRAHAM

OTT/OUT Collaboration Fuel Cell PRDA

- Critical Components for Transportation Fuel Cells
  - lightweight hydrogen tanks for on-board applications
    - 1.8 kg H_2 ,35 MPa (5000 psia), 300 K min
    - 1000 pressure cycles @ 50-5000 psig
    - 100 temperature cycles @ 80-375 K
  - other storage concepts >10% by wt H_2

Fuel Cell Program Technical Challenges

- Start-up & Transient Response
- Fuel Processing/Storage
- CO Clean-up / Tolerance
- Size & Weight Reduction
- System Integration
- Reliability & Durability Demonstration
- Manufacturing Cost Reduction

Conclusion

- Fuel cells will revolutionize the auto industry.
- Fuel cells and renewable-based hydrogen will improve U.S. energy security, air quality, and competitiveness.
- The DOE Fuel Cell and Hydrogen Programs are addressing critical research and development to remove barriers to a sustainable transportation future.

FUEL CELLS FOR FUTURE TRANSPORTATION: THE DEPARTMENT OF ENERGY OTT/OUT PARTNERSHIP

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Introduction

The transportation sector is the single largest user of petroleum in the United States, consuming approximately two-thirds of the total. About three-quarters of this amount is used by automobiles, trucks, and buses. Nearly half of all petroleum consumed in this country is imported and oil consumption by automobiles and light-duty trucks now exceeds domestic production. The number of vehicles on our roads and the total miles driven each year continue to increase steadily (See Figure 1).

This increased use of petroleum is contributing to U.S. air pollution. The poor air quality in many of our cities and increasing levels of greenhouse gases in the atmosphere are national health concerns. Eighty million Americans live in areas that regularly violate Federal air quality standards. Despite significant progress in vehicle exhaust reduction, emissions from transportation sources remain a major problem (See Figure 2).

Global competition in the transportation market is another concern. Improvement in the nation's balance of trade and American job opportunities will result as the United States continues its development of innovative technologies and gains an increasing share of the emerging global market for clean, energy-efficient vehicles. To address these challenges effectively, the DOE Office of Transportation Technologies (OTT) is currently engaged in the development and integration of R&D activities which will enable us to reduce oil imports, and move toward a sustainable transportation future.

DOE Fuel Cells for Transportation Program

Within OTT, the Office of Advanced Automotive Technologies is supporting development of highly efficient, low or zero emission fuel cell power systems as an alternative to internal combustion engines. The objectives of the program are:

By 2000, develop and validate fuel cell stack system technologies that are

- greater than 51% energy efficient at 40 kW (maximum net power)
- more than 100 times cleaner than EPA Tier II emissions
- capable of operating on gasoline, methanol, ethanol, natural gas, and hydrogen gas or liquid

By 2004, develop and validate fuel cell power system technologies that meet vehicle requirements in terms of:

- cost -- competitive with internal combustion engines.
- performance, range, safety and reliability.

The research, development, and validation of fuel cell technology is integrally linked to the Energy Policy Act (EPACT) and other major U.S. policy objectives, such as the Partnership for a New Generation of Vehicles (PNGV). Established in 1993, PNGV is a research and development initiative involving seven Federal agencies and the three U.S. automobile manufacturers to strengthen U.S. competitiveness. The PNGV will develop technologies for vehicles with a fuel efficiency of 80 miles per gallon, while maintaining such attributes as size, performance, safety, and cost.

Fuel-Flexible Fuel Strategy

The DOE Fuel Cells for Transportation Program is pursuing a fuel-flexible fuel strategy which utilizes the existing conventional fuel infrastructure as well as the alternative fuel infrastructures currently being developed. This strategy takes maximum advantage of alternative fuels development programs in the OTT and the OUT Hydrogen Program. Use of conventional fuels encourages the initial market introduction and consumer acceptance of fuel cell vehicles by allowing refueling to be virtually identical to that of a conventional vehicle. Use of alternative and renewable fuels leads to greater energy security. Several DOE alternative fuels programs support development of the infrastructure needed for production and distribution of ethanol. The potential use of methanol, ethanol, or hydrogen from renewable energy sources affords an opportunity for a gradual transition to sustainable alternative fuels as the supply and distribution infrastructures are made available (See Figure 3).

Therefore, DOE is developing a fuel-flexible fuel processor which will enable gasoline, methanol, ethanol, and natural gas to be utilized in fuel cell vehicles. This technology will have virtually the same design for all of these fuels. When fully developed, a fuel-flexible fuel processor will be capable of reforming several hydrocarbon fuels. Preliminary analyses show that fuel cell power systems operating on conventional and alternative fuels can be competitive, in terms of efficiency, with other electric and hybrid power system technologies being developed for automotive applications. At the same time, fuel cell vehicles with on-board fuel reformers are expected to maintain tailpipe emissions well below Federal Tier II standards.

Because demonstrations of direct-hydrogen fuel cell systems have less technical risk than on-board fuel processors, the Program is developing hydrogen storage technologies in an important boration with the DOE Hydrogen Program. The potential of fuel cell technology can, therefore, ore easily realized through near term demonstrations of direct hydrogen fuel cell vehicles using ıtrally located and controlled fueling infrastructure. Early demonstrations could accelerate ɔgen infrastructure development.

Hydrogen Program

To help address the critical issue of fuel and fuel infrastructure development for advanced vehicles, the DOE Office of Utility Technologies (OUT) has directed the Hydrogen Program to provide national leadership in the research, development, and validation of advanced technologies to produce, store, and use hydrogen. An objective of the Program is to work in partnership with industry to advance hydrogen systems to the point where they are cost effective and integrated into the energy economy. This integration will enable the Program to reach its objectives of displacing 10 quads per year by 2030 in all end-use sectors, which will represent about a 10% penetration into the total U.S. energy market.

The Program's g[illegible] near-term production and environmental costs of hydrogen by increasing the energy efficiency and reducing the carbon dioxide emissions from conventional steam reforming of natural gas and encouraging greater utilization and gradual expansion of the hydrogen delivery and service infrastructure. A key Program goal is to help ensure that the technology and infrastructure are available so that hydrogen systems can be cost effectively integrated into the energy economy, including the transportation sector.

Near-Term Hydrogen Fuel Transition Strategy

The OUT Hydrogen Program has identified transportation as a key market for hydrogen and has developed a transition strategy to renewable hydrogen production and use in vehicles that is consistent with OTT's fuel-flexible fuel strategy. Facilities owned by the U.S. Department of Defense, as well as many state governments, utilities, and private companies, use natural gas to fuel their fleet vehicles. These vehicles would be converted to hydrogen, or hydrogen would be blended into the natural gas, to further reduce emissions. Using hydrogen allows the option of lean combustion, which greatly reduces NOx emissions. This transition strategy, using a hydrogen ICE hybrid with electric drive, will lead to the development of a hydrogen infrastructure and facilitate OTT's fuel-flexible fuel strategy for PEM fuel cell vehicles.

The Hydrogen Program is also exploring opportunities that the expansion of conventional reforming capacity may provide to supply the demands of transportation, particularly in bus and fleet applications. These applications are particularly attractive in "Clean Corridors" where new sources of hydrogen and the need to improve urban air quality coincide. Southern California is a good example where such Clean Corridor projects based on hydrogen may emerge. There, the need to improve air quality is a paramount public concern, new hydrogen production facilities have been built, both as part of refineries and as stand-alone plants, and a large bus and fleet vehicle population could provide an initial niche market for hydrogen fuel.

The Clean Corridors approach is being applied nationally to build a hydrogen fuel infrastructure in key urban areas. This strategy will lead to more advanced hydrogen technologies that incorporate renewable energy resources. Biomass technologies will provide a renewable pathway for producing hydrogen, and, in the future, hydrogen can be produced from virtually inexhaustible supplies of water as the feedstock and wind, hydropower, and sunlight as the energy source. Development of a renewable hydrogen fuel infrastructure will complement development of the PEM fuel cell vehicle.

Transportation Fuel Cells - Technical Progress and Challenges

Despite significant recent advances, PEM fuel cell technology must progress beyond the current state-of-the-art before it can be considered a viable alternative to the ICE. The technical challenges include the fuel cell stack, the fuel processor, and balance-of-plant components. Significant advances in fuel processing and delivery are necessary for fuel cells to make a substantial market penetration. A direct hydrogen fuel cell vehicle with on-board hydrogen storage will reduce system complexity, manufacturing cost, and start-up and transient response time. In the long-term, hydrogen will be the preferred fuel for fuel cells, but the fueling infrastructure does not exist to service a large number of cars. The OTT is addressing fuel infrastructure issues by developing fuel processor capability which provides fuel flexibility, coordinating activities with alternative fuels providers and developers in government and industry, defining fuel supply and distribution strategies and integrating ongoing research with DOE Hydrogen and Alternative Fuels Programs.

Fuel Cell System Development

OTT currently supports two development efforts focused on direct-hydrogen fuel cell systems. Chrysler/Pentastar's fuel cell work, being done by Allied Signal, is focussed on a design-to-cost approach in which materials development plays a critical role. Low-cost bipolar plates and low-cost membranes have been developed. Work is progressing with fabrication of a multi-cell stack and durability testing of low-cost bipolar plate materials. Performance problems encountered with the scale-up of the low-cost fuel cell design are being resolved. Pentastar is supported by Chrysler Liberty, Allied Signal Aerospace, Allied Signal Automotive, and Allied Signal Research and Technology.

Ford's Phase I competition among five fuel cell developers is completed. Two developers - International Fuel Cells and Mechanical Technology Incorporated - were selected to continue in Phase II with the design, fabrication and testing of a 50-kW fuel cell system. A preliminary conceptual vehicle design and an extensive hydrogen infrastructure and vehicle safety analysis have been completed. Directed Technologies, Air Products & Chemicals, Praxair Inc., Electrolyser Corporation, and BOC Gases performed the hydrogen-related issues analyses. A new state-of-the-art hydrogen storage tank liner was developed by Lawrence Livermore National Laboratory, EDO Fiber Sciences and Aero Tec Labs. This technology greatly reduces the fuel storage size which is critical in the vehicle design.

To help integrate hydrogen-related R&D, the OTT Fuel Cell Program and the OUT Hydrogen Program will collaborate on activities such as the optimization of lightweight storage tanks and fuel cell outreach projects.

Partnership Strategy

The partnership between the Fuel Cell Program and the Hydrogen Program is designed to effectively implement the research and development of highly efficient, low or zero emission fuel cell power systems and fuel infrastructure as a viable alternative to the ICE and petroleum based fuels. The partnership strategy is effected through cooperative research and development and interactive management of the two programs. Managers and key staff participate in program reviews held by each Program and also participate in key industry meetings, such as the annual meeting of the National Hydrogen Association (NHA) and the Fuel Cell Seminar. Also, staff from the Fuel Cell Program participate in meetings of the Hydrogen Technical Advisory Panel (HTAP), and staff from the Hydrogen Program participate in the activities of the Fuel Cell Alliance (FCA). Both the NHA/HTAP and the FCA allow DOE to fully utilize the excellent technical capabilities and resources that exist within industry and government, including automakers, fuel cell and fuel processor developers, component suppliers, national laboratories and universities, fuel providers, and other government agencies to advance the research, development, and technology validation of hydrogen and fuel cell technologies.

Figure 1: U.S. Dependence on Vehicles and Petroleum

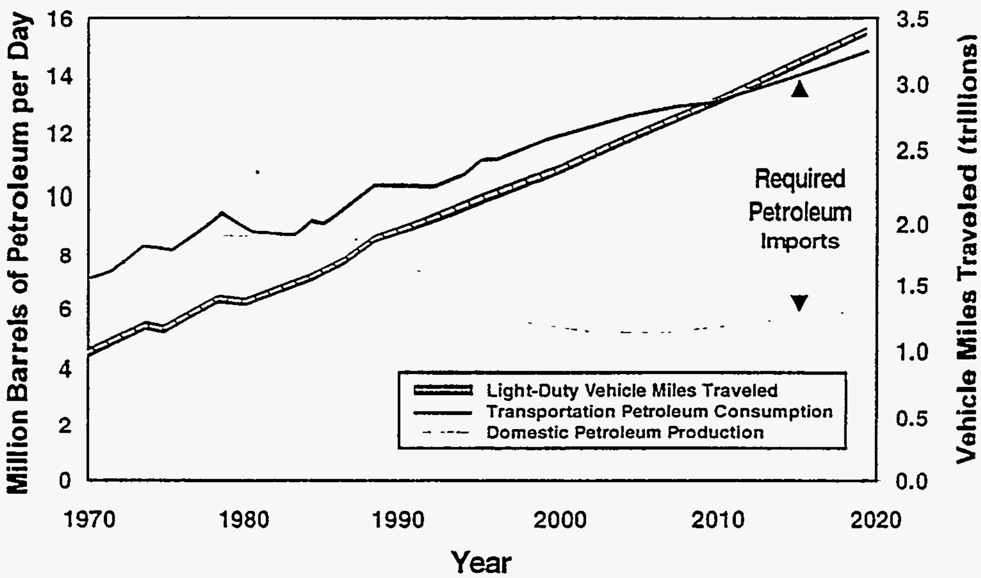


Figure 2: Despite reductions in new vehicle emissions over the past two decades, highway vehicles still contribute significantly to U.S. air pollution because of increased vehicle miles traveled.

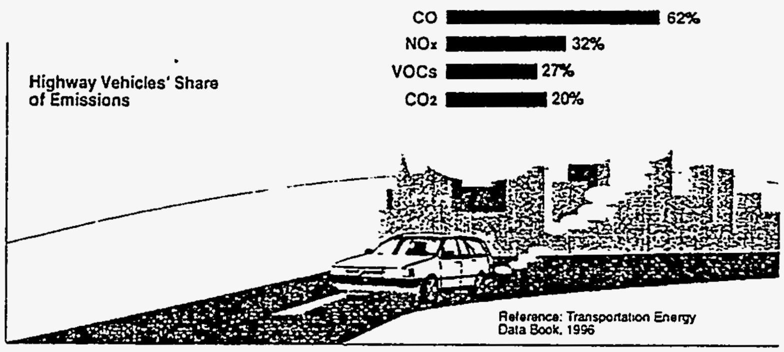
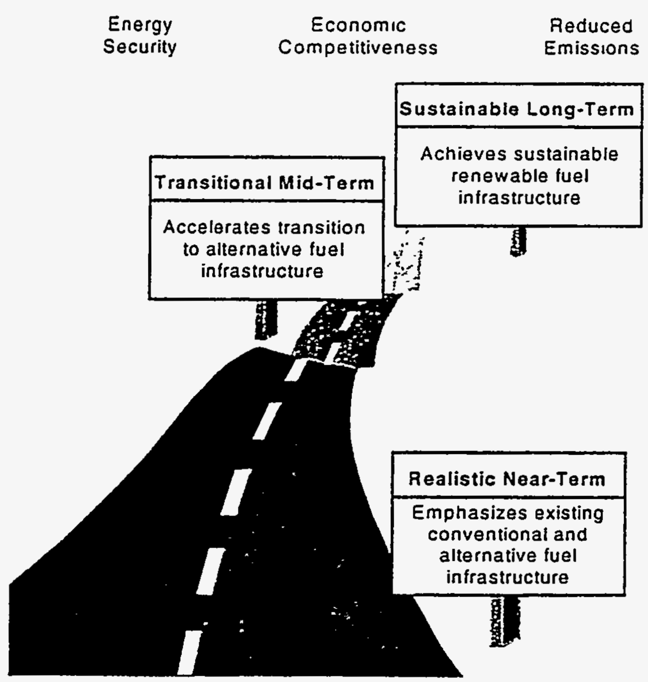


Figure 3: The DOE/OTT Fuel Cell Program is concurrently developing fuel cell technology which utilizes conventional, alternative, and renewable fuels.



SOURCE: Abacus Techology Corporation

GENERAL SESSION II:

Government/Industry Partnerships: Demonstrations

NEVADA'S ROLE IN THE HYDROGEN ECONOMY

Mr. Terry Vaeth
Acting Manager, Nevada Operations
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

NEVADA'S ROLE IN THE HYDROGEN ECONOMY

As we have heard from Senator Reid, the scientific community and the media, there is an increasing awareness of the importance of a hydrogen economy. This should not be a surprise since hydrogen is the most plentiful element in the universe, is readily available from water, traditional fuels and alternate fuels and is perhaps the cleanest burning fuel. For these reasons we expect that hydrogen will become the significant source of our energy as it begins to replace today's primary energy source - imported oil. The prospects for hydrogen's contribution will be significantly reduced air emissions.

Despite the glowing prospects for hydrogen, a number of barriers must be overcome before it can be used extensively in the transportation and power generation sectors of our economy. Hydrogen production methods must be developed which are cost effective with competing fuels and are as readily available as today's fuels. At this conference we are learning about new and innovative concepts which have the promise for meeting these requirements.

Another problem, often cited, is hydrogen storage. This storage problem is most critical to the use of hydrogen in the transportation sector where sufficient quantities of fuel in the limited space of today's vehicles so that the vehicle range is not adversely affected and yet still satisfies rigorous safety standards. Based on research results, there is cause for optimism that good solutions are underway.

The conversion of hydrogen to useful power is also a critical area for research. Practical engines must be developed to convert this fuel. Today we are learning about fuel cells and engines which operate on 100% hydrogen and engines which use hydrogen blended with natural gas and synthetic fuels. Research results are proving that hydrogen fueled engines operate cleaner than engines fueled by traditional fuels.

In addition to solving these production, storage and conversion concerns, it will also be necessary to develop the supporting infrastructure: localized production facilities, re-fueling facilities, training programs, and maintenance capabilities. Then the real challenge begins, the introduction of hydrogen in the market place. None of these obstacles appear to be insurmountable, but will require a coordinated effort to cause an early, widespread, implementation of this fuel. This country has met more difficult challenges and is fully capable of solving this challenge as well.

Nevada in partnership with the other 49 states has a vested interest in supporting the implementation of this exciting resource for its impact on the reduction of energy imports and Nevada selfishly cherishes the opportunity to reduce Nevada's air pollution through its introduction. Nevada, as many of you know, is one of the fastest growing states in the Union and the Las Vegas metro area is one of the fastest growing areas in the US, adding about 6,000 new residents per month. This growth is the source of an increasingly serious air pollution problem, largely the result of vehicular travel which accounts for an estimated 60% of the pollution in the Las Vegas basin. EPA currently classifies the Las Vegas valley as a "serious" PM-10 non-attainment area and a "moderate" CO non-attainment area. These air parameters and NOX will only get worse with the high population growth and the commensurate vehicle traffic.

The Cities of Las Vegas, Reno and their surrounding communities are moving aggressively to address this pollution problem. Both areas applied for and received designations as "Clean Cities" under the Department of Energy's "Clean Cities" program. Las Vegas and their "Clean Cities" partners now have the largest CNG fleet in the US and it's growing. Seven CNG refueling stations are in operation in the Las Vegas area.

Soon, Nevada also hopes to join forces with California in the development of a "clean corridor" between Nevada and California and perhaps even Utah may be a partner as we may have a "clean corridor" stretching from Salt Lake City through Sacramento, to San Francisco, to Los Angeles to Las Vegas and back to Salt Lake City. In support of this "clean corridor" initiative, Las Vegas, with the assistance of the State Energy Office and the DOE, will be building their first LNG/CNG refueling station as part of this "clean corridor" initiative.

Nevada's Senators have expressed strong support of Nevada's hydrogen program and Las Vegas's Mayor and her staff have also voiced their interest in participating in new hydrogen initiatives. Wouldn't it be great if we had the vehicles, refueling stations and related infrastructure to add hydrogen power vehicles to the government and commercial fleets?

My vision is that Nevada will be the first "clean state" based on a hydrogen economy and that we will fulfill this vision through the commercialization of emerging hydrogen technologies being discussed in this conference with the assistance of:

- excess resources of the Nevada Test Site,
- resources from the Community Reuse Organization which I have charged with the responsibility for putting excess government property to work,
- the highly visible Las Vegas image to stimulate grass roots interest in purchasing cleaner burning, alternate fueled, vehicles.

On December 9, 1996, a Record of Decision for an Environmental Impact Statement for the Nevada Test Site was signed by the Secretary of Energy. This EIS expanded the use for the NTS and provided for alternate energy work at the site including hydrogen and alternate fuel technologies.

As the Acting Manger of the Nevada Operations Office, I am committed to the test, demonstration, and commercialization of alternate energy technologies. In response to this commitment, I have established an alternative energy program as an official Nevada business line. A major component of the alternative energy program is the Solar Enterprise Zone being developed in Nevada. This commitment evolved from a 1992 Congressional directive for a study to assess the potential for using the resources of the NTS in support of alternate energy. The resulting study supported the benefits of the NTS for alternate energy test and demonstration. To realize the alternate energy potential of the NTS, a Solar Enterprise Zone was established and not-for-profit corporation was formed, the Corporation for Solar Technologies and Renewable Resources (CSTRR), managed by Rose McKinney James. Through the efforts of my staff and CSTRR, I plan to cause the construction of a 10 MW solar photovoltaic power plant on the Nevada Test Site (NTS) and the power produced will serve NTS loads. When completed, this photovoltaic system, will provide nearly 20% of the energy needs at this site. This 10 MW system was only the opening gun and now the CSTRR organization has another 63 MW on the drawing boards with more to come. I believe Nevada, the NTS, their reuse organizations, the Nevada communities and local economy have the kind of dynamics to do much more and would like the opportunity to apply these resources to the commercialization of hydrogen. Make no mistake, the hydrogen technology is part of the site reuse vision.

For those not familiar with the Nevada Test Site, the site is located about 65 miles northwest of Las Vegas. It was originally established as the test site for nuclear weapons. The mission for the NTS has changed as the last nuclear test was conducted in 1992, but the site is required to remain in a test readiness condition. Today, we are looking for ways to put this 1350 square mile site to work for the good of the nation, Nevada, and the local community. What better way than to test emerging hydrogen transportation products and stationary hydrogen powered generating equipment.

This remote and secure site can be an ideal site for final test and demonstration of emerging hydrogen technologies. It has over 300 miles of roads traversing the site at altitudes ranging from 2000 to 7000+ feet. The climatic extremes at this site match the extremes found throughout the US. This site also has over 1200 vehicles ready for conversion to alternate fuel concepts and the extensive infrastructure and trained staff needed to fully maintain any type of vehicle. The facilities include automotive shops, dynamometers, welding shops, fabrication and assembly facilities. If hydrogen is the fuel of choice, the test site can fully support that as well.

The Las Vegas "Clean City' partners also stand ready to support new, cleaner, vehicle initiatives. The partners include the City of Las Vegas and surrounding suburbs, Clark County, the Las Vegas Valley Water District, the Regional Transportation Commission, gas and electric utilities, commercial fleet operators, and Nellis Air Force Base. This consortium in the "Clean City" initiative have already put their money on the line. They have converted over 1000 vehicles and have built 7 CNG re-fueling stations. We have received assurances that they want to participate in future initiatives as well, if it makes sense.

I have also taken steps to support the commercialization element of any new enterprise that can utilize the excess resources at the test site and create jobs. Toward this objective, I established the Community Reuse Organization (CRO) called the NTS Development Corporation, whose President, Mr. Tim Carlson, is in the audience. This organization operates under the terms and conditions of the Defense Organization Act and has been provided funding to support emerging technologies. Two hydrogen projects are currently being considered by this CRO for test and commercialization. One of these projects is a blended hydrogen/CNG fuel being developed by the NRG Corporation. The second project is a stationary electric generator burning an 85% CNG and a 15% hydrogen & CO fuel produced from the Arthur D. Little reformer developed under DOE contract. The stationary electric generator/reformer system would be tested in partnership with Bechtel and EPRI at the NTS site and if successful would be marketed as a commercial product.

The NRG fuel will be dynamometer tested. Then it will be introduced into a few NTS vehicles to prove its road worthiness and low emission performance. Simultaneously, the CRO would expect to develop the re-fueling system and train maintenance staff for a larger scale demonstration. If this blended fuel product passes this gate, then the CRO would look to the local fleets for the larger scale demonstration. There are a number of excellent fleet conversion options to consider. Las Vegas has one of the largest taxi fleets in the US, over 20,000. The Las Vegas "Clean City" members with over 1,000 CNG conversions already in place are another candidate as they have expressed an interest in supporting new, cleaner burning, technologies and more specifically hydrogen fueled vehicles. The casino industry with hundreds of vans would make ideal, high visibility, demonstrations of proven technologies.

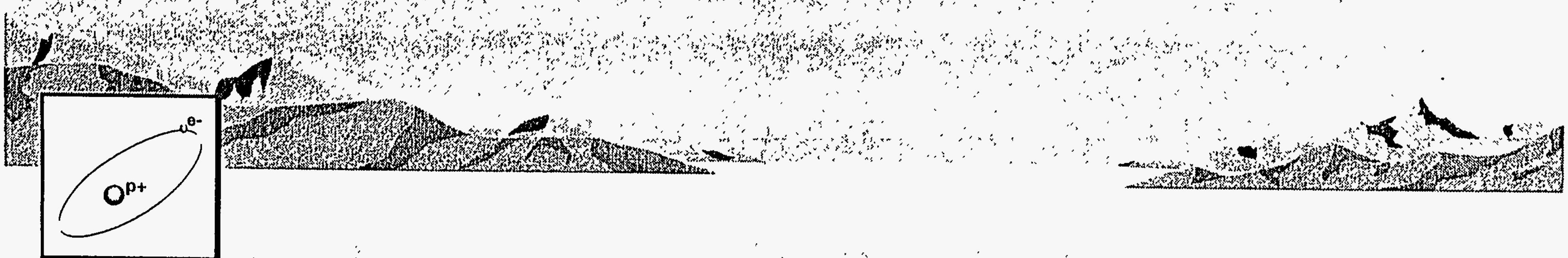
Best of all, the CRO has the authority and ability as a 501 (c) 3, not-for-profit corporation, to issue bonds to commercialize these and/or other proven products.

I have identified two near term possibilities for test, demonstration, and commercialization using the resources of the Nevada Test Site and the authorities granted to the NTS Development Corporation. I would like to emphasize that these should only be considered the first of what we hope will be many new products. I would now like to extend an open invitation to the hydrogen community to bring promising hydrogen projects to the CRO for their consideration and partnership in carrying new products into the market place.

The introduction of new technologies is a lengthy process. It begins with an idea. Through thoughtful research and engineering development, the idea is transformed into a product. Then the hard part begins as you must convince the consumer of the merits of the idea, overcoming the prejudices and mind sets before the mass consumer embraces the concept. Nevada and the CRO want to engage the hydrogen R&D community when they feel they are ready to move from R&D into the market place. If you, or anyone you know, are ready to commercialize a product, come and see us. Or better yet, contact Tim Carlson at the CRO at 702-257-7900.

The Department of Energy and Nevada in a Hydrogen Economy

March 12, 1997

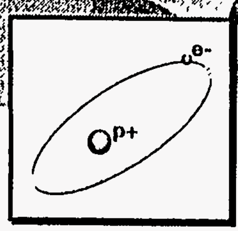


Hydrogen
Its Promise and Its Future

- ✔ Most plentiful fuel in the universe
- ✔ Readily available
- ✔ Clean burning
- ✔ Supports DOE strategic goals
  - Replaces imported oil
  - Reduces air emissions

Hydrogen Opportunities

- ✔ **Applications:**
  - Transportation
  - Stationary power generation
- ✔ **Conversion options:**
  - Fuel cells
  - 100% hydrogen powered engines
  - Blended w/CNG and alternate gaseous fuels



Barriers

- ✔ Safe, compact storage
- ✔ Safe, efficient, energy conversion
- ✔ Infrastructure development
  - – Localized, distributed, re-fueling systems
  - – Re-fueling stations
  - – Training programs
  - – Maintenance capabilities
- ✔ Market acceptance

Nevada Test Site - Its Past & Its Future

✔ **Mission:**

- **Was:** Weapons Test
- **Is:** Test Readiness & application of its resources to national needs

Pahrump Valley Times, 1/17/96

DOE has Bradshaw boiling

Nye County left out of Double Tracks Test Site clean up plans

By HENRY BREAN

Plans by the Department of Energy for cleaning up a contaminated area of the Nellis Air Force Range in central Nye County have angered at least one county official, but not because of any perceived danger to area residents.

Les Bradshaw, manager of the Nye County Nuclear Waste Repository Project Office, said DOE's plan for removing levels of plutonium at the Double Tracks Test Site appear safe. He just wishes he had heard something about it sooner.

An angry Bradshaw said county officials first learned of the Double Tracks clean-up plan on Jan 3, when DOE sent him a copy of the more than 125-page draft environmental assessment (EA) for the project, along with a request for any and all public comment within 30 days.

"It's just nuts," he said. "It's not the sort of relationship DOE should have with Nye County."

On the same day he received the EA, Bradshaw fired back a letter asking for more time. A few days later, a DOE official called to tell him that the county had been granted a 15-day extension, which is when Bradshaw said he "launched into my best lecture on how we cannot have an effective community dialog on this issue in 30, 45 or even 60 days."

"I asked the man, 'why didn't you involve us in this 6-8 months ago?' Bradshaw said. "Nye County needs to be involved in these sort of test site issues early on, not at the point where we have 30 days to comment on a 'done deal' document."

That is doubly true for the Double Tracks plan, he said, because the entire contaminated site is located in Nye County, and the clean-up calls for trucks filled with contaminated soil to pass through Tonopah, Goldfield, Beatty and Amargosa on their way to a low level radioactive waste dump on the southern end of the Nevada Test Site.

…

…south on U.S. 95 through Goldfield, Beatty and Amargosa Valley, and onto the NTS via …

Bradshaw said only very low levels of plutonium exist at the site, and someone would have to breathe some of the contaminated dust into his or her lungs to suffer any sort of health risk. "We're certainly not suggesting there is some huge risk here," he said.

However, Bradshaw and others involved with Nye County's oversight efforts suggest that simply burying the contaminated area would be safer and easier than transporting the soil. "This sort of contamination is very difficult to clean up," Bradshaw said. Plutonium clings to dust particles, and gusting winds may blow it off …

If the clean-up plan is approved, Bradshaw said the very earliest work would start is sometime during the next fiscal year.

Las Vegas Review-Journal, 11/30/95 (1A)

(Circulation: 148,619 daily, 220,300 Sunday)

More test site layoffs due

☐ Reduced budget figures translate into job cuts as one contractor replaces three at the testing facility.

By Keith Rogers
Review-Journal

Nearly 900 employees who work for companies that do business at the Nevada Test Site will not be rehired when the new contractor, Bechtel Nevada Corp., takes over in January, Department of Energy officials said …nesday.

…e figure, 889, includes 458 from …lds Electrical & Engineering Co., …from EG&G Energy Measurements Inc., and 166 from Raytheon … Nevada, said Roxanne Day, a …man for the Department of … Nevada Operations Office.

"…been a lot of anxiety and … around our office," she …

Since Oct. 27, when Bechtel Nevada officials signed the new five year, $1.5 billion contract to replace the three outgoing contractors, company and Department of Energy officials had anticipated 200 to 500 employees would not be offered jobs.

But this month, when President Clinton signed the 1996 Energy and Water Development Appropriations Act, test site officials learned they would be receiving $402 million in funding next year, which is $107 million less than the $509 million they had planned to spend.

Another department spokesman, Darwin Morgan, said the reduced budget figure translates directly into about 400 more cuts than the highest figure of 500 that had been expected.

Bechtel Nevada Corp. spokeswoman Colleen Curran Ortego said the company's management …

total of 4,111 … ment officials … da Corp. will … 2,500 employee… counting the 8… retired, the … have lost 723 … ly through ret… or education…

With the … partment of … worker redu… 1994 will … the 1,800 … last predic… Clinton … tions act fo…

Terry V… the Neva… said he w… hard-wor… workers."

"As un… doing th… only wa…

Nevada Power battling to keep NTS contract

By John G. Edwards
Review-Journal

Nevada Power Co., the federal government and two other utilities are battling in court and before the state Public Service Commission in a dispute over who may sell electricity to the Nevada Test Site.

The outcome of the case affects Nevada Power's ability to retain one of its biggest customers — the test site, said Dwight Etheridge, Nevada Power director of pricing and economic analysis.

For 40 years, Nevada Power has been the primary provider of electricity used at the nuclear proving grounds. Nevada Power receives $5.5 million in annual revenue from the test site.

The test site is one of several large customers, including the Southern Nevada Water Authority and Mirage Resorts Inc., which threaten to stop relying on Nevada Power for electricity. Mirage Resorts plans to build its Calif., municipal utility were selected for secondary contracts. Glendale intends to transmit its power over lines owned by Valley Electric.

In December, Nevada Power asked the PSC to stop the Department of Energy from buying electricity from Glendale, saying municipal system wasn't certified as a utility in Nevada.

The test site will be buying power from Glendale for use within Nevada Power's designated service area within the Nevada Test Site, Nevada Power contends.

Nevada Power asked the PSC to prohibit Glendale and the test site from entering into the contract.

In a response to the complaint, the Energy Department argued that the PSC shouldn't consider Nevada Power's proposal until the government signs a contract with Glendale. An attorney for the federal agency also contends that the PSC has no authority to

DOE NEWS

News Media Contact:
Roxanne C. Day, 702-295-1379

For Immediate Release:
November 29, 1995

Department of Energy Announces an Additional 400 Job Reductions in Nevada

About 400 contractor position reductions will occur at the DOE's Nevada Operations Office (DOE/NV) by December 31, 1995. Significant budget reductions and existing contractor consolidation efforts led to this additional reduction.

Previously, DOE/NV announced as many as 1,800 contractor positions could be reduced. This could now bring the total up to 2,200 reductions from October 1, 1994 through December 31, 1995.

DOE/NV's budget for fiscal year 1995 was $683.5 million. The proposed …n for fiscal year 1996 is $402 million. This represents a $281.5 million …rom 1995, and a $107 million reduction from an earlier planned budget for …1996 (see attached chart). Cuts in the budget translate directly into … cuts.

…ating three existing contractors into one streamlined, efficient … contract is necessary to meet the new budget ceiling and eliminate …cation. Bechtel Nevada will take over the work currently performed by …trical & Engineering Co., Inc.; EG&G Energy Measurements, Inc.; and …ices Nevada on January 1, 1996. Bechtel Nevada will begin the five …n contract with about 2,500 employees.

…Vaeth, Acting Manager of the Nevada Operations Office, said, "I am …d by the necessity of laying off dedicated, hard-working, and highly-… It is especially upsetting because it is happening during the holiday … retained the maximum number of employees our budget will …mainder of the fiscal year. All of the benefits associated with the …rogram are being offered to these impacted employees. As … we are doing the right thing. This is the only way the Test Site … late 1990s and move into the 21st century."

-more-

Las Vegas SUN, 11/29/95 (1A)

(Circulation: 39,000 daily; 220,300 Sunday)

Test Site will get radioactive acid

SUN STAFF AND WIRE REPORTS

The U.S. Department o[f] Energy is shipping 369 stee[l] drums of radioactive acid waste from Ohio to the Nevada Te[st] Site for disposal.

The department said Tues[day] it has finished neutralizing [and] solidifying the 6,000 gallo[ns] wastes at the Fernald site miles northwest of Cincin[nati].

The thorium nitrate had been stored since th[e] 1970s in a tank on the 1,0[00] Fernald site. The wast[e was] kept at the site during th[e] 40 years that the plant [processed] uranium for the gove[rnment's] production elsewhere [of] weapons.

Las Vegas Review-Journal, 11/02/95 (9D)

(Circulation: 148,619 daily; 220,300 Sunday)

Test site workers told of termination

☐ Involuntary separation notices have been sent to more than 4,000 as required by federal law.

By Keith Rogers
Review-Journal

Nevada Test Site contr[actors met] Wednesday's deadline for [60-]day job termination notic[es to] workers affected by [a] ... a new manag[ement] ... Nevada Co[rp.] ... Bechtel Nev[ada] ... Energy, whi[ch] ... miles north ... the new five

billion, performance-based contract last week. It takes effect Jan 1

Federal law requires the current contractors, EG&G Energy Measurements Inc., Reynolds Electrical and Engineering Co. and Raytheon Services Nevada to send their employees involuntary separation notices 60 days ...

Services Nevada, 460.

Department of Energy spokesman Darwin Morgan said jobs for another 389 federal workers at the test site will not be affected by involuntary separations.

Morgan said in all there are about 6,000 Nevada Test Site workers in-

Las Vegas Review-Journal, 2/1/96 (1B)

(Circulation: 148,619 daily; 220,300 Sunday)

Test site's future bleak

☐ Complete closure of the nuclear testing facility is an option that Sen. Harry Reid thinks may become a reality.

By Tony Batt
Donrey Washington Bureau

WASHINGTON — The economic outlook for the Nevada Test Site is so bleak that it is in danger of being completely shut down, Sen. Harry Reid said Wednesday.

"I think the future of the test site is in jeopardy," said Reid, D-Nev.

Although he previously has expressed concern about layoffs at the test site, this is the first time Reid has said he thinks it might close.

Reid and other members of the Nevada congressional delegation met in his office for more than an hour Wednesday with Department of Energy officials and executives of the Bechtel Nevada, the test site contractors, to discuss the site's future.

Since 1987, the test site's work force has plummeted from 9,500 to its current level of 2,836.

The lawmakers wanted to be briefed after the department released a report Tuesday that offered alternatives for operating the test site, 65 miles northwest of Las Vegas.

Energy Department officials said they are considering complete closure because that would make it easier to monitor the facility. Another option is to close sections used before a testing moratorium began after the last nuclear blast on Sept. 23, 1992.

Rep. John Ensign, R-Nev., said

Department's policy for charging businesses using the facility. Reid said.

"If a company wants to do experiments at the test site, it is not charged for the facilities used. It is charged a proportionate share of the entire test site," Reid said. "It's the only DOE site that does that, and it discourages companies from coming in."

Department officials said they would consider changing the policy, Reid said. Bechtel and Energy Department officials could not be reached for comment.

Other alternatives being considered for the test site include advanced hydrogen research, alternative energy programs such as solar power, a remote sensing program to detect mine fields and a counter proliferation program to combat nuclear terrorism.

Ensign said bringing any of these programs to the test site would not be easy.

"The problem is that a lot of other congressmen want these programs for their districts, and it's very competitive," he said. "We have to show that we are not just trying to bring pork to our district. We need to prove these projects belong at the test site for scientific reasons."

Asked how long the test site

Las Vegas SUN, 11/29/95 (4A)

(Circulation: 39,000 daily; 220,300 Sunday)

No happy holidays for laid-off Test Site workers

400 more employees to be idled by Dec. 31

By Mary Manning
LAS VEGAS SUN

Another 400 workers at the Nevada Test Site will lose their jobs by the end of the year, officials said today.

While reductions of 1,800 employees were announced in October, the congressional ax sliced an extra $100 million off the Test Site's budget.

The total layoffs will equal 2,200 by Dec. 31. The work force at the 44-year-old nuclear weapons experimental site has been dropping since October 1994. President Bush announced a nuclear weapons test moratorium in 1992 that is still in place.

"I'm deeply saddened by the necessity of laying off dedicated, hard-working and highly skilled workers," said Terry Vaeth, acting manager of the Department of Energy's Nevada Operations Office.

"It is especially upsetting because it's happening during the holiday season," he said. "We have retained the maximum number of employees our budget will support for the remainder of the fiscal year."

The Test Site's 1995 budget was $683.5 million. DOE planners expected to fund $500 million in 1996.

But the federal energy bill signed by President Clinton two weeks ago allowed only $402 million, a $281.5 million loss since 1995, translating directly into employee cuts.

DOE's Nevada Operations Office officials consulted with workers, contractors, community leaders, union representatives, educational institutions, Nevada congressional representatives and other interested parties to develop a transition plan for the dismissed workers.

"All the benefits associated with the worker transition program are being given to these impacted employees,"

Vaeth said. "As unfortunate as it is, we are doing the right thing. This is the only way the Test Site can compete in the late 1990s and move into the 21st century."

More than three years ago the DOE began consolidating services such as laboratory work. Energy Secretary Hazel O'Leary announced a leaner DOE as the Cold War eliminated the demand for nuclear weapons testing.

"What you're seeing is further consolidations," said Colleen Curran Oriego of EG&G Energy Measurements, one of the companies that will no longer have a contract at the Test Site after Jan. 1.

"These are Nevada families, Nevada people and it hits pretty darn hard," she said.

Oriego said the three major contractors – Reynolds Electrical & Engineering Co. (REECo), EG&G Energy Measurements and Raytheon Nevada Corp. – are working with state agencies to retrain workers and polish resumes.

As of Dec. 31, the contract employees are officially off work, although some may be rehired by Bechtel Nevada.

Bechtel Nevada won a five-year, $1.5 billion agreement to operate the Test Site and plan for its future. The company will have 2,600 workers left

when it comes on the job New Year's Day.

O'Leary announced that the Test Site contractors would have to bid on the operations last year.

Although the DOE has announced a large number of reductions, Bechtel may rehire some of those workers, said Bechtel spokeswoman Helen Foley.

Meanwhile, at the DOE's Yucca Mountain Project Office, officials are still bracing for 800 employee cuts, said spokeswoman Samantha Richardson.

That amounts to more than 40 percent of the work force at the proposed nuclear waste dump site, 90 miles northwest of Las Vegas, where scientists are studying Yucca Mountain to see if it can contain high-level nuclear wastes for hundreds of thousands of years.

Sitelines, Bechtel Nevada, 6/31/96

NTS Development Corporation receives $5 million grant

By Darwin Morgan

The Department of Energy recently awarded the NTS Development Corporation $5 million to pursue projects that could use existing Nevada Test Site resources in new ways. The goal of the projects is to stimulate economic development in Nevada, offsetting the negative impact of recent downsizing at the test site.

"We could see the loss of jobs for scientists and highly skilled workers and the effect on the state's economy," said Tim Carlson, president of the NTS Development Corporation. "We're looking forward to working with the DOE to maximize the utilization of the Nevada Test Site, its people, and its facilities."

The non-profit corporation will use the $5 million grant to fund a business development and marketing program that will promote opportunities for commercial enterprises at the test site. It also will create a business assistance program designed to help technological start-up operations, and it will offer a capital finance program.

U.S. Senator Harry Reid of Nevada, working with DOE's Community Worker and Transition Office, was instrumental in securing the grant for the corporation.

"With DOE's support of the NTSDevelopment Corporation's grant application, a new era of the Department's commitment to a healthy economy based upon science and technology programs has begun," said acting DOE/NV Manager Terry Vaeth. "Nevada can be proud of the partnerships established throughout the state and with DOE."

Since 1988, the prime contractor work force at the Nevada Test Site has fallen from more than 8,000 to less than 3,000. Since 1993, those prime contractors have had to cut an added 1,350 subcontractor positions.

In 1995, the state of Nevada recognized the potential damage these cuts could have on its economy and it formed the NTS Development Corporation last July to try to reverse any negative impacts. The corporation is made up of representatives of the state, members of the Nevada Congressional delegation, city and county governments, labor unions, banks, the Greater Las Vegas Chamber of Commerce, the Nevada Development Authority, homeowners associations, and the University of Nevada educational system. More than 50 Nevada business leaders serve on the corporation's board of directors, reflecting the state's vital interest in these ventures and a new era at the test site.

Earlier this month, DOE/NV announced a new name for the Spill Test Facility at the Nevada Test Site. The facility is now known as the Hazardous Materials (HAZMAT) Spill Center.

The HAZMAT Spill Center provides a unique test bed for federal, state, tribal, local, and foreign governments and companies in the private sector. The one-of-a-kind ... demonstration facility ... to allow

Las Vegas Business Press, NV 2/03/97

Yes, it is rocket science

Local company competes with defense giants

By Thomas Moore
Staff writer

Sometimes smaller is better.

That's the case with Gary Rosenfield's Las Vegas companies, Industrial Solid Propulsion Inc. (ISP) and Aerotech Consumer Aerospace Inc., which manufacture solid fuel rocket motors for the military, science, motion picture and hobbyist markets.

Rocket motors are measured in two ways; either the diameter of the motor, or the total impulse. Impulse is the thrust, in pounds of pressure, multiplied by the amount of time the motor burns in seconds.

ISP can make motors as small as 20 pounds per second or 1.5 inches to as large as 36,000 pounds per second or ... inches in diameter.

Fitting into this niche has ... for Rosenfield. Although he ... hard numbers, Rosenfield ... ness grew by 30 percent ...

Rosenfield's compa... two basic fields ...

Aerotech makes ... the advanced rocket h... ...ture spec... ...vies A... ...d in a... ...he F...

...ld says he... ...eing innovative... ...h and ISP developed a ... ...r the hobby industry and by ...e cut the cost of a flight in

Nevada Development Authority Business Update July / August 1996

Nevada Test Site promotes public and private industry partnerships

Decades after the U.S. government began nuclear testing at the Nevada Test Site (NTS), Nevadans will begin to have major influence over the use of those federal lands and facilities.

U.S. Senator Harry Reid recently joined officials from the Department of Energy-Nevada (DOE-Nev.), NTS Development Corporation (NTSDC) and the test site's prime contractor, Bechtel Nevada, in announcing a program to make the vast technological and scientific resources of the Test Site available to private industry for the first time in history. The NTS is located 60 miles northwest of Las Vegas.

The first in a series of public and private industry partnerships, designed to attract business to the area and to utilize the expertise of its workers, was showcased by Kistler Aerospace Corporation which is slated to become NTS's first commercial tenant.

NTS Development Corporation, a Nevada nonprofit entity was formed last year as an outgrowth of recommendations issued by Governor Bob Miller's Economic Adjustment Task Force on the future of the Test Site and its workers. The NTSDC is the economic development corporation for the Test Site, through which the community is empowered by the DOE to influence what kinds of commercial activity will occur at the site.

Senator Harry Reid

The joint mission of the NTSDC, DOE-Nevada and Bechtel Nevada is to facilitate reuse, to expand use and to develop of alternate uses for the test site, a parcel of land the size of Rhode Island, replete with facilities, equipment, scientific laboratories and highly-skilled technical manpower.

The DOE-Nevada operations office, will fund the project for four years with an annual $5 million grant. ■

Las Vegas SUN, 7/2/96 (3B)
(Circulation: 39,000 daily; 220,300 Sunday)

DOE boosts Nevada's solar energy project

SUN STAFF REPORTS

The U.S. Department of Energy has promised to buy 10 megawatts of solar power from the Corporation for Solar Technology and Renewable Resources, giving a big boost to plans for Nevada to host a major alternative energy project.

The DOE's promise marks the first official business for Southern Nevada's fledgling solar production program, said Sen. Richard Bryan, D-Nev., interim board chairman of CSTRR, who attend a signing ceremony Monday.

CSTRR has been working with the DOE to develop a solar enterprise zone in Nevada to establish the state as the leader in solar research, technology and power generation. The first generation is expected in three to five years.

Terry Vaeth, acting manager of the DOE's Nevada Operations Office, said the power would be used at the Nevada Test Site, 65 miles northwest of Las Vegas.

With the DOE signed on as the first customer, other federal agencies could follow, said Rose McKinney-James, CSTRR president and chief executive officer.

About 50 energy managers from federal agencies around the West met in Las Vegas last week to explore opportunities to purchase CSTRR power.

Las Vegas Review-Journal, 7/2/96 (1 D)
(Circulation: 148,619 daily; 220,300 Sunday)

Future bright for company

• The Energy Department becomes the first customer to sign on with a Las Vegas area solar power marketer.

By John G. Edwards
Review-Journal

With the temperature hitting 104 degrees outside, the U.S. Department of Energy Monday formally agreed to buy 10 megawatts of power from solar power facilities expected to begin operation in Southern Nevada by 1999.

The department agreed to buy pov[...] er for the Nevada Test Site. It is t[...] first organization to make a comm[...] ment with the Corporation for So[...] Technologies and Renewable Reso[...] es, a public-private organization [...] is marketing energy for solar en[...] projects.

"This could put Southern N[...] and Las Vegas on the map in te[...] renewable resources that coul[...] global implications," Sen. Ric[...] ard Bryan, D-Nev., said [...] press conference at the Ene[...] Department's local offices.

The department would p[...] estimated $1.4 million fo[...] megawatts annually.

"It's the right thing to [...] we continue to challeng[...] federal agencies to join u[...] venture," said Terry Va[...] ing manager of the depa[...] Nevada Operations Offi[...]

The federal Envir[...] Protection Agency ho[...] solar power from th[...] tion when it moves it[...]

DOE NEWS

News Media Contact
Darwin J. Morgan, 702-295-3521

For Immediate Release
April 17, 1996

DOE Grants $5 Million to NTS Development Corp.

The U.S. Department of Energy (DOE) has approved a $5 million grant to the Nevada Test Site (NTS) Development Corporation to mitigate the impacts of downsizing at the test site. The NTS Development Corporation will serve as a means to continue the use of Nevada Test Site assets to stimulate economic development.

With the end of the Cold War and the changing mission at the NTS, the prime contractor work force has reduced from more than 8,000 in 1988 to less than 3,000 by the end of 1995. These cuts represent a 64-percent work force reduction, but do not include impacts on the subcontractor employees' roles. Since 1993, for example, about 1,350 subcontractor positions have been cut, in addition to more than 2,970 contractor positions.

The State of Nevada recognized the severity of these impacts on the state and its economy and moved to form the NTS Development Corporation. Made up of representatives from the State, the Congressional offices, city and county governments, unions, banks, the Greater Las Vegas Chamber of Commerce, the Nevada Development Authority, homebuilder associations, and the University of Nevada system, the NTS Development Corporation was formed July 5, 1995, with an initial grant of $500,000 from the DOE

Working with the Department's Community Worker and Transition Office, U.S. Senator Harry Reid (NV) was instrumental in getting the $5 million grant for the NTS Development Corporation.

Terry Vaeth, acting manager of the Nevada Operations Office, said, "With DOE's support of the NTS Development Corporation's grant application, a new era of the Department's commitment to a healthy economy based upon science and technology programs has begun Nevada can be proud of the partnerships established throughout the state and with DOE "

NV-96-34

- more -

Pahrump Valley Gazette, 11/14/96

NTS Development Corporation moves forward with new uses for test site

Plans to use the Nevada Test Site to develop hydrogen-based fuels and to train emergency workers moved closer to reality recently after a meeting of the NTS [...]opment Corporation (NTSDC) board of directors.

The NTSDC board, which includes 57 local bus[...]

[...] media.

Terry Vaeth, manager of the Department of Energy's [...] the test site operates a [...]

The Lincoln County Record, 11/21/96

New uses coming to Nevada Test Site

Plans to use the Nevada Test Site to develop hydrogen-based fuels and to train emergency workers moved one step closer to reality this week after a meeting of the NTS Development Corporation board of directors.

The NTSDC board, which includes 57 local business and civic leaders, agreed Oct. 29 to spend $150,000 during the next four months to study the feasibility of establishing a statewide training center at the test site to prepare emergency workers to respond to weapons of mass destruction.

NTSDC President Tim CarlSon said a proposed First Responder Training Center would be a perfect use for the Nevada Test Site which was the nation's nuclear weapons proving ground until a 1992 moratorium on nuclear testing took effect and reduced its workforce.

Carlson said the test site is ideal because of its size. It is vast, covering 1,350 miles, an area the size of Rhode Island. It is remote, located 60 miles northwest of Las Vegas and surrounded by thousands of acres of land withdrawn from the public domain. It is one of the largest secured areas in the United States.

Las Vegas business leader John O'Reilly, chairman of the board of the NTS Development Corporation, said the test site is perfectly positioned to utilize potentially available federal funding to train emergency response workers to deal with terrorist attacks and other safety and security issues.

"Congress is calling for a training facility capable of recreating urban and suburban environments including multistory buildings and underground tunnels, facilities the Nevada Test Site has readily available," O'Reilly said. "Best of all, we believe that a statewide training center operating at the NTS would be well-positioned to be designated as the national training center."

Carlson said potential users could include state and local law enforcement officers, firefighters, emergency medical technicians, utility workers, equipment manufacturers and even the news media.

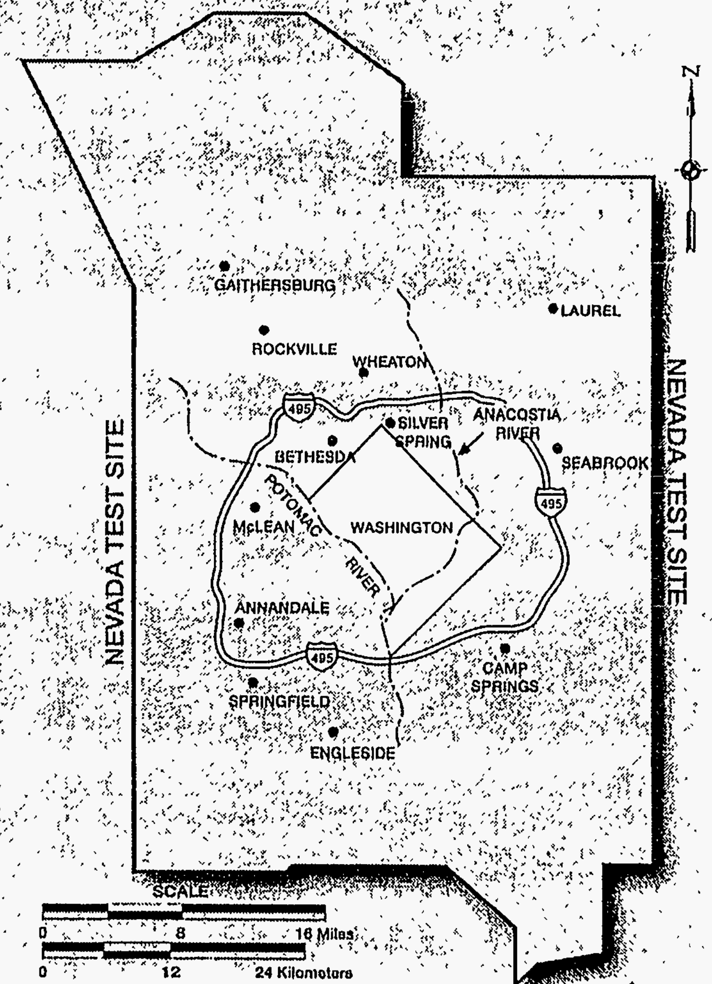
Terry Vaeth, manager of the Department of Energy's Nevada Operations Office, said the test site already operates a HAZMAT spill center, a training program in which hazardous chemicals are released in controlled situations. It also has a staff skilled in weapons testing and areas where fires and explosives can be ignited and monitored.

Sens. Harry Reid and Richard Bryan, both D-Nev., attended the Oct. 29 meeting and lent their support to the organization's efforts to find alternative uses for the test site.

Nevada Gov. Bob Miller also sent a letter stating his support.

NTS Infrastructure

- ✔ 1,350 sq.mi - Larger than state of Rhode Island
- ✔ 1,436 buildings - 2,900,000 sq. ft.
- ✔ 700 mi. of primary and secondary roads
- ✔ Air strip and helicopter pads
- ✔ Over 1200 vehicles available for conversion
- ✔ Vehicle support facilities and personnel

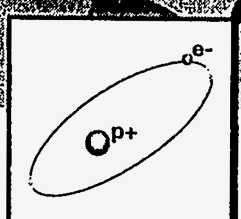


The EIS ROD is Behind Us

- ✔ Record of Decision supports present & future NTS missions
  - Stockpile stewardship and management
  - Materials disposition
  - Nuclear emergency response
  - Low-level and mixed waste disposal
  - Constructing and operating solar power production facility
  - Alternative fuels demonstration project
  - Public education awareness
- ✔ With the Record of Decision, "The expanded use alternative...provides for increase use of the Nevada Test Site and...make the Nevada Test Site more available to both public and private institutions for purposes of demonstrating new technologies."

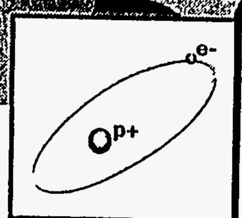
Nevada's Site Reuse Organizations

- ✔ **CSTRR's accomplishments:**
  - 10 MW solar electric, PV, power plant designated for NTS
  - 63 additional MW planned for 8 new sites
  - "Green Power" power program planned
- ✔ **NTS Development Corporation accomplishments:**
  - Kistler space launch site planned
  - 2 hydrogen projects in negotiation
  - Other privatization projects in development



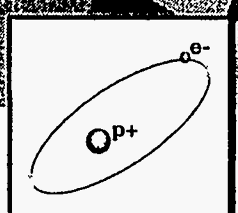
Nevada's Challenge

- ✔ Nevada has potential to become a leader in establishing a "clean state" based upon a Hydrogen Economy. Nevada can contribute to the rapid introduction of hydrogen through the combined resources of the NTS Development Corporation, excess resources at the Nevada Test Site, and commercial interests in the state.



Nevada Stakeholder's Interest

- ✔ Supporting DOE strategic goals
  - – Energy independence
  - – Reduced emissions attributable to:
    - Transportation
    - Power production
- ✔ Reducing air emissions in Las Vegas and Reno metro areas



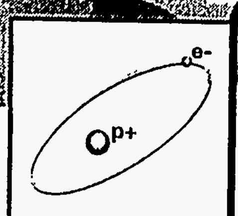
Situation Analysis

✔ **Las Vegas metro area**

- 6000 new residents per month
- Population Tripled from 1987 to 1997
- Rapidly deteriorating air quality
  - "Serious" non-attainment for PM-10
  - "Moderate" non-attainment for CO
  - Increasing concern for NOX & ozone

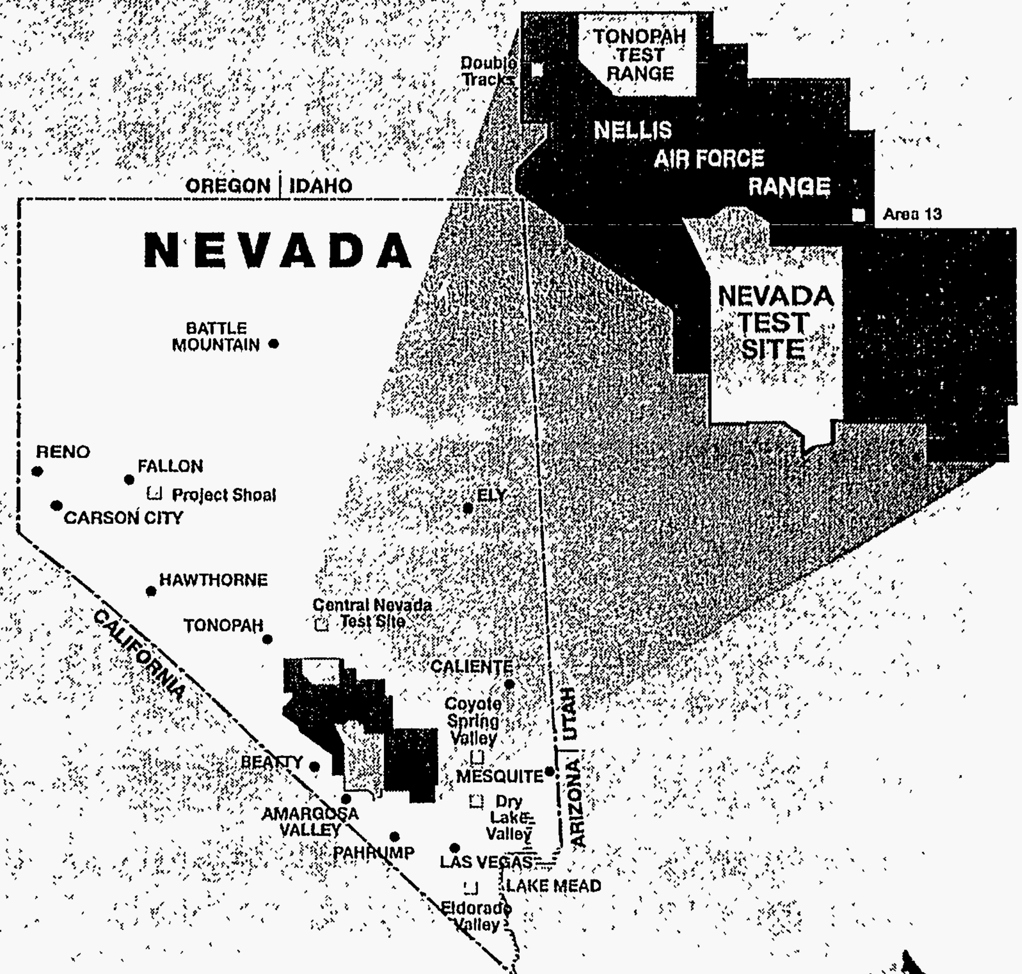
✔ **Reno metro area**

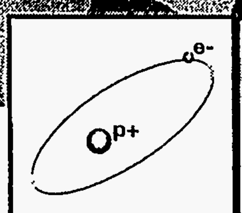
- 9000 new residents per year
- Deteriorating air quality
  - "Moderate" non-attainment for PM-10
  - "Moderate" non-attainment for CO
  - "Marginal" non-attainment for ozone



Clean Cities Concept

- ✔ Clean cities exist
- ✔ Two population Density Areas
- ✔ Move to clean state status



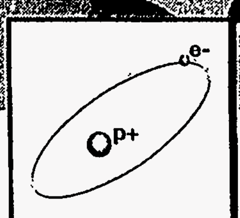


Opportunity for Hydrogen in Nevada

- ✔ Strong Congressional and local support
- ✔ Initiatives
  - "Clean city"
  - "Clean corridor" w/ CA/NV/UT
  - "Clean state"
- ✔ "Clean City" participants looking for clean fuels
- ✔ Re-fueling sites
  - 7 CNG sites in operation
  - 1 LNG/CNG re-fueling site planned
- ✔ Would like to add hydrogen to the re-fueling mix

My Invitation to the Hydrogen Community

- ✔ The NTS Development Corp., our stakeholders, and the Nevada Test Site welcome the opportunity to support the market development, production, and commercialization of emerging energy technologies and in particular hydrogen based technologies.



SAFETY EVALUATION OF A HYDROGEN FUELED TRANSIT BUS

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Abstract

Hydrogen fueled vehicle demonstration projects must satisfy management and regulator safety expectations. This is often accomplished using hazard and safety analyses. Such an analysis has been completed to evaluate the safety of the H2Fuel bus to be operated in Augusta, Georgia.

The evaluation methods and criteria used reflect the Department of Energy's graded approach for qualifying and documenting nuclear and chemical facility safety. The work focused on the storage and distribution of hydrogen as the bus motor fuel with emphases on the technical and operational aspects of using metal hydride beds to store hydrogen.

The safety evaluation demonstrated that the operation of the H2Fuel bus represents a "moderate" risk. This is the same risk level determined for operation of conventionally powered transit buses in the United States. By the same criteria, private passenger automobile travel in the United States is considered a "high" risk.

The evaluation also identified several design and operational modifications that resulted in improved safety, operability, and reliability. The hazard assessment methodology used in this project has widespread applicability to other innovative operations and systems, and the techniques can serve as a template for other similar projects.

Introduction

The H2Fuel Bus Project is a joint development effort to manufacture and demonstrate a hydrogen-fueled, 27-passenger transit bus. This bus will qualify as a near-zero emission vehicle. A key initiative in the hydrogen bus development effort is a rigorous evaluation of operational safety. A systematic and comprehensive hazard analysis process has been performed to evaluate and mitigate safety concerns that are unique to the use of hydrogen as a motor fuel. The U.S. Department of Energy (DOE), in association with the H2Fuel Bus Project Team, commissioned the Westinghouse Savannah River Company (WSRC) to lead this hazard analysis. The scope of the analysis included transit operations, maintenance, cleaning, battery recharging, and vehicle storage.

The H2Fuel bus will be operated by the Augusta-Richmond County Public Transit (ARCPT) fleet with minimal limitations. While the driver and maintenance personnel will be provided with special instructions and training, the goal is for the riding public to observe no difference between the operational effectiveness and safety of the H2Fuel bus and a standard bus.

The Air Liquide America Corporation at its Augusta, Georgia facility will accomplish hydrogen refueling. Since this facility routinely handles hydrogen, an analysis of the refueling operation was considered unnecessary. The batteries for the H2Fuel bus will be recharged during the night at the ARCPT maintenance facility. This recharging extends the operating range of the bus.

H2Fuel Bus Description

The H2Fuel bus platform is a production model electric bus manufactured by Blue Bird Body Co. The vehicle is 32'-10" long with a 193" wheelbase and a gross vehicle weight of 33,000 pounds. The bus is propelled by electric power. A hydrogen-fueled 70 kW engine-generator set was added to permit continuous battery recharging.

Hydrogen is stored in two fuel containers. Each container holds 7.5 kg of hydrogen in 24 hydride vessels. Figure 1 shows a schematic of the hydrogen piping system. Downstream of each cylinder manifold is an excess flow valve. The excess flow valve is a safety feature that automatically shuts under a high-flow condition, such as a line break downstream.

The hydride beds contain lanthanum/nickel/aluminum metal that adsorbs large quantities of free hydrogen at low pressure within a small space volume. When the bus is operating, hot water from the engine coolant system is circulated through the hydride vessel cooling/heating coil, and hydrogen is desorbed at a rate and pressure practical for use as engine fuel feed. This development solves the safety and technical shortcomings associated with storing hydrogen gas in high-pressure cylinders.

The metal hydride vessels are refilled by circulating cold water through the hydride vessel cooling/heating coil and admitting pure hydrogen to the hydride material from a compressed hydrogen source. The total system capacity is 15 kg of hydrogen.

The H2Fuel bus is equipped with a flammable gas detection system consisting of multiple detectors and an alarm indication at the driver's station. Detectors are located in the motor compartment, undercarriage, and the passenger compartment. The engine will shutdown automatically when a detector indicates the location exceeds 25% of the Lower Flammability Limit (LFL). A high-high alarm sounds at 50% of the LFL. Additional detectors are located in the fuel containers. The shutdown setting is 15% and the high-high alarm is 25% for these detectors.

The status of the detection system is indicated at driver's control panel and by three lamps near the back bumper of the bus. Green indicates that the system is functioning normally. Yellow indicates a shutdown level is exceeded. Red indicates a high-high alarm. There is no audible alarm for this detection system. This approach was used because of a concern that an audible alarm would distract drivers in other vehicles. Such distractions were considered a greater safety risk than any potential risk avoidance accomplished with the audible alarm.

Maintenance Facility Description

The ARCPT maintenance facility is located in Augusta, Georgia. The facility consists of 6 buildings: Administration Building, Detail Cleaning Building, Fuel Island, Maintenance Building, Paint Shop, and Wash Building. The total size of these buildings is 2,260 m^2 (23,300 ft^2). The buildings are masonry construction and would be considered unprotected structures as defined by the *Standard Building Code (SBC)* and NFPA 220, *Standard on Types of Building Construction* (Type IV per SBC, and Type II-000 per NFPA 220). The buildings are not provided with any special fire protection features (e.g., automatic sprinklers.)

The three buildings most affected by the H2Fuel bus are the Maintenance Building, Detail Cleaning Building and Wash Building. The Maintenance Building houses the 6 maintenance bays and the inspection bay that are used in maintaining the bus fleet. In addition, this building houses offices, locker rooms, a money vault, and miscellaneous small shops. The building roof has an unprotected steel frame arched roof with a membrane cover over wood decking.

The ARCPT buses are cleaned each evening after they return from rounds. Interior cleaning is accomplished in the Detail Cleaning Building. Exterior cleaning is completed using the automatic bus wash equipment housed in the Wash Building. Both the Detail Cleaning and Wash Buildings are relatively small buildings (capable of holding only one vehicle at a time). In each building are two openings in this building; one at either end

Hazard Analysis Methodology

The hazard analysis for the H2Fuel bus was produced in three stages: overview, rolling operations, and maintenance/storage facility. The overview hazard analysis consisted of an intensive, structured, and comprehensive hazard identification and classification process. Hazards that represent the greatest risk were then evaluated in detail during the rolling operations and maintenance/storage facility stages.

Definitions

There are several terms used in this report that have a special context. These terms are discussed below:

Risk is the product of expected frequency and corresponding consequences. The frequency is an expression of likelihood of occurrence. Usually expressed as the estimated number of accidents per year. Example: 4E-03/yr. (This means 0.004 per year or 1 in every 250 years.) The consequence is the result of an event (e.g., injury to people, loss of property, operational interruption, and environmental damage.)

Explosions are categorized by the rate of expansion of the combustion gases. Deflagrations have defined as having expansion velocities that are subsonic, while detonations have supersonic velocities.

Process

The methodology used by WSRC to produce the H2Fuel bus hazard analysis was based on that used by the DOE in establishing and documenting the operational safety of its nuclear and chemical processing facilities. This methodology employs a systematic, graded approach and ensures that the greatest attention is applied to the most significant concerns. The steps below summarize the method.

1. Hazard identification. The process began by identifying any hazardous material or energy source associated with the H2Fuel Bus. A checklist was used as a guide to aid in developing a comprehensive list of hazards. Hazards were characterized in terms of form, quantity, and location.

2. Scenario development. The second step in the overview hazard analysis was development of detailed, reasonable-worst-case, credible scenarios describing process upsets, human errors, system failures, etc. that result in unwanted or unacceptable consequences. These scenarios were postulated without regard for existing design safety features.

3. Risk assessment. The scenarios developed in step 2 were individually assessed to determine (a) likelihood of occurrence (expressed as frequency of occurrence per year), and (b) severity of consequence. This assessment was made by considering both the cause(s) of the scenario (or initiating event(s)) and the hazardous material or energy released as a result of the scenario. During this phase of the analysis, no credit is taken for preventive or mitigative features in reducing frequency or consequence, thereby focusing on those hazards that are of greatest concern.

4. Risk binning. Each hazard was plotted on a frequency/consequence matrix. The risk-binning matrix used is shown below as Figure 2. Tables 1 and 2 define the frequency and consequence criteria used to define the risk bins.

5. Graded approach. Hazards falling in the High and Moderate risk bins were carried forward for further analysis, and the results of that work are reported here in this report. Low- and negligible-risk hazards are addressed further as management/operational issues, but are excluded from further attention in the formal hazard analysis work.

Table 1. Frequency criteria used for risk binning

Acronym	Description	Frequency level
A	Anticipated, Expected	> 1E-2 /yr
U	Unlikely	1E-4 < f ≤ 1E-2 /yr
EU	Extremely Unlikely	1E-6 < f ≤ 1E-4 /yr
BEU	Beyond Extremely Unlikely	≤ 1E-6 /yr

Overview Hazard Analysis

Twenty-seven accident events were evaluated in the *Overview Hazards Analysis* [Hovis 1996]. A breakdown by event category is given in Table 3. Of the 27 event scenarios evaluated, 3 were binned as High risks and 10 were binned as Moderate risks. These 13 events were carried forward for further, quantitative risk evaluation as part of the *Rolling Operations Analysis*. The results of that evaluation work are discussed in the next section.

Table 2. Consequence criteria used for risk binning

Consequence Level	Impact on Populace	Impact on Property/Operations
High (H)	Prompt fatalities, Acute injuries - immediately life threatening or permanently disabling	Damage > $1 million Vehicle destroyed & surrounding property damaged
Moderate (M)	Serious injuries, Permanent disabilities, Hospitalization required	$10,000 < damage < $1 million Vehicle destroyed Minor impact on surroundings
Low (L)	Minor injuries, No permanent disabilities, No hospitalization	Damage < $10,000 Reparable damage to vehicle, Significant operational down-time, No impact on surroundings
Negligible (N)	Negligible injuries	Minor repairs to vehicle required, Minimal operational down-time

Table 3. Summary of events by risk level

Event Category	Description	Risk level (combination of frequency and consequence)				
		H	M	L	N	Total
E-1	Fire	1	2	2	0	5
E-2	Explosion	0	2	6	0	8
E-3	Loss of confinement (leaks, etc.)	0	0	0	4	4
E-4	Persons exposed to hydrogen gas	1	1	0	0	2
E-5	External hazards (road hazard, etc.)	1	0	1	0	2
E-6	Natural phenomena (wind, etc.)	0	3	0	0	3
E-7	Others	0	2	0	1	3
	Totals	3	10	9	5	27

Examples of the 14 low and negligible risk events include fires that don't propagate to involve the fuel system, engine mechanical failure, and hydrogen leaks where ignition does not occur.

Rolling Operations Hazard Analysis

The *Rolling Operations Analysis* [Coutts 1996] was conducted in three separate phases: component level review, high and moderate risk event quantification, and a detailed fire and deflagration analysis. The detailed fire and deflagration analysis was developed since these events were demonstrated to be the most significant risks associated with the H2Fuel bus.

To put the H2Fuel bus risk in perspective the existing bus fire risk was analyzed. In the United States buses and trackless trolleys have averaged 2,320 fires per year between 1988 and 1992. These fires have resulted in 5 civilian (non-firefighter) deaths, 69 civilian injuries, and direct property damage of $13.7 million. Thus for the fire frequency for a given bus is 4E-03 (0.0036) fires per year or 4E-07 fires/mile traveled. Using this same information, for a given bus, the frequency of an occupant fire injury or death is 4E-05 per year and 4E-06 per year respectively.

Component Level Review

A team consisting of safety analysts, designers and hydrogen researchers conducted the H2Fuel bus component level review. The team conducted a systematic and unbiased *What-If* analysis to identify plausible and significant accident scenarios. The *What-If* was performed by systematically stepping through the H2Fuel bus conceptual design, one major component at a time. The team postulated reasonable what-if questions, used engineering judgment to assess the functions of protective features, and made recommendations for additional protection where needed to satisfy the consequence criteria.

The component level analysis postulated twenty scenarios. Of these twenty scenarios, seven identified action items. These action items were considered best practice recommendations and implementation of these was at the discretion of the design team. Typical items identified included drains on the fuel containers and vents in the bus skirt to limit hydrogen accumulation

Risk Quantification

Hazards that were identified during the overview analysis as moderate or high risk were subject to additional risk evaluation. With the exception of those events that were determined to be standard hazards, a quantitative risk estimate was prepared.

Many hazards associated with the H2Fuel bus can result from events that can be considered accepted risks in public transportation. These hazards were referred to as standard hazard events. They would include wind and tornado induced damage, earthquake induced damage, mechanical failure, energetic release of pressurized systems, and vehicle impacts. All can result in injuries, fatalities or property damage. Where these events did not affect the hydrogen system no further evaluation was deemed necessary. Postulated events that included fires or hydrogen releases were treated as one event and are discussed in the fire and deflagration section.

Hazards unique to the hydrogen system that were analyzed quantitatively were:

- Collision causes rapid hydrogen leak and ignition
- Detonation of leaked hydrogen
- Asphyxiation
- Confinement damage resulting from environmental extremes (both high and low temperature)
- Maintenance error damages confinement system
- Maintenance error damages flammable gas detection systems
- Total power failure

Fire and Deflagration Events

Fires on buses are considered an accepted societal risk. Since the H2Fuel bus contains all of the features of a standard bus, it is expected to have at least the same fire risk. The presence of hydrogen on the H2Fuel bus creates the potential for explosions that do not exist for diesel fueled buses. A similar explosion potential also exists for other alternative fueled (natural gas, propane, etc.) buses. To simplify the evaluation general fires, hydrogen leak-induced fires, and hydrogen deflagrations were evaluated as a single event.

Fires that grow to involve the hydrogen system are not expected to result in explosions. Leaks caused by the fire (e.g., melted seal or burned hose) are expected to be readily ignited, thus preventing the accumulation and mixing necessary to create deflagrations and detonations. A severe bus fire is expected to burn until all fuel is exhausted (about 20 minutes). Unless the bus is adjacent to a large building when a severe fire occurs, losses should not exceed the bus itself and any adjacent vehicles (a moderate property consequence).

A large-scale deflagration under the bus was demonstrated to result in peak pressure less than 1 psig and would not significantly lift the bus (< 1 inch). The major hazard associated with such a deflagration would be the resulting flame jet issuing from under the bus. A secondary hazard would be the potential for portions of the skirt to be torn loose and thrown a short distance. The property damage that would therefore be caused by the most severe deflagrations would be classified as moderate. Bus occupant fatalities as a direct effect of the deflagration are not expected.

The results of this analysis are summarized in Table 4. The fire and deflagration events involving the H2Fuel bus are considered moderate. This is the same risk as derived for other transit buses.

Table 4. Fire and deflagration risk for the H2Fuel bus

	Description	Consequence	Frequency	Risk
Operation of H2Fuel bus	Property loss	< $1 million	6E-3/yr	moderate
		> $1 million	6E-5/yr	moderate
	Populace	high	6E-5/yr	moderate
	Base risk	< $1 million	4E-3/yr	moderate
Maintenance, battery charging and storage	Property loss	< $1 million	3E-3/yr	moderate
		> $1 million	9E-5/yr	moderate
	Base risk	< $1 million	3E-2/yr	high
		> $1 million	6E-4/yr	high

Maintenance Facility Hazard Analysis

The introduction of the H2Fuel bus will increase risk at the maintenance facility. This would also be true for additional operations or new vehicles at the facility. Several different methods were used in evaluating the maintenance and storage risks associated with the H2Fuel bus [Coutts 1997]. These methods included quantitative frequency and consequence estimates, qualitative analysis, and a partial code compliance review.

Baseline Fire Risk

Fire is an existing hazard at the maintenance facility. No other existing hazards were identified that were considered to be modified by the presence of the H2Fuel bus. The primary factors that affect fire frequency are the size of the facility, the hours of operation, the installed fire protection features, and the expected fire department response. The existing frequency of a fire at the maintenance facility, that requires fire department response, is 0.029/yr. This would be considered the frequency of a low consequence event (monetary loss less than $10,000). Such an event is thus considered a moderate risk.

The frequency of a fire causing a loss in excess of $1,000,000 is estimated as 6.3E-4/yr. Such an event would be considered a high risk. This is the base case for the H2Fuel bus comparison. If an automatic sprinkler system were installed in the Administrative and Maintenance Buildings the frequency would be reduced such that the facility would be a moderate risk.

Increased Fire Risk

The frequency that the H2Fuel bus causes a fire in the Maintenance Building is estimated to be 9.0E-5/yr. If such an occurrence were to always result in a high consequence, the event would be considered of moderate risk. This is lower than the present risk for the maintenance

The frequency that the H2Fuel bus causes a fire in the Detail Building was estimated to be 2.8E-3/yr. The frequency was even lower for the Wash Building. The monetary consequence of such an event was considered moderate, thus a moderate monetary risk. The worker safety consequence was considered high (possible prompt fatalities), however since the frequency of this consequence is extremely unlikely, the worker safety risk is also moderate.

Explosion Risk

The H2Fuel bus does introduce a new hazard, hydrogen explosions. The peak pressure resulting from deflagration was calculated using a correlation developed by Bradley and Mitcheson for the three buildings of greatest risk. Detonations, with the exception of the under bus scenario (discussed earlier) were not investigated since their frequency was judged to be beyond extremely unlikely. (See Thomas 1997 for details on this work.)

Detail Cleaning and Wash Buildings

The Detail Cleaning Building has two large openings at either end to allow bus entry, however the stop roughly 6 feet from the roof line. This effectively provides a small volume in which hydrogen can accumulate. Thus it was recommended to increase the existing forced ventilation in building.

The hydrogen mass available for rapid release (3.3 kg) is just slightly greater than that required to bring the volume to LFL (i.e., 4 percent by volume), assuming no loss of hydrogen from the enclosure and perfect mixing. The hydrogen mass required to bring the enclosure to the stoichiometric concentration (19 kg or 30 percent by volume) is larger than the total available (15 kg). Thus a stoichiometric mixture is not expected.

At a concentration of 10%, which is judged to be bounding given the amount of hydrogen available, the predicted peak pressure is 0.4 psig. The amount of vent area (e.g., open doors) greatly affects the peak explosion pressure. If the H2Fuel bus is parked in the center of the building the doors will provide a significant vent path, thus reducing the peak pressure. If a bus was parked in the door, it would effectively block one of the vent paths and the peak explosion pressure would be higher. Thus procedural controls on the parking of buses near this doors was recommended.

Deflagration pressures approaching 0.4 psig represent the high end of the potential spectrum, and values of a few tenths of a psig are judged to be the most likely. Such peak pressures might damage the building[1], but are not expected to result in the injury of building occupants[2]. Because of the presence of flames, and the proximity of occupants to the ignition, the maximum consequence of this event is a worker death. The results for the Wash Building were similar.

To allow personnel to immediately evaluate the vicinity if a hydrogen leak were to occur, the installation of a hydrogen or flammable gas monitor with an audible and visual alarm was recommended.

Maintenance Building

The Maintenance Building has a domed roof such that a significant quantity of hydrogen could accumulate in the building even with the roll-up doors open. Thus the improvement of the building ventilation system was considered very important. The installation of an exhaust system above the bus fuel-box-vent-lines was recommended.

The inspection, cleaning, and large bay enclosures were each examined separately. The limited hydrogen quantity available for rapid release (3.3 kg) is approximately equal to that required to bring the volume to LFL for the inspection and cleaning bays, assuming no loss of hydrogen from the enclosure and perfect mixing. A much greater amount of hydrogen would be required to bring the main bay section to a given uniform concentration since its volume is much larger than that of the inspection and cleaning bays.

At a concentration of 10%, which is judged to be bounding given the amount of hydrogen available, the predicted peak pressures ranged from 0.2 to 0.4 psig if the roll-up doors were open. For the case where the roll-up doors are closed, the peak pressure would be a few psig above the pressure at which the roll-up doors fail (e.g. are blown clear of the doorway). The predicted peak pressures with the doors closed would be expected to damage the building and could cause permanent disabilities to building occupants. In addition, the presence of flames, and the proximity of occupants to the ignition could result in a worker death. As with the Detail Cleaning Building a hydrogen or flammable gas detection system was recommended.

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[1]Minor structural damage is expected for overpressures of 0.4 psig [FM Data Sheet 7-0S].

[2]Eardrum damage is expected at 2 psig, lung damage at 5 psig, and 1 percent mortality at 30 psig [Zalosh 1988].

In addition, maintenance activities that could potentially lead to a breach of the hydrogen storage or delivery system should be tightly controlled. Specifically, maintenance procedures should include steps to ensure full isolation of the fuel storage system. Forced convection (e.g. high capacity box fans) should be provided to the underside of the bus during actual maintenance activities, although this is not judged to be necessary during inspections.

Hazard Comparison with Engineering Codes and Standards

A partial code compliance review was conducted for the maintenance facility to validate the hazard analysis results. The reviewed documents were the Standard Building Code, NFPA 70, NFPA 88B, and NFPA 497A. Compliance with these codes and standards while not always required was considered to be a good practice. In many instances the codes and standards review identified similar items as discussed earlier. This is expected since engineering codes and standards attempt to mitigate or prevent hazards. The primary findings of this review were:

- Electrical systems in the Detail Cleaning and Maintenance Buildings must meet Articles 501, 510, 511 in NFPA 70 (i.e., *The National Electric Code*) where the H2Fuel bus is present.
- Ventilation of the Detail Cleaning and Maintenance Buildings is necessary when the H2Fuel bus is present.
- The design of the charging system in the Detail Building must meet NFPA 70, Article 625.

Conclusions

The public and property risk associated with the H2Fuel bus is characterized as moderate; the same risk category as determined for all standard public transit buses. The safety of passengers on the H2Fuel bus has been shown to be dependent to some degree on the training and proficiency of the bus operator.

The recommendations from the hazard analysis effort can be summarized as:

- Provide adequate hydrogen safety training to bus operations and maintenance personnel.
- Verify "as built" design of bus conforms to hazard analysis assumptions.
- Provide adequate ventilation and electrical systems where the H2Fuel bus will be maintained and stored.

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Figure 1. Hydrogen fuel system

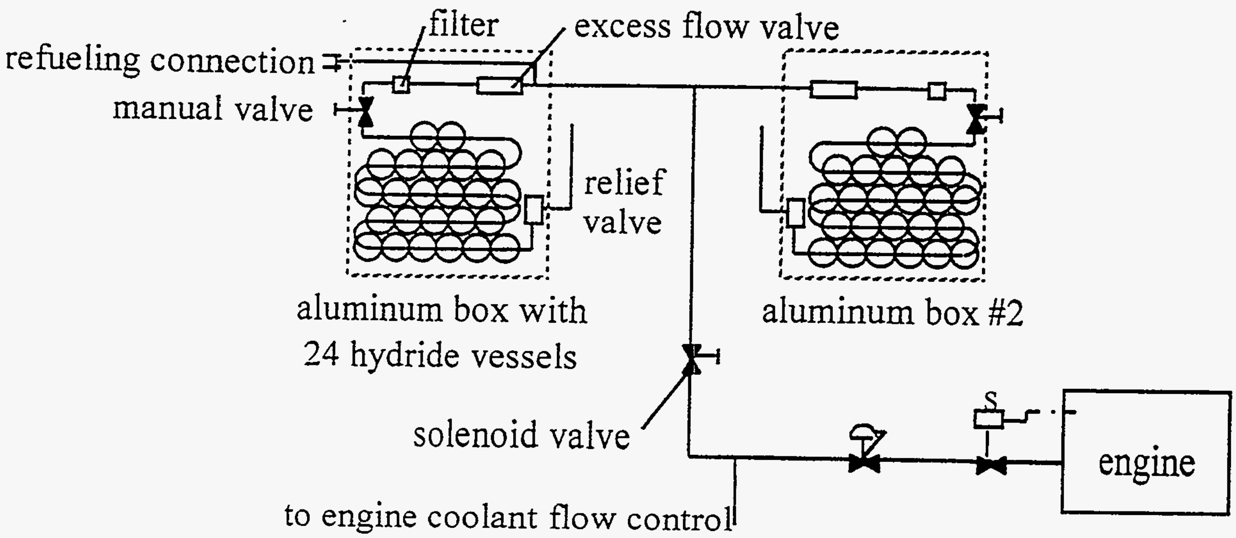

Figure 2. Risk binning matrix used for hazard analyses

Frequency → / Consequence ↓	Beyond extremely unlikely $f \leq 10^{-6}\ yr^{-1}$	Extremely unlikely $10^{-4} \geq f > 10^{-6}$	Unlikely $10^{-2} \geq f > 10^{-4}$	Anticipated $f > 10^{-2}\ yr^{-1}$
High		7	4	1
Moderate	10	8	5	2
Low		9	6	3
Negligible	11		12	

Key:

- Risk Bins 1, 2, 4 ("High" risk)
- Risk Bins 3, 5, 7 ("Moderate" risk)
- Risk Bins 6, 8, 9 ("Low" risk)
- Risk Bins 10, 11, 12 ("Negligible" risk)

Safety Evaluation of a Hydrogen-Fueled Transit Bus

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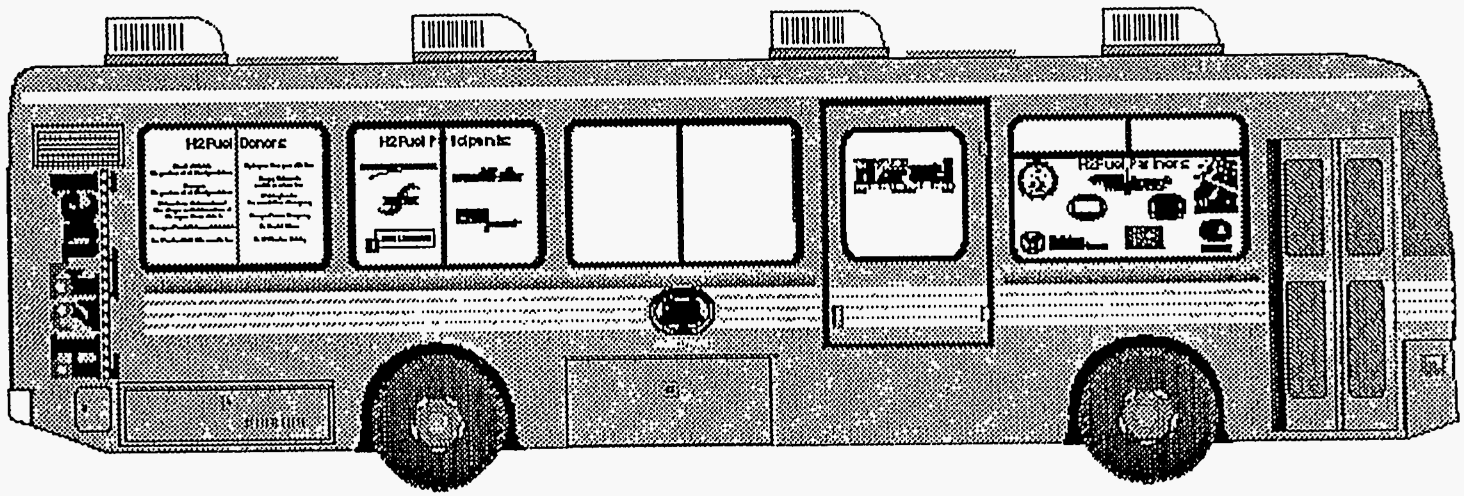
Project Partners and Participants

Department of Energy
Westinghouse Savannah River Company
Southeastern Technology Center
Georgia Tech Research Institute
Augusta-Richmond County Commission-Council
Education, Research & Development Association of Georgia Universities
Hydrogen Components, Inc.
Blue Bird Corporation
Power Technology Southeast, Inc.
Energy Research and Generation, Inc.
Air Products and Chemical, Inc.
Air Liquide America Corporation
Northrop Grumman Corporation

H2Fuel Bus

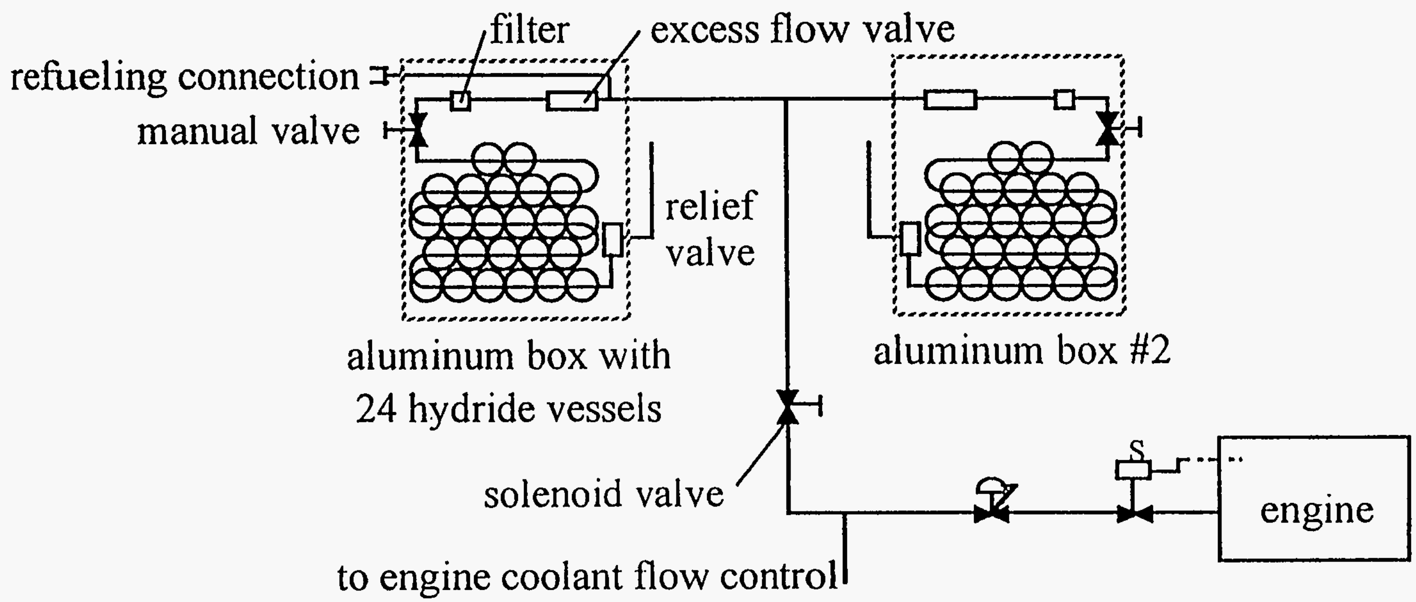

H2Fuel Donors
H2Fuel Participants
H2Fuel Partners
H2Fuel

Highlights

Blue Bird Body Co. Model QBEV 3210 Electric Bus

Length:	**32'-10"**
Wheelbase:	**193 inches**
Gross vehicle weight:	**33,000 lb.**
Passenger capacity:	**27 seated**
Electric propulsion system:	**230 hp AC induction motor**

Hydrogen Piping



Hazard Analysis Process

1. Hazard identification
2. Scenario development
3. Risk assessment
4. Risk binning
5. Graded approach

Base Risk (per bus)

Fire frequency	4E-03 (0.0036) fires per year
	4E-07 fires/mile traveled
Occupant	
Fire death frequency	4E-06 per year
Fire injury frequency	4E-05 per year

Frequency Definitions

Acronym	Description	Frequency level
A	Anticipated	f > 1E-2 /yr
U	Unlikely	1E-4 < f ≤ 1E-2 /yr
EU	Extremely Unlikely	1E-6 < f ≤ 1E-4 /yr
BEU	Beyond Extremely Unlikely	f ≤ 1E-6 /yr

Consequence Definitions

Consequence Level	Impact on Populace	Impact on Property/Operations
High (H)	Prompt fatalities,	Damage > $1 million
	Acute injuries - immediately life threatening or permanently disabling	Vehicle destroyed & surrounding property damaged
Moderate (M)	Serious injuries,	$10,000 < damage < $1 million
	Permanent disabilities,	Vehicle destroyed
	Hospitalization required	Minor impact on surroundings
Low (L)	Minor injuries,	Damage < $10,000
	No permanent disabilities,	Reparable damage to vehicle,
	No hospitalization	Significant operational down-time,
		No impact on surroundings
Negligible (N)	Negligible injuries	Minor repairs to vehicle required,
		Minimal operational down-time

Risk Binning

Frequency → Consequence ↓	Beyond Extremely Unlikely $f \leq 10^{-6} yr^{-1}$	Extremely Unlikely $10^{-6} < f \leq 10^{-4} yr^{-1}$	Unlikely $10^{-4} < f \leq 10^{-2} yr^{-1}$	Anticipated $f > 10^{-2} yr^{-1}$
High	10	7	4	1
Moderate	10	8	5	2
Low	10	9	6	3
Negligible	11	12	12	12

High risk

Moderate risk

Low risk

Negligible risk

Risk Binning Results

Event Cat.	Description	Risk level (combination of frequency and consequence)				
		H	M	L	N	Total
E-1	Fire	1	2	2	0	5
E-2	Explosion	0	2	6	0	8
E-3	Loss of confinement (leaks, etc.)	0	0	0	4	4
E-4	Persons exposed to hydrogen gas	1	1	0	0	2
E-5	External hazards (road hazard, etc.)	1	0	1	0	2
E-6	Natural phenomena (wind, etc.)	0	3	0	0	3
E-7	Others	0	2	0	1	3
	Totals	3	10	9	5	27

Results for Bus

Fire and deflagration	4
Detonation	2
Standard hazard	3
Asphyxiation	1
Confinement damage	1
Maintenance error	1
Power failure	1
Total	13

Fire and Deflagration Risk During Operation

Description	Consequence	Frequency	Risk
Property loss	< $1 million	6E-3/yr	moderate
	> $1 million	6E-5/yr	moderate
Populace	high	6E-5/yr	moderate
Base Risk	< $1 million	4E-3/yr	moderate

Fire and Deflagration Risk During Maintenance and Storage

Description	Consequence	Frequency	Risk
Property loss	< $1 million	3E-3/yr	moderate
	> $1 million	9E-5/yr	moderate
Base Risk	< $1 million	3E-2/yr	high
	> $1 million	6E-4/yr	high

Conclusions

The H2Fuel Bus represents a moderate risk during operation, storage, maintenance and electrical recharging. This risk is similar to that observed for other buses operating in the United States.

HYDROGEN GENERATION, STORAGE, AND DISPENSING SYSTEM SAFETY ASSESSMENT - A CASE STUDY

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Abstract

A safety assessment and evaluation of the Clean Air Now! (CAN) solar photovoltaic hydrogen generation, storage, and dispensing system was performed by the Energy Technology Engineering Center (ETEC). This system is located at the Xerox Corporation facilities in El Segundo, California, and is used by the Xerox Corporation and the City of West Hollywood to fuel a small fleet of utility vehicles. These vehicles have been retrofitted with hydrogen storage and fuel injection systems which allow these vehicles to operate on clean burning hydrogen.

The safety assessment was qualitative in nature and based upon the effectiveness of system design features to mitigate potential casualty events, and on the extent to which the system designer adhered to applicable codes and standards. During this assessment many safety issues and concerns were identified, many of which were direct code deviations requiring system modifications. After all required modifications were completed, the safety assessment showed that the CAN system was safe to operate. As a result, a permit to operate the facility was issued by the City of El Segundo.

Many lessons learned, which are directly applicable to the DOE Hydrogen Program, were identified during the performance of this safety assessment. Specifically, it was determined that: 1) a safety assessment should be performed on all hydrogen projects prior to construction; 2) to prevent startup delays, required permitting and safety officials should be brought in and briefed on project safety issues early in the project; and 3) construction oversight and post-construction safety reviews are critical to system safety. In addition, the assessment showed that codes, standards, and safety practices, which can be applied to hydrogen facilities, exist to the extent that these facilities can be built, permitted, and safely operated. However, for this to occur, systematic safety assessments and post-construction safety reviews must be performed.

Introduction

The primary objective of this project at the Energy Technology Engineering Center (ETEC) was to perform a safety assessment of the Clean Air Now! (CAN) solar photovoltaic powered, hydrogen generation, storage, and dispensing system (Reference 1). The system was reviewed against the codes and standards listed in References 2 through 6, and the safety assessed by means of a systematic casualty study using design information provided by the designers and from information obtained during on-site inspections. The system was primarily designed per the codes and standards of References 2 through 6. The Electrolyser Corporation designed the water electrolysis system and the high pressure compression and storage systems, Praxair Incorporated designed the low pressure storage system and the dispenser station, and Solar Engineering Applications Corporation designed the photovoltaic array. This system is located at the Xerox Corporation facilities in El Segundo, California.

The CAN project demonstrates a practical application of renewable hydrogen. The project uses a photovoltaic system with Fresnel lenses which track the sun, capture and condense sunlight, and convert it into electricity. The electricity generated by the photovoltaic arrays power the electrolysis system which separates incoming feedwater into its two component parts, hydrogen and oxygen. The hydrogen produced from this electrolysis system is then dried, compressed to 4,200 psig, and stored in high pressure storage vessels. Electricity produced from the photovoltaic array also provides power to the hydrogen compressor. The storage vessels are used to supply the fueling station dispensing nozzles with high pressure hydrogen. A fleet of utility vehicles, operated by the Xerox Corporation and the City of West Hollywood, are fueled with these nozzles. The vehicle fleet was retrofitted to operate on pure hydrogen and air.

CAN oversaw, directed and managed the overall project. Other team members included the Xerox Corporation; The Electrolyser Corporation; Praxair Incorporated; Solar Engineering Applications Corporation; Kaiser Engineering; City of West Hollywood; W. Hoagland & Associates, Incorporated; Touchstone Technology; the University of California, Riverside, College of Engineering - Center for Environmental Research & Technology; Matrix Construction and Engineering, Incorporated; and the Energy Technology Engineering Center. The project was funded by the White House Technology Reinvestment Project (contracted through the U.S. Department of Energy), Clean Air Now, the South Coast Air Quality Management District, and the rest of the project team.

Background

Project Objective

Towards the end of the facility construction period, an application for a facility operating permit was submitted to the City of El Segundo by CAN. After reviewing the CAN facility and the permit application, personnel from the City of El Segundo became "uncomfortable" with this "new" hydrogen technology being sited in a populated industrial complex. As a result, the City of El Segundo requested that an independent safety assessment be performed prior to receiving City approval. As a result, ETEC was hired by CAN to perform this assessment. The primary technical goal was to assess the safety of the CAN solar photovoltaic powered, hydrogen generation, storage, and dispensing system from a systems standpoint. A simplified flow diagram of the system is provided in Figure 1. During this assessment. the safety of the following systems, subsystems, and components were analyzed: the Photovoltaic Array; the Feedwater Treatment System; the Electrolyser System and its Ancillary Equipment; the Hydrogen Compression and Storage System; the Hydrogen Dispensing System; and the Power Conditioning and Ancillary Electrical Systems. A safety and performance review of the retrofitted fleet vehicles was previously performed by ETEC (References 7 and 8), and will not be discussed herein.

System Safety Overview

The overall safety assessment was qualitative in nature and was based upon the effectiveness of system design features implemented by the system designers to mitigate potential casualty events and on the extent to which the system designer adhered to the applicable codes and standards, as identified by ETEC (References 2 through 6). In order to perform the safety assessment, a casualty study was first performed for the CAN system. The casualty study systematically identified events which could cause components or whole subsystems to fail or be damaged. It is important to understand that the casualty study pertained to system equipment and hardware only and did not pertain to personnel safety. However, the subsequent safety assessment, utilizing the identified casualty events, assessed the impact of these events on personnel safety. From the casualty study, a casualty table was produced, which summarized the casualty events. This table listed initiating events, fault frequency classifications, potential effects, event severity without protection, event detection systems, event protection systems and protective actions, and event severity with protection. The system design and installation was also reviewed against the codes and standards identified in References 2 through 6. These codes and standards were felt by ETEC to be applicable for this project. Although the codes and standards identified were for the most part followed and applied, portions of the system initially deviated from these codes and standards.

Casualty Study

The purpose of the casualty study was to identify those events which could cause damage to facility equipment and subsystems. In performing this study, only single component failures were analyzed, while the analysis of simultaneous double component failures was not performed. The potential casualty events identified were Abnormal Temperature High, Abnormal Pressure High, Abnormal Pressure Low, Abnormal System Fluid Level Low, Abnormal System Fluid Level High, Unplanned Hydrogen Combustion, Excessive Water Vapor In Hydrogen Gas, Abnormal Water Purity Low, Unplanned Venting of Hydrogen, Excessive System Dynamic Loading, Excessive System Static Loading, and Chemical Spill.

Because the CAN system compresses, stores, and utilizes hydrogen gas at high pressure levels, one of the primary casualty concerns identified during this study was a system failure caused by

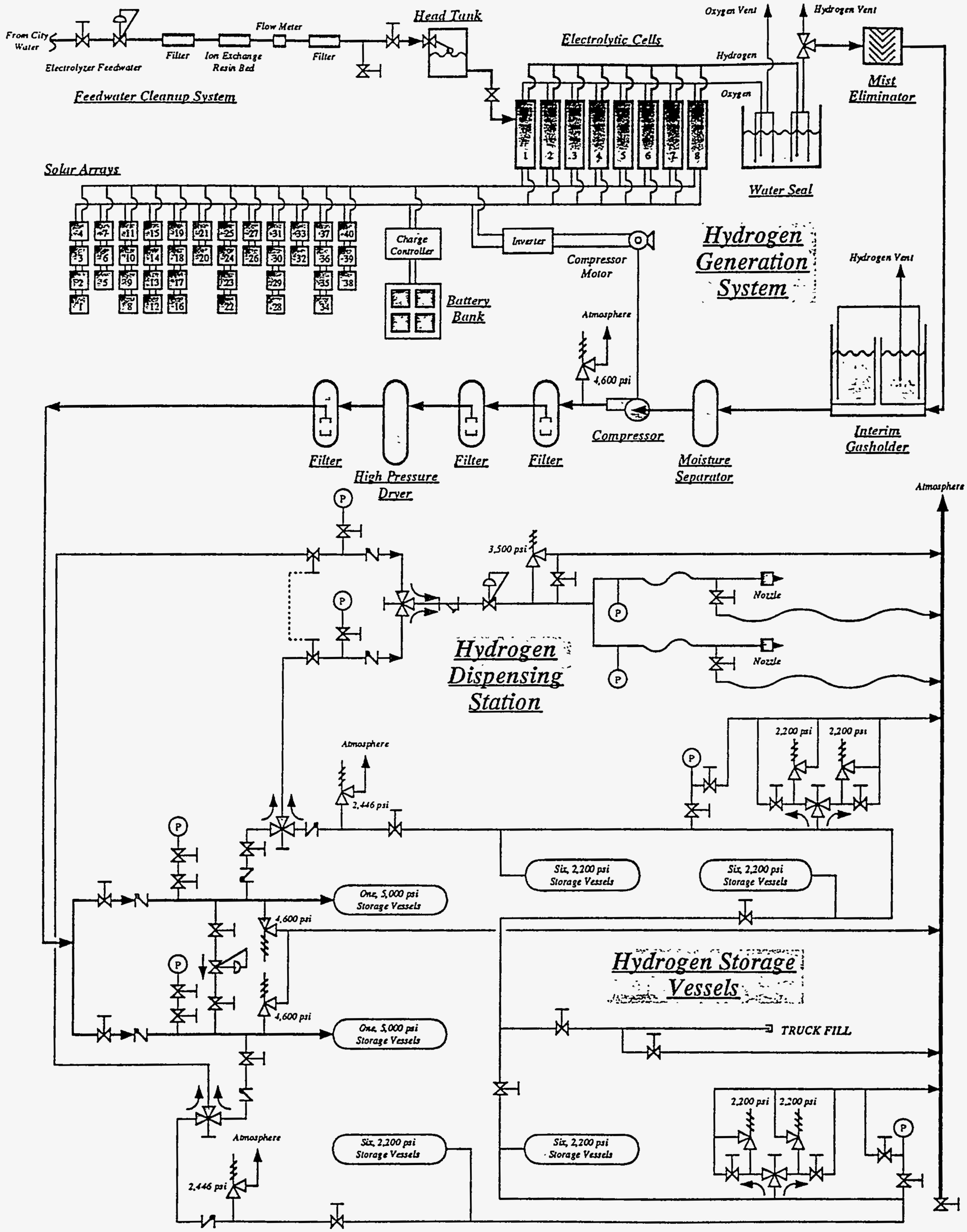

Figure 1. CAN Solar Photovoltaic Hydrogen Generation, Storage, and Dispensing System Flow Diagram

pressurizing components or subsystems beyond their rated service pressures. As a result, a table was created to show how each component in the system was protected from an over-pressure event.

Safety Assessment

The safety assessment addressed the impact on personnel due to the hazards associated with the activities conducted during the operation of the CAN solar photovoltaic powered, hydrogen generation, storage, and dispensing system. The assessment was also qualitative in nature and was based on the effects of the casualty events identified in the casualty study, and on the complete adherence of the system designer to the applicable codes and standards as identified by ETEC (References 2 through 6).

The results of the safety assessment showed that the CAN solar photovoltaic powered, hydrogen generation, storage, and dispensing system, can be safely operated by trained operators and mechanics familiar with industrial type operations. Furthermore, the hazards encountered during system operation can be categorized as being similar to those hazards routinely encountered and accepted by the general public. It was ETEC's assessment that the reviewed operations would not result in significant injury or occupational illness, nor result in a significant negative impact on the environment. It is important to note, that to maintain the present level of safety and to minimize personnel exposure to the identified hazards, CAN and the Xerox Corporation must provide adequate system maintenance, personnel training, and system operating procedures.

Findings

Of significant safety concern identified during the assessment was the identification of valves installed in systems which could be operated at pressure conditions greater than the valves rated design pressure, and the identification of electrical components in locations inappropriate for use in hydrogen service applications. For example, several valves rated for 3,000 psig service were found to be installed in a system rated for 5,000 psig service and protected by safety relief valves with set pressures of 4,740 psig. As a result of this finding, the 3,000 psig valves were either removed from the system entirely, or were removed and replaced with valves rated for 5,000 psig service. Subsequently, several other valves installed in this system were found to be rated for 4,600 psig service. Removal and replacement of these valves was found to be difficult since these valves were welded into the system. Therefore, instead of removing and replacing these valves with valves rated for 5,000 psig service, it was decided to simply de-rate the system design pressure from 5,000 psig to 4,600 psig. This action required that the pressure relief set points of the appropriate safety relief valves be reset for a maximum relief setting of 4,600 psig. As a result of the lowering of the safety relief valve set points to 4,600 psig, the hydrogen storage system was limited in operation to a maximum pressure of 4,200 psig, instead of the originally planned 5,000 psig. Operation at 4,200 psig precludes premature relief valve operation and leakage.

On the electrical side, the electrical code (Reference 6) and the hydrogen code (Reference 4) both classify the electrolytic cell skid area to be a Class I, Division 2, Group B location, i.e., a hazardous location based on the potential existence of hydrogen. As such, the referenced codes require that all electrical devices and components installed and operated in this location be rated for operation in a Class I, Division 2, Group B location. However, during ETEC's review of the system, several electrical components (including electrical conduit and bus bars) were determined to be inappropriate for use in a Class I, Division 2, Group B location. Subsequently however, all electrical deficiencies were reworked to comply with the required codes.

Another important issue identified during this assessment was the fact that the Electrolyser Corporation, by choice, did not use the Reference 5 design code for their portion of the system design. The Reference 5 design code is the code for designing and building compressed natural gas fueling stations. ETEC recognizes that the Reference 5 design code pertains to natural gas systems only. However, since no equivalent code exists for hydrogen use, ETEC believes that the adoption of this code for hydrogen systems, where applicable, is logical and appropriate until a specific code for hydrogen systems has been generated. The Reference 5 design code requires strict adherence to the design codes of References 2, 3, and 6, but then adds additional design requirements to them, ultimately raising the level of component and system safety for use by the general public. The fact that the Reference 5 design code was not used by the Electrolyser Corporation does not imply that the existing CAN fueling system is unsafe, nor does it imply that the Electrolyser Corporation made a mistake. The codes and standards used by the Electrolyser Corporation are adequate and are recommended and accepted for industrial type applications, however, the CAN system should not be treated as a system which would be used in and by the general public. As a result, ETEC recommended to CAN that future CAN hydrogen generation, storage, and dispensing systems, where general public access is planned, be designed and built using the Reference 5 design code, where applicable, until an equivalent hydrogen code is available.

Conclusions and Recommendations

ETEC's safety assessment of the CAN solar photovoltaic powered, hydrogen generation, storage, and dispensing system showed that the CAN system can be operated safely. Although safety issues and code deviations were identified during ETEC's initial review, adequate modifications to the system were made such that the system complied and conformed with the applicable codes and standards. More importantly, after reviewing ETEC's safety assessment and the modified CAN facility, permitting officials from the City of El Segundo granted the CAN facility an operating permit. Although ETEC's safety assessment shows that the CAN system can be operated safely, to maintain system safety and to minimize personnel exposure to the identified hazards, CAN and the Xerox Corporation must provide adequate system maintenance, personnel training, and system operating procedures. The assessment also showed that no "new" hazards were identified. That is, the identified hazards were found to be equivalent to other commonly encountered and accepted public and industrial type hazards. Furthermore, the safety assessment showed that codes, standards, and safety practices, which can be applied to hydrogen facilities, exist to the extent that these facilities can be built, permitted, and safely operated. For this to occur, however, systematic safety assessments and post-construction safety reviews must be performed.

Several lessons learned, which are applicable to other hydrogen demonstration projects, were also identified as a result of this safety assessment. The first lesson learned deals with the time in which a system safety assessment should be performed for a given project. Specifically, to prevent construction delays and post-construction system modifications, the system safety assessment should be performed prior to the initiation of all construction activities. Secondly, to preclude start-up delays, and in order to educate city officials, appropriate permit, regulatory, and safety personnel should be identified and briefed early in the execution of a project. It should also be noted that the appropriate personnel are site specific, and can be different from project to project. Thirdly, construction oversight is critical to ensure that the system that was designed and safety reviewed, is the same system being built. In the case of the CAN system, the lack of adequate construction oversight resulted in the de-rating of the pressurized storage and delivery system. Finally, post-construction safety reviews and operational readiness reviews are also critical. These actions will identify any problems missed during construction oversight activities. Additionally, safety must be approached and assessed with a systems point of view and not from a simple component point of view. That is, the safety of a system must be assessed with the knowledge of how the system functions and how the system can fail.

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RECENT PROGRESS IN THE PALM DESERT PROJECT

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RECENT PROGRESS IN THE PALM DESERT PROJECT

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RECENT PROGRESS IN THE PALM DESERT PROJECT

Topics

- Overview of the Palm Desert Renewable Hydrogen Transportation Project
- Design and production of the first fuel cell powered personal utility vehicle (PUV)
- Performance of the first PUV
- Testing of the first neighborhood electric vehicle (NEV)
- Progress in design and siting of the hydrogen refueling station
- Future plans

Schatz Energy Research Center Humboldt State University Arcata, CA 95521

RECENT PROGRESS
IN THE PALM DESERT PROJECT

Palm Desert Project Goal

To develop a clean and sustainable transportation system for a community and demonstrate the practical utility of hydrogen as a transportation fuel and PEM fuel cells as vehicle power plants.

Schatz Energy Research Center Humboldt State University Arcata, CA 95521

RECENT PROGRESS
IN THE PALM DESERT PROJECT

Palm Desert Project Objectives

- Design and construct 3 PUVs and 2 NEVs and deliver them to the City of Palm Desert. These fuel cell powered vehicles will be driven around the City for normal day-to-day activities and their performance will be recorded and evaluated.

- Design and construct a solar hydrogen refueling station in the City. The facility will use photovoltaic electrolysis to produce the hydrogen which will be compressed and stored. Fuel dispensing to the vehicles will occur at a refueling island and be convenient and safe.

- Equip a fuel cell vehicle maintenance facility at the City's corporation yard. This facility will have diagnostic capability; personnel will be trained to maintain and service the vehicles.

RECENT PROGRESS
IN THE PALM DESERT PROJECT

Fuel Cell Design Criteria and Resultant Technologies

Design Criterion	Resultant Technology
Sufficient voltage for the cart's traction bus	64 cell stack
Sufficient power for hill climbing	300 sq cm active area
Low parasitic load	Low pressure operation Use of high efficiency blower Parasitic load ≈ 5-10%
Sufficient cooling capacity	Water cooling with large heat exchange area
Efficient operation	0.71 volts/cell @ cruising 57% stack efficiency (LHV)

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RECENT PROGRESS
IN THE PALM DESERT PROJECT

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RECENT PROGRESS
IN THE PALM DESERT PROJECT

Cart Construction Process

1. The original, battery powered cart was instrumented and tested.

2. Individual subsystems were designed and tested. This included the cooling, gas storage and delivery, air delivery, and electrical systems, the on-board computer hardware and software, and the fuel cell.

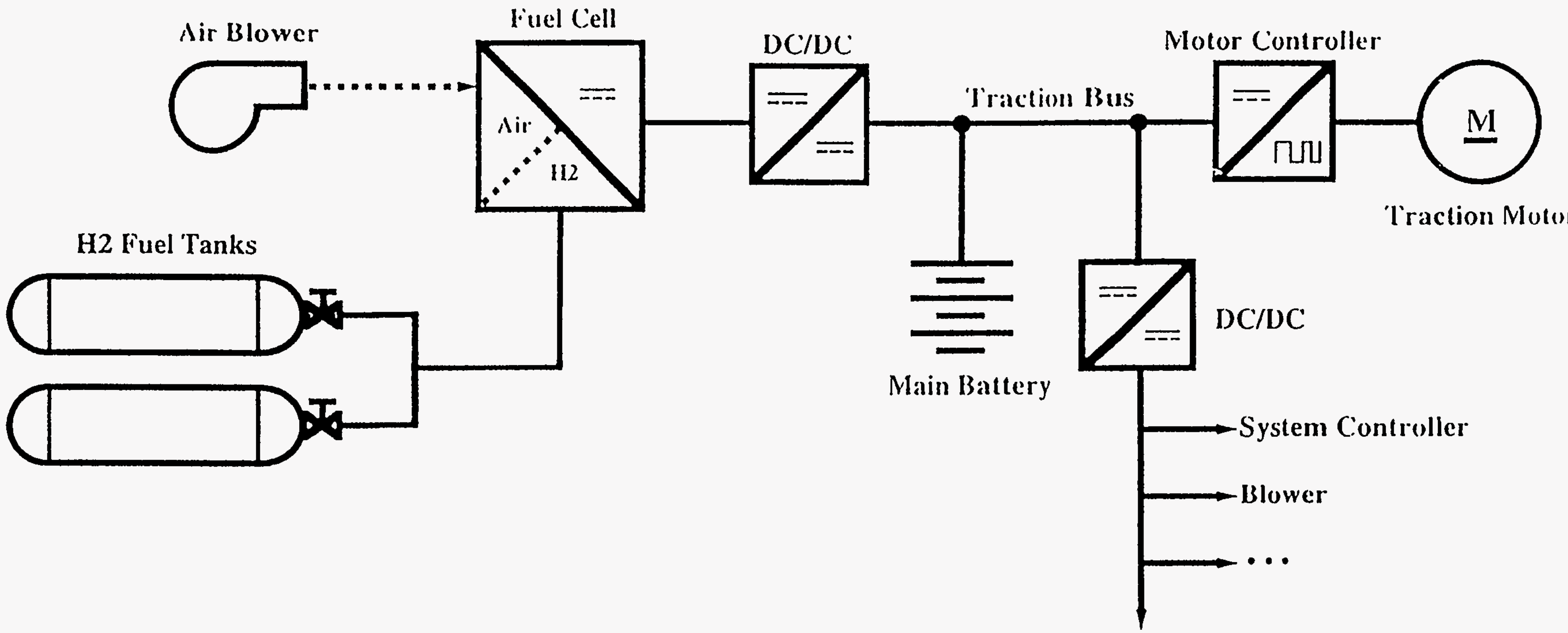
3. All components were assembled on a prototype test bench fitted with a programmable load to mimic driving cycles. Numerous tests were performed to optimize the operational algorithm and wring out bugs.

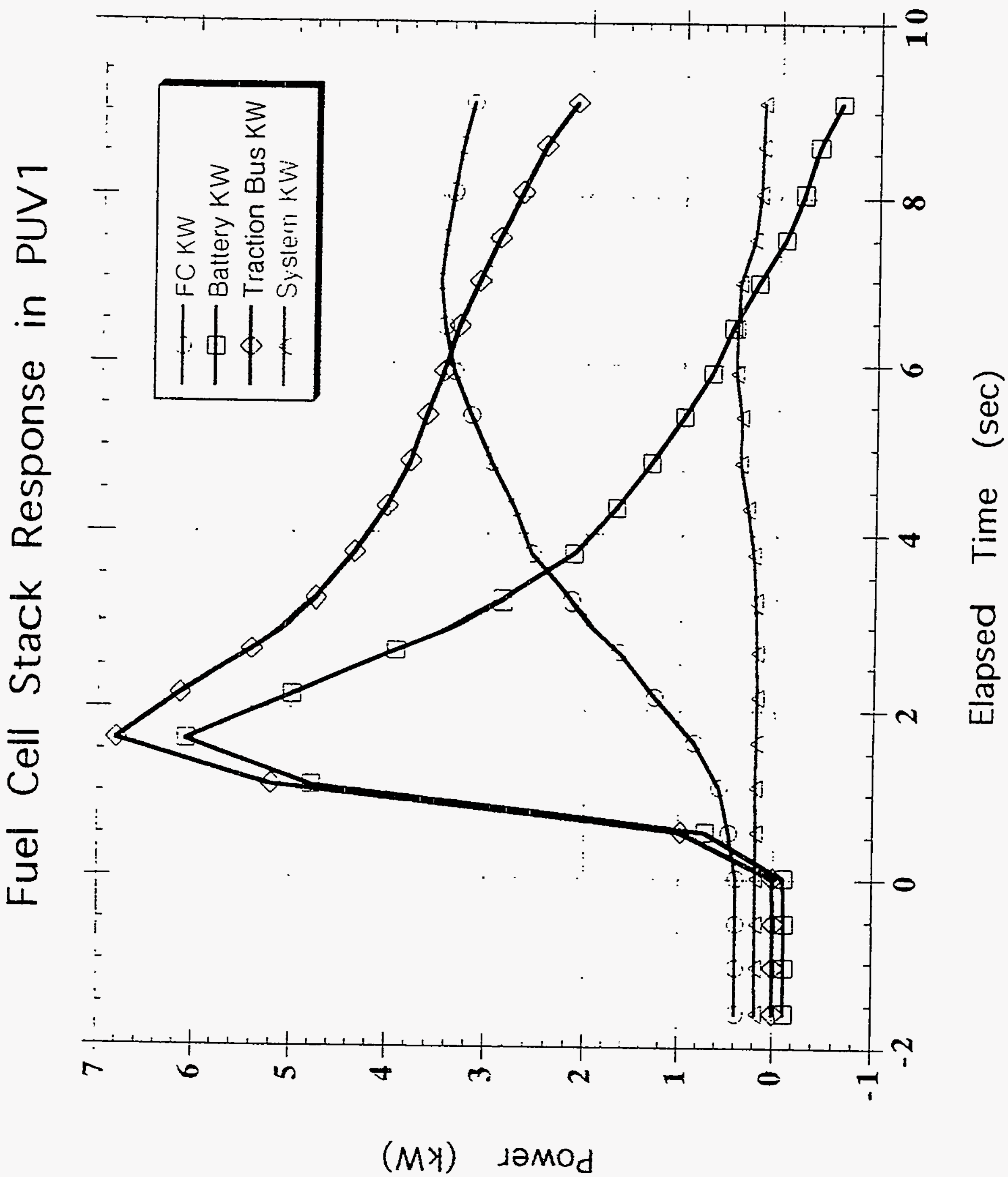
4. The cart was gutted, structural changes were made, and a custom, fiberglass cover was crafted to cover the gas storage area. The fuel cell and other subsystems were installed; the fit was tight.

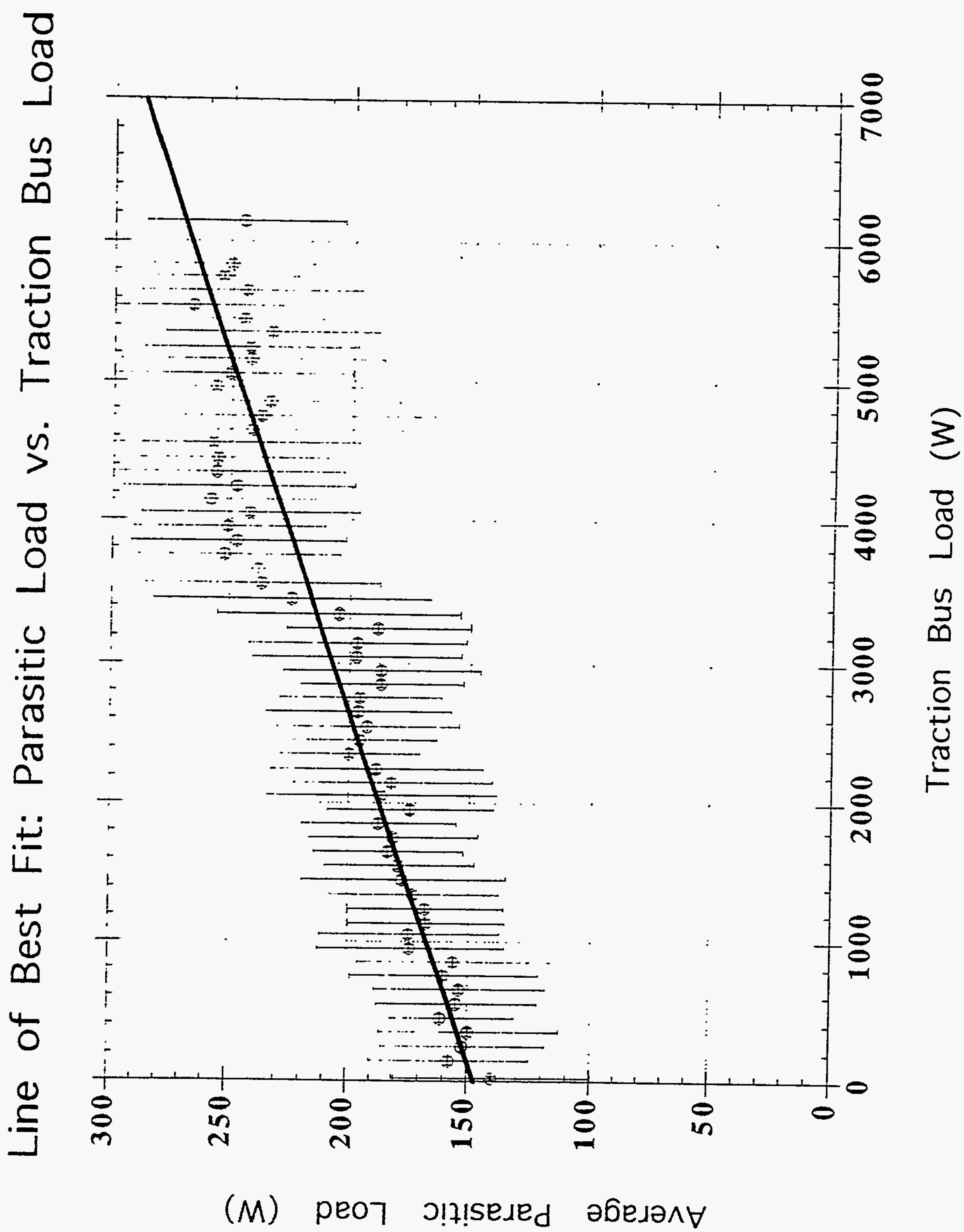
5. The on-board computer and transducers were installed, wired, and debugged.

6. The cart was road tested and final adjustments were made.

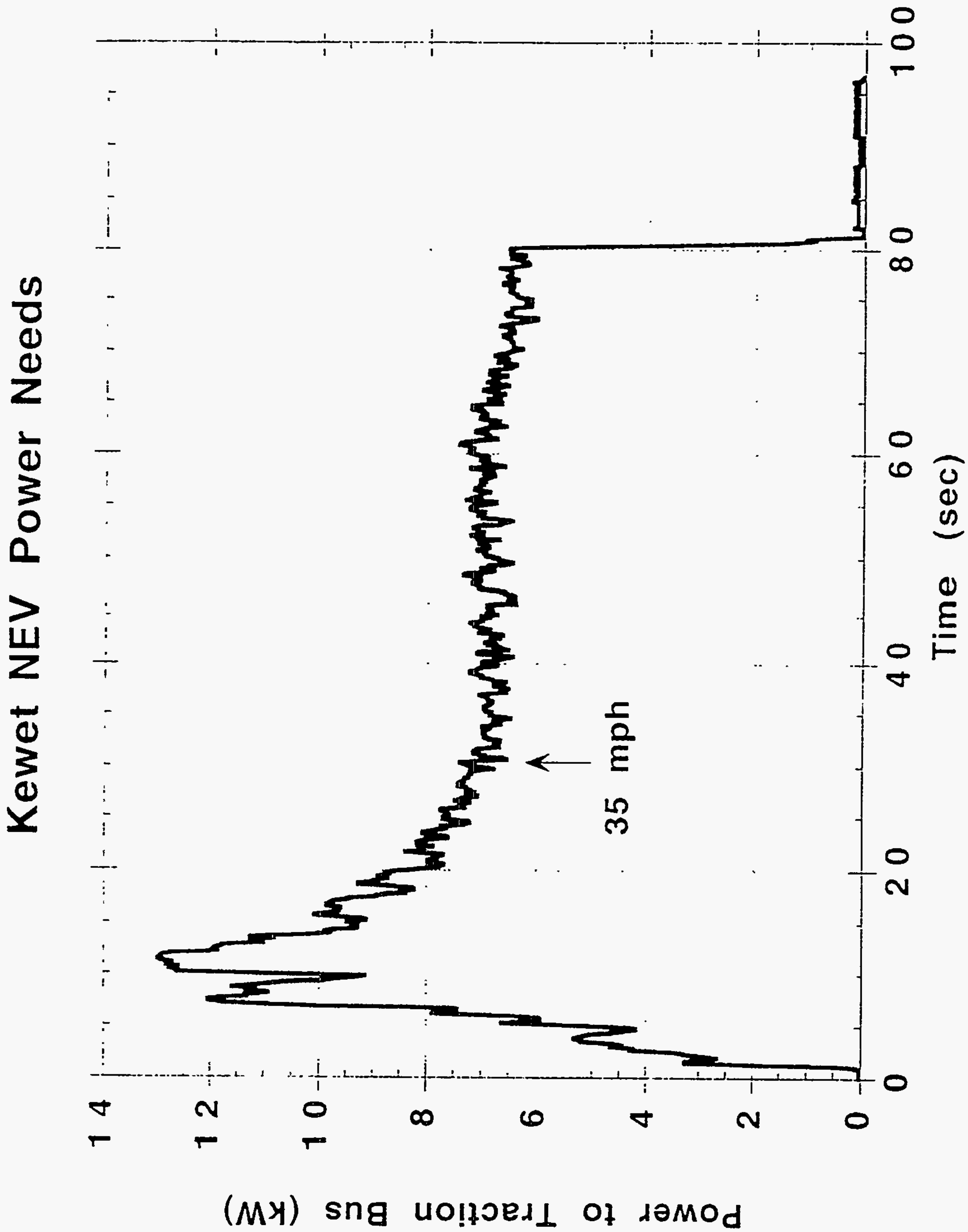
Figure 1. Schematic of Prototype SERC PUV



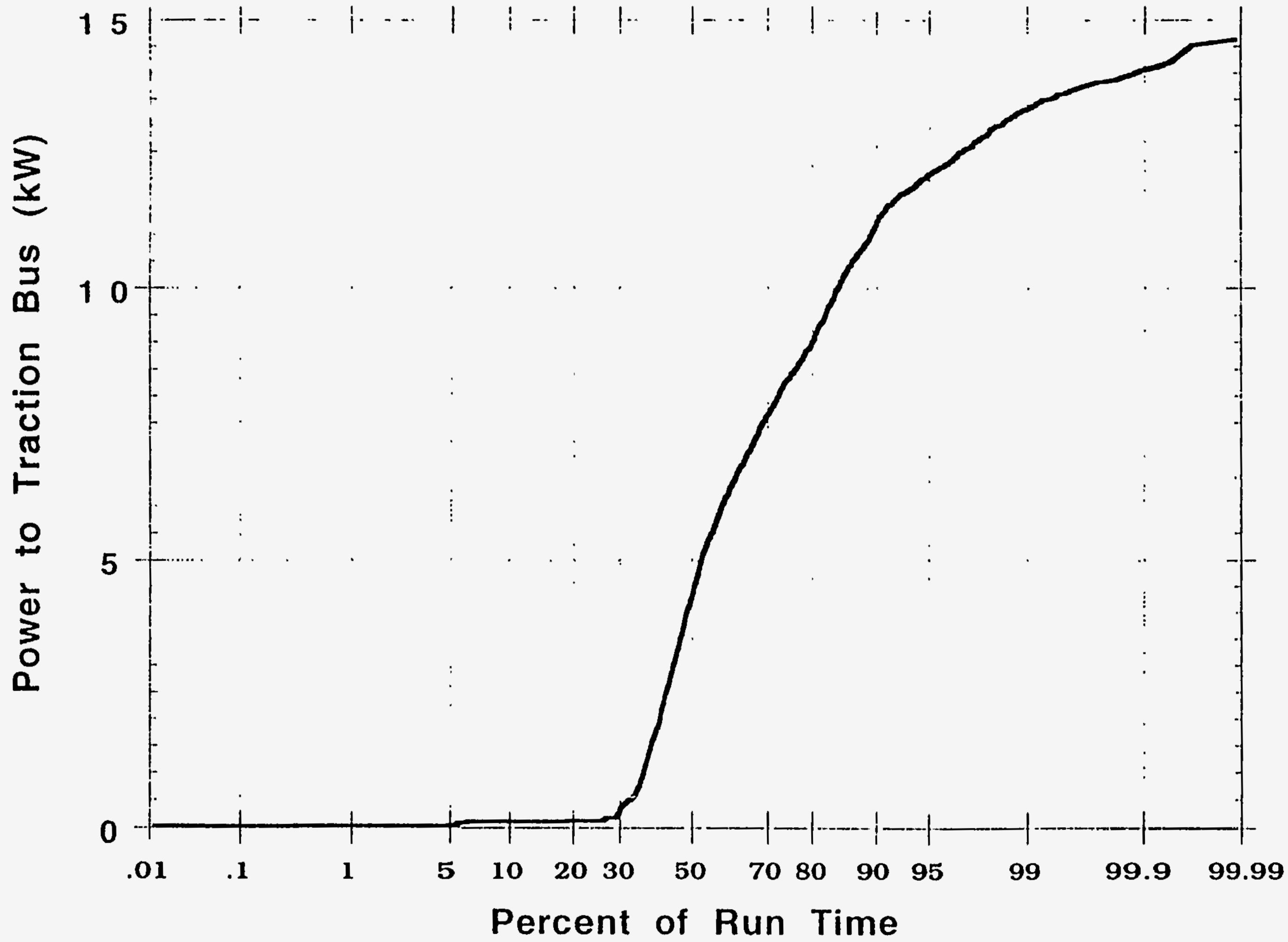

Fuel Cell Stack Response in PUV1
FC KW
Battery KW
Traction Bus KW
System KW
Power (kW)
Elapsed Time (sec)
-2
0
2
4
6
8
10
-1
0
1
2
3
4
5
6
7



Line of Best Fit: Parasitic Load vs. Traction Bus Load
Average Parasitic Load (W)
Traction Bus Load (W)
0
50
100
150
200
250
300
1000
2000
3000
4000
5000
6000
7000


Kewet NEV Power Needs
Power to Traction Bus (kW)
Time (sec)
35 mph
0
2
4
6
8
10
12
14
0
20
40
60
80
100

Cumulative Distribution of Power Demand in Kewet NEV
Stop & Go City Driving



RECENT PROGRESS
IN THE PALM DESERT PROJECT

Solar Hydrogen Refueling Station

- Preliminary design of the refueling station has been completed. The system is sized to provide refueling for each vehicle every other day.

- A hazards analysis of the facility has been completed. The analysis identifies potential hazards and includes our response to mitigating those hazards. It will serve as a safety guide during installation.

- Siting the refueling station has been an adventure. Our preliminary site on City park land was not approved by the City Council. We them turned our attention to a site on the campus of the College of the Desert. This site was recently approved by the Trustees of the college.

- The plans must now go to the Office of the State Architect for approval. Once approved, the construction job will go out to bid. We plan to break ground in mid-summer.

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USING HYDROGEN TECHNOLOGY
CODES AND STANDARDS, SAFETY, AND COMMON PRACTICE

CITY OF PALM DESERT
ADMINISTRATIVE CONFERENCE ROOM
73-510 FRED WARING DRIVE, PALM DESERT
NOVEMBER 13, 1996
9:30 AM - 1:00 PM

- THE PALM DESERT RENEWABLE HYDROGEN TRANSPORTATION SYSTEM
  Dr. Peter Lehman, Director, Schatz Energy Research Center

  An overview of the current project being conducted in Palm Desert including the technologies to be introduced, previous experiences in their use, and how the project addresses attempts to clean up the air and provide economic development opportunities for the region.

- EXPERIENCE IN THE USE OF ELECTROLYTIC HYDROGEN GENERATORS
  Charles Wolf, Program Manager, Teledyne-Brown Engineering, Energy Systems

  An review of codes and standards as they apply to hydrogen generators and peripheral equipment and an account of experience using the electrolytic hydrogen generators that will be employed in Palm Desert.

- SAFETY ENGINEERING THE PALM DESERT PROJECT
  Charles Hoes, CEO and Principal Engineer, Hoes Engineering

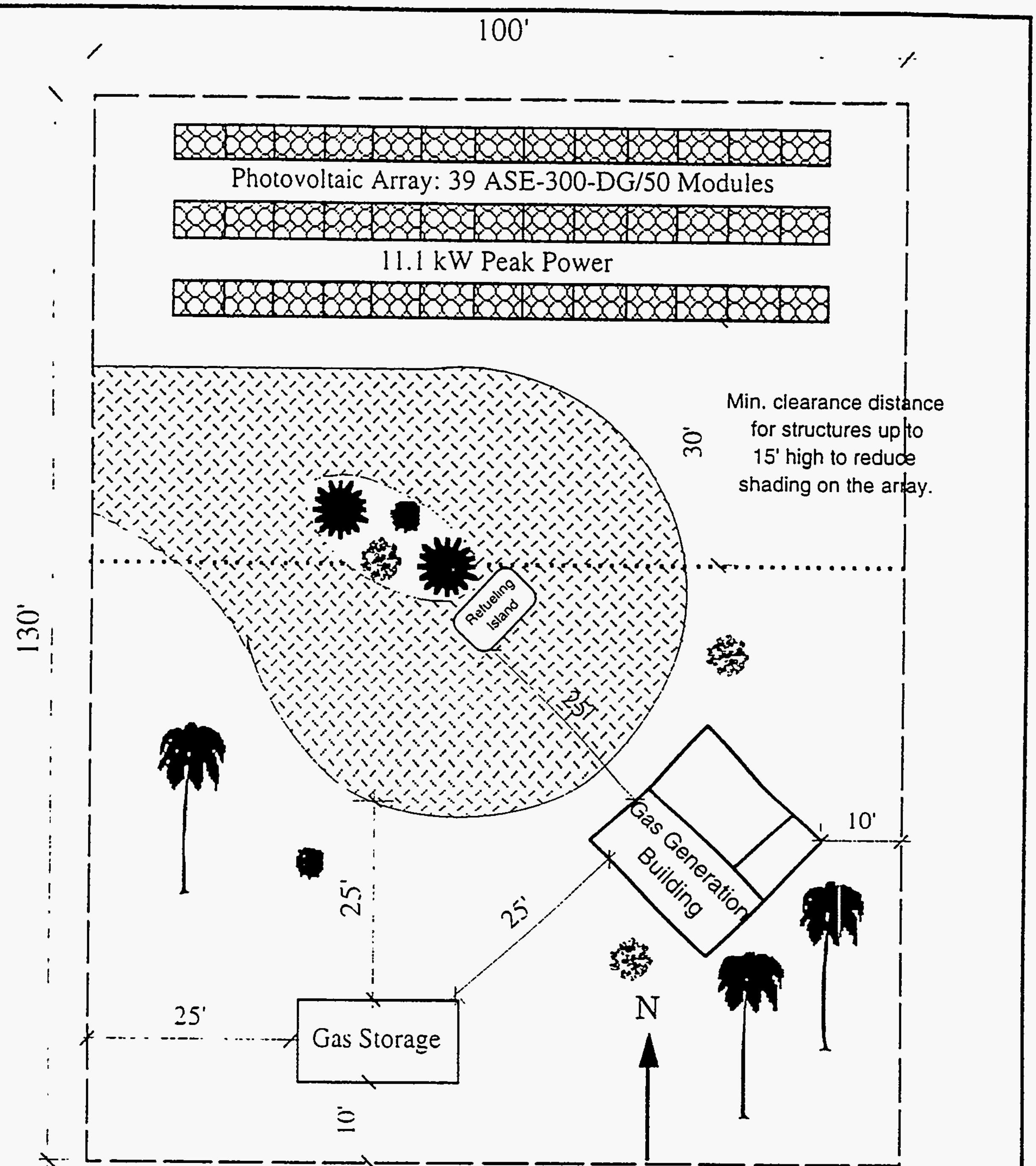
  A description of the safety engineering process employed in the Palm Desert project including the development of a hazards analysis for various technology systems t be implemented and the responses to that analysis.

- PERMITTING THE CLEAN AIR NOW SOLAR HYDROGEN GENERATING AND REFUELING STATION
  Kevin Knudsen, Associate Program Manager, Energy Technology Engineering Center

  An account of the permitting process for the solar hydrogen generating station now being operated by the Xerox Corporation and Clean Air Now. This system, similar to the system envisioned for Palm Desert, has recently been approved in El Segundo, CA.

- EXPERIENCE WITH UC RIVERSIDE'S SOLAR HYDROGEN GENERATING AND REFUELING STATION
  James Heffel, Sr. Project Engineer, Center for Environmental Research & Technology

  A description of the solar hydrogen generating and refueling station that has operated at UC Riverside for the past 5 years, including safety systems in place for the generator and refueling equipment, and an account of operating experience.



Solar Hydrogen Refueling Station
City of Palm Desert, Ca

Scale: 1" = 20'	Schatz Energy Research Center Humboldt State University	Date: 3/7/97

RECENT PROGRESS IN THE PALM DESERT PROJECT

Future Plans

In the next year, we plan to:

- complete PUVs #2 and #3 and deliver them to the City. They will be equipped with pick-up beds so they can be used by maintenance workers and gardeners.
- site and install the refueling station.
- design, construct, and deliver the first fuel cell powered NEV.
- begin designing the maintenance facility and training program.

Schatz Energy Research Center Humboldt State University Arcata, CA 95521

THE HINDENBURG DISASTER

A Compelling Theory of Probable Cause and Effect

by
Addison Bain

NOTE: The author wishes to acknowledge the support of **PRAXAIR, INC** and the **NASA** Materials Science Laboratories in the development of this study.

The study examines the disaster of the airship Hindenburg, which occurred at Lakehurst, New Jersey, on May 6, 1937. With a background of years of association with hydrogen utilization in aerospace activities and the accumulation of an extensive library on airships, the author provides an in-depth investigation into the circumstances surrounding the disaster.

For nearly 60 years, the prevailing hypothesis has been that the Hindenburg's hydrogen gas used for buoyancy was the basic design flaw. Two separate boards of inquiry each rationalized the premise of two sets of conditions to justify the cause, namely the presence of free hydrogen and the subsequent presence of an ignition source. The investigation process in each case proceeded down the path of rationalizing the most credible reason for free hydrogen to materialize and then to rationalize the most credible source of ignition. Although the airship wreckage was examined, nothing was found to conclusively support any other rationalization. Some experimental testing was done (gas cell conductivity) but nothing conclusive was reported at the time. Eyewitness accounts and photographic coverage constituted the principal evidence for the investigation.

The question this research effort is intended to address is based on the author's examination of the original film footage and other documentary evidence in an attempt to explain certain conspicuous observations as follows:

1. The Hindenburg did not explode, but burned very rapidly in omni-directional patterns.
2. The 240-ton airship maintained trim many seconds after the fire initiated.
3. Falling pieces of fabric were aflame and not self-extinguishing.
4. The inferno colorization is characteristic of a forest fire not a hydrogen fire as experienced by the author.

Numerous theories were postulated by outside sources as well as the American and German investigative teams. These were all categorized and reviewed. In the final reports, the Hindenburg envelope was never mentioned as being suspect. In a newspaper account at the time and then, later as an article in a magazine, a Ralph Upson, inventor of the metalclad airship, did question the use of fabrics for airships in hydrogen service. A professor Max Dieckmann later conducted fabric test comparisons but this was oriented toward electrostatic conductivity.

The purpose of the study is threefold. First, it is intended that a more compelling theory can be established that would in fact exonerate hydrogen as the causing factor Thus, secondly, since the dramatic image of the disaster is etched in the public consciousness, these negative images must be replaced by positive images of hydrogen as a clean, safe energy carrier to smooth the introduction of hydrogen energy technologies into the marketplace. And, finally, to conclude that the Hindenburg disaster was a result of the frailty of human engineering not unlike the Titanic, Space Shuttle Challenger and similar disasters.

The initial approach to the study (1990) was to conduct an exhaustive review of the literature and make contacts with airship experts and airship historians. The focus was on airship materials as the author was suspicious of the fabric covering having learned that a cellulose nitrate dope with powdered aluminum was perhaps used on the Hindenburg. During the fall of 1995 and throughout 1996, a number of unexpected events occurred which dramatically revealed sources of significant information and complemented the course of the study. Fabric samples were provided from an individual stationed at Lakehurst, fabric samples were provided by collectors (or purchased from them), interviews were conducted with survivors and eyewitnesses. The NASA Materials Science Laboratories at the Kennedy Space Center provide analytical services. The pinnacle of the study occurs when the author is provided the unprecedented opportunity (for an American) to examine files at the Zeppelin Archive in Friedrichshafen, Germany. The Zeppelin works and new museum were visited.

The NASA lab testing included chemical and physical analysis using the scanning electron microscope, X-ray energy dispersive spectroscopy, optical microscopy, infrared spectroscopy, and tests on flammability, electrostatics, conductivity, surface and volume resistivity, thermogravimetric analysis and corona discharge exposure. The focus was on the characteristics of the airship fabric. Comparisons were made with other airship fabrics. The more significant findings indicated; the Hindenburg fabric was made up of a cotton substrate with an aluminized cellulose acetate butyrate dopant, the fabric exibited very high resistivity, was flammable, and would ignite when subjected to an electrical arc.

The overall study identifies two important aspects. The prevailing atmospheric conditions and the unorthodox method of landing at Lakehurst could prompt severe corona activity on the airship. This factor is consistent with the original conclusion concerning the ignition source but is further embraced by modern experts of static electricity and experiences of airline pilots. The fabric envelope of the airship was not only very flammable but also so were many materials used in the makeup of the envelope. Evidence that further supports the conclusion include examination of the design of LZ-130 (Hindenburg sister ship). This research reveals numerous modifications (after the disaster) to counteract static buildup and reduce the flammability of the airship hull. Unpublished German tests, uncovered by the research, substantiates the flammability of the Hindenburg envelope when subjected to electrostatic discharge.

The author arrives at the following conclusion:

- Atmospheric and airship conditions at Lakehurst were conducive to formation of a significant electrostatic activity on the airship
- The Hindenburg envelope design was incompatible with the environment encountered at Lakehurst at the time of the incident
- The envelope fabric and doping process employed on the Hindenburg was sensitive to arc ignition and very susceptible to promoting flame propagation
- The premise of free hydrogen within the airship hull is not necessary to justify the cause of fire initiation
- Hydrogen, as well as airship materials of construction contributed to the resulting conflagration

Hydrogen Safety
Fire and Gas Detection Systems
Presented at the 1997 NHA Annual Meeting
by Heidi L. Barnes from NASA Stennis Space Center

Introduction

I am delighted to have the opportunity to talk about hydrogen safety, specifically hydrogen fire and gas detection. If hydrogen is leaking, it is either on fire or a gas leak and the types of detection technologies are very different for the two situations. When I was asked to speak at the National Hydrogen Association's Annual meeting, I did what every well trained government employee does and I started assembling a huge binder full of technical view-graphs on hydrogen fire and gas detection.....Then I learned that I would be giving the dessert presentation and that I would be lucky to get one view-graph up before heads would start to nod.... So I threw out the huge binder of view-graphs and instead put on my blue flame-proof Nomex jumpsuit and brought a whole bunch of neat pictures from NASA's John C. Stennis Space Center (SSC) in Southern Mississippi dealing with hydrogen fire and gas detection.

Now if you haven't heard of Stennis Space Center, just talk to some of the leading hydrogen manufacturers in the country Praxair or Air Products because they know us very well. Stennis is the largest consumer of liquid hydrogen in the country if not the world. Over 1 million gallons of liquid hydrogen is consumed every month in the testing of rocket propulsion systems. Every space shuttle main engine (SSME) is tested and flight certified at John C. Stennis Space Center before it flies on the Space Shuttle, and that brings us to Picture #1, that of the Space Shuttle Main Engine firing. The space shuttle main engine burns liquid hydrogen and liquid oxygen.

Hydrogen Fires

When I first started work at SSC I knew that hydrogen gas is quite flammable, it takes very little energy to light it at ambient temperature in air. But what I did not fully grasp was how invisible a hydrogen flame is. Hydrogen burns with oxygen like that in air to produce water H_2O, and just like a glass of water one can see right through a hydrogen flame during the brightness of the daytime. We have had 100 foot hydrogen flames on the flare stacks at SSC and they did not even appear to be lit. Like the one in seen in Picture #2, showing the B-1 test stand firing an SSME in the background.. A good example of this invisible phenomenon is the stars. No one hits a light switch and turns the stars off during the daytime, the stars are burning with the same light intensity that they do at night it is just that during the daytime the sunlight is much brighter. A hydrogen flame is the same way, it cannot be seen in the brightness of the daytime, however at night it does emit enough light to be seen. So if it is convenient, all one needs to do is wait till it gets dark and then they can locate a hydrogen fire. For instance Picture #3 shows a flare stack at night at one of SSC's smaller test facilities. The hydrogen flare in this picture is close to 150 feet high above the 75 foot flare stack.

Broom Fire Detection

About 6 years ago at SSC we had some personnel doing some routine repairs on one of the large hydrogen barges that transports liquid hydrogen to the rocket engine test stands, when they heard a loud pop, the sound of a hydrogen flame igniting. The operations personnel immediately vacated the area and called the fire department, who came racing out with their fire detection system. The fire detection system that they used is mentioned in the National Fire Protection Associations Fire Protection Handbook and was used quite often by NASA during the Apollo program and that elaborate system is the corn straw broom. Yes, a corn stray broom! The same kind that you use to sweep your house. Now the principle seems simple, extend the broom into the suspect area, and hope that it catches fire before you do.

Last summer we invited the local community fire fighters to SSC to try the latest in hydrogen fire imaging and detection technology, and we made them also try the corn-straw broom method as you can see in Picture #4. These fire fighters quickly learned three very important characteristics of hydrogen fires. First when approaching the hydrogen fire, we told them not to worry it was only an eight inch flame, however, as they got close they realized that this small eight inch flame had a four or five foot heat wave, vapor trail, and the broom handle seemed mighty short. In fact instead of holding the broom comfortably, they were now stretching it out as far as possible and edging towards the flame.....

Then they got their second lesson in hydrogen flames, hydrogen is very light or buoyant in air and the same is true for the hot by-products of combustion. This means that if there is any wind, the flame will follow the path of the wind. The flare stack that you saw earlier in Picture #3, is over 100 feet high and I actually saw it lay over horizontal on a windy day. Now back to our broom operator, he new exactly where the flame was supposed to be and yet when he finally got there and started waving the broom over the top of the post, the broom would not light. The wind was blowing the flame sideways, and he had to rotate the broom to the side in order to ignite it.

Now that brings us to our final lesson in hydrogen fires, they do not radiate heat that well, there is no carbon or soot in the flame. I have gone up to this small 8 inch flame at night and put my hand right next to the flame and it is not that warm. So unless you are in the direct path of a small flame, it is often difficult to even feel the heat from it.

Hand-held Fire Imager

Now when we had to use this broom fire detection technology 6 years ago at SSC, it was put in the weekly reports and went rippling up through the management structure, and quite a few people started realizing that this technology was out of date, with all the advances being made in optical imaging systems there had to be a better way, and sure enough our friends at Kennedy Space Center (KSC) had discovered that thermal imaging systems worked quite well and they had been using them on the launch pads at KSC. There was only one problem, KSC had paid anywhere from $30,000 to $75,000 for their systems and the cost of buying, training personnel, and maintaining such systems for every operation at SSC that used hydrogen was going to be exorbitant. The problem was simple we needed a hydrogen fire imaging technology that could replace the broom in emergency situations, and cost significantly less then a $30,000 thermal imaging system.

Through research and development funding from NASA Headquarter's Office of Safety, Quality and Mission Assurance, Dr. Fred Gregory, Stennis Space Center developed the Hand-held Fire Imager, which is now commercially available under the name of "FireSCAPE". This technology allows the user stand back at a safe distance from the hydrogen flame, 50 feet for the small 8 inch flame, 1000's of feet from a large flame and see a black and white image of the scene with the hydrogen flame appearing as a bright white wavering image. The technology is simple to use in emergency situations; an on/off switch, and a switch for sunny or cloudy conditions.

The Hand-held Fire Imager technology has been in operation for over a year now with the SSC Fire Department. The first real test of this new technology happened a year ago in February, one cold morning there was a loud explosion heard across the test sight. Then the sounds of sirens could be heard as the fire trucks went racing out to the B-1 Rocket engine test stand (Picture #5), and our biggest advocate of this new technology, SSC Fire Chief James C. Webber, set up his command post, got on the walkie-talkie (Picture #6) and had two of his men move in with the Hand-held Fire Imager (Picture #7). They immediately started reporting the exact location (on the vent line going to the flare stack) , size (8 feet) , and how the wind was bouncing it around. They were also able to quickly determine when the flame was extinguished and scan the rest of the area to insure that no other flames existed.

One of the biggest uses for this new fire imager technology at SSC is in the confirmation that a hydrogen flame does not exist.

Hydrogen Facility Camera

At the same time that the handheld fire imager was being developed, we would often get requests for a facility surveillance camera that could see hydrogen flames. Now the facility monitoring camera is a tougher problem, if you have ever looked into the cost of installing cameras with pan, tilt, zoom, and housing for Class 1, Div. II, Group B hydrogen environments with cabling to take the signals back to a distant control room or a fire station, you will quickly realize that the camera can be the least expensive item. This means that you do not want to have to install special hydrogen fire imaging cameras in addition to the regular facility surveillance cameras. Ideally, one would like to have a normal color surveillance camera that if there is a hydrogen fire, it colors it in red and makes it obvious to the viewer. Through a Small Business Innovative Research Award, the company Duncan Technologies has developed the Hydrogen Safety Camera (Picture 8) to do just that. It is designed to be a plug in replacement to existing facility cameras with regular NTSC video output, and yet it colors the hydrogen flames in red if they are present. I hesitate to show you a view-graph of the images because I have had people say it looks like someone cheated and just used a red crayon after the fact, so please stop by the NASA booth where you can see it in operation.

Optical Hydrogen Fire Detection

I should also touch briefly on non-imaging fire detectors. A facility needs some method of continuous fire detection monitoring to set off an alarm or turn on a water deluge if a fire is present. In the past this has been done with heat sensors or heat sensitive wire that is simple and reliable to use, however, optical fire detectors are becoming quite popular in other industries because they are fast acting and cover a larger area with just one sensor. Be careful when purchasing these systems, many of the commercially available optical fire detectors are designed to detect the radiation from a hydrocarbon infra-red emission at 4.3 microns and will not work on hydrogen fires. A better choice for hydrogen fires is the UV emissions or the infra-red 2.7 micron hot water band emission. The UV detectors are used at KSC and SSC but it was quickly discovered that a reflection from a large flare stack or an engine test can easily set off UV detector and cause a false alarm.

Kennedy Space Center they has developed a new optical hydrogen fire detector (Picture 9) that is specifically designed for hydrogen fires and uses special algorithms that compare the UV and IR signals along with flicker frequencies to prevent false alarms from flare stacks and rocket engines. This technology is currently being evaluated at the launch pad at KSC and is available for commercialization.

Hydrogen Gas Detection

Now I have spent a significant amount of time on fire detection, but as I mentioned previously, if you have a hydrogen leak it is either on fire or it is not on fire, and if it is not on fire then you have a gas leak and the previously mentioned fire detection technologies are completely useless when it comes to gas detection. Hydrogen gas detection is very important at Stennis Space Center and it is often called our primary leak detect system since a leak is most likely to start off as a gas leak and may never be ignited into a flame. The fire detect system is then used as a secondary or back-up leak detection system.

The most common hydrogen gas sensor available today, was developed by NASA's Apollo program back in the 60's and uses the catalytic metal bead technology. Catalytic meaning that a palladium or platinum metal is used as a catalyst to facilitate the reaction between hydrogen and oxygen, and then a sensor is used to detect the heat from that combustion. This technology has been refined for reliable operation. however, there is one significant drawback, it requires oxygen to operate. Think about it, if you put 100% hydrogen on a catalytic hydrogen sensor, it will not detect any hydrogen! This is a big problem for NASA, since they would like to monitor nitrogen and helium purged compartments, measure the inertness of purged hydrogen lines, and have sensors that work in the vacuum of space.

Other systems exist for hydrogen gas detection, such as electrolytic sensors, thermal conductivity sensors, and mass spectrometers, but they all have there drawbacks not to mention cost. The electrolyte is consumed and dries out, thermal conductivity sensors do not work in helium backgrounds, and mass spectrometers are expensive and heavy.

Microelectronic Hydrogen Sensors

About 5 years ago, SSC noticed that the Department of Energy's Sandia National Labs was spending a significant amount of funding developing a new microelectronic hydrogen sensor technology (Picture 10) that could operate in inert environments with no oxygen present, and be mass produced using the same technology used to make computer chips.

The Sandia Sensor uses semiconductor fabrication technology that allows them to build in large square heaters for faster sensor response, and to fabricate multiple sensors for wide dynamic range. A transistor with a special PdNi coating that absorbs hydrogen can detect hydrogen in the ppm level and a PdNi resistor allows detection all the way to 100%. The importance of microelectronic hydrogen sensor technology was also recognized by my colleagues at NASA Lewis Research Center where they have been funding research at Case Western Reserve University on a similar micro-electronic hydrogen gas sensor that stems from the same basic research started by Bob Hughes at Sandia Labs.

Bagged Leak Detection

The first application that we have tried these sensors on at SSC is in bagged leak detection. The next generation liquid hydrogen tanks for reusable launch vehicles are being made out of light weight composite materials and are typically shaped to fit inside of an aerodynamic vehicle. The test requirements for these new liquid hydrogen tanks required leak detection that did not just say that a leak was present, but rather quantify the leak rate in terms of cubic centimeters per second. So at Stennis we came up with a bagged leak detection method similar to what is used in the boat tail of the space shuttle at KSC, and that is to enclose or bag the area of leak detection and then flow in a nitrogen or helium purge gas to collect the leak and push it out an exhaust line to a measurement system such as a mass spectrometer where the concentration of hydrogen can be measured. The concept is simple, if the mass spectrometer tells you the concentration or percentage of the flow that is hydrogen and you know the flow rate of your purge gas, then the actual flow rate or leak rate of hydrogen into the bagged enclosure can be determined.

When we first started doing bagged leak detection for the National Aerospace Plane prototype liquid hydrogen tank (Picture 11), we borrowed two mass spectrometers from KSC. Now mass spectrometer systems are expensive (they can easily exceed $100,000) and because of this require elaborate sampling systems so that one mass spectrometer can be used to measure hydrogen concentrations at multiple locations. The micro electronic hydrogen sensors would be great for this application of measuring hydrogen in a nitrogen purge background, but they were not a proven technology. The first step to testing the new microelectronic hydrogen sensors was to put them in the exhaust line coming from the mass spectrometer so that a comparison could be made and confidence in the sensors could be gained.

I am excited to report that in the testing of the latest composite liquid hydrogen tank (Picture 12) for the X-33 program or the next generation space shuttle that we are using the Sandia sensor technology (which has been licensed to DCH Technology) in parallel with the mass spectrometers as a requirement on the test program for detecting high concentrations of hydrogen. To put it simply, the mass specs were designed to look for low ppm level leaks and are typically not used for concentrations of hydrogen over 4%. Also, the metal in the mass spectrometers vacuum chambers tends to absorb hydrogen, and it takes a significant amount of time to recover from high 20 to 30% hydrogen concentrations (1 to 2 hours) before the hydrogen can be purged out.

Now one of the things that the engineers like to do in tank testing is to go back and forth between ambient hydrogen gas pressurization tests and liquid hydrogen cryogenic cycle tests, and if you have ever dealt with cryogenic systems, the leaks at ambient can often be undetectable while the leak at cryogenic temperatures can easily be a 1000 or 100,000 times larger then those at ambient temperatures. Thus it was necessary to have the micro-electronic hydrogen sensors available to measure the high concentrations at cryogenic temperatures, and have the mass spectrometers for their accuracy in measuring the low ppm levels.

NASA is very excited about the microelectronic hydrogen sensor technology since it provides a viable option for flight leak detection systems that have to operate in the oxygen free environments of space. Currently the Space Shuttle uses sample bottles. Little bottles take a sample of the air at specific times and then when the shuttle lands back on earth, the sample bottles are flown to Johnson Space Flight center for analysis. This does not lend itself to quick turn-around ground operations, and is why the next generation space shuttle or X-33 program is already developing a flight system based on microelectronic hydrogen sensors.

Conclusion

This brings me to the conclusion of my presentation where I would like to talk about my vision for the next generation space shuttle (Picture 13), the full scale X-33 or Venture Star being built by Lockheed Martin Skunk Works. With the advances in handheld hydrogen fire imaging, hydrogen facility cameras, and improvements in optical fire detectors we hope that this is a NASA program that will not have to rely on the antiquated broom fire detection technology. Also, it is a program that will hopefully push the limits of the new microelectronic hydrogen sensor technology to provide a reliable, light weight flight leak detection system for detecting hydrogen from ppm levels all the way to 100%.

NASA's and the DOD's space programs used to consume more hydrogen then all of industry in the US, but that is no longer true. Industry now uses more hydrogen then the government in a wide variety of manufacturing and food processing plants, for example hydrogenation of oils such as Crisco or creamy peanut butter. The use of hydrogen is on an exponential rise and with the potential to be used as an alternative energy source, it is important that these new hydrogen fire and gas detection technologies help insure that hydrogen is a safe fuel for the future.

GENERAL SESSION III:

Entering the Market: Partnerships in Transportation

MARKET PENETRATION SCENARIOS FOR FUEL CELL VEHICLES

by C. E. (Sandy) Thomas
Brian D. James and
Franklin D. Lomax, Jr.
Directed Technologies, Inc.
Arlington, Virginia 22203
703-243-3383; FAX: 703-2432724

Abstract

Fuel cell vehicles may create the first mass market for hydrogen as an energy carrier. Directed Technologies, Inc., working with the U.S. Department of Energy hydrogen systems analysis team, has developed a time-dependent computer market penetration model. This model estimates the number of fuel cell vehicles that would be purchased over time as a function of their cost and the cost of hydrogen relative to the costs of competing vehicles and fuels. The model then calculates the return on investment for fuel cell vehicle manufacturers and hydrogen fuel suppliers. The model also projects the benefit/cost ratio for government -- the ratio of societal benefits such as reduced oil consumption, reduced urban air pollution and reduced greenhouse gas emissions to the government cost for assisting the development of hydrogen energy and fuel cell vehicle technologies.

The purpose of this model is to assist industry and government in choosing the best investment strategies to achieve significant return on investment and to maximize benefit/cost ratios. The model can illustrate trends and highlight the sensitivity of market penetration to various parameters such as fuel cell efficiency, cost, weight, and hydrogen cost. It can also illustrate the potential benefits of successful R&D and early demonstration projects.

Results will be shown comparing the market penetration and return on investment estimates for direct hydrogen fuel cell vehicles compared to fuel cell vehicles with onboard fuel processors including methanol steam reformers and gasoline partial oxidation systems. Other alternative fueled vehicles including natural gas hybrids, direct injection diesels and hydrogen-powered internal combustion hybrid vehicles will also be analyzed.

Introduction

Fuel cell vehicle market penetration will require significant investments by both industry and government. Government support will be required to fund R&D and technology validation demonstrations, before industry is convinced of fuel cell vehicle market profitability. Much larger industry investments will eventually be needed to develop and mass produce fuel cell vehicles and to build a hydrogen fueling infrastructure. Neither can succeed alone. Government cannot afford the large investments required for commercialization, and industry will not make the necessary high risk investments with payoffs many years or even decades in the future. And government alone has the charter to develop those technologies that will benefit society, including reduced environmental impact and reduced dependence on imported fossil fuels.

Key decision makers in both industry and government must choose between many options to achieve their respective goals of profitability and improved social conditions. Within the transportation sector, fuel cell vehicles must compete with other alternative vehicles including natural gas vehicles and a range of various hybrid electric vehicles that could achieve similar reductions in pollution and oil imports. And the fuel cell vehicle itself could utilize onboard hydrogen storage or it could include an onboard liquid fuel processing system. The intent of the computer simulation model described here is to assist those decision makers as they weigh the costs and benefits of various clean car transportation options.

General Model Description

The basic model combines four key aspects of the fuel cell vehicle domain: vehicle technology, fuel, vehicle markets, and government actions (for more details, see Thomas 1997a).

The key input variables to the model include vehicle market scenarios and government actions, as illustrated in Figure 1. The major outputs include the return on investment for the automobile industry and for the hydrogen gas supply industry, along with estimates of benefit/cost ratios for government. Government benefit/cost ratios are calculated for the environment and for oil import reductions.

While this model produces a quantitative estimate of future profitability and future environmental improvements, it is not meant to predict the future. Rather, the model outputs should be taken as a very broad, qualitative indication of what is possible over the long run. Its greatest value will be in comparing alternative transportation options, and in assessing the impacts of various government and industry actions. This model should be seen as just one of many tools that can assist officials as they choose between alternative transportation options.

The model currently calculates eight major time functions as shown in Figure 1, including the number and cost of the fuel cell vehicles on the road each year, the quantity and cost of hydrogen, and the investments and profits for the auto and hydrogen gas industries. These functions are all linked to the number of fuel cell vehicles sold each year. The quantity of hydrogen is determined directly by the number of vehicles on the road and their fuel economy. The annual investment is determined by the increase in vehicle sales "N" years in the future, where "N" is the construction time of the production plant or equipment (taking advantage of perfect predictive capability inherent in such a computer model.)

Market Penetration Model

The number of fuel cell vehicles sold each year is determined by two price elasticity curves --one for vehicles and one for hydrogen -- and two vehicle markets -- the zero emission vehicle (ZEV) market and the conventional (non-ZEV) light duty vehicle market.

The ZEV market currently includes California and the five northeastern "opt-in" states, beginning with 10% of the new car sales in 2003. The model assumes that 50% of this ZEV market is available to FCVs. The actual number of FCV's sold out of this 50% potential market depends on the FCV price each year, and on the price of hydrogen relative to gasoline.

The vehicle price elasticity curve shown in Figure 2 has two parameters: the price of the competitive vehicle and the market share for FCVs at twice the price of the competition. For the ZEV market, the baseline model assumes that the battery electric vehicle is the competition, with a default price of $25,000. The model assumes that the FCV will capture 50% of the available ZEV market (or 25% of all ZEVs sold) if it also costs $25,000, which may be conservative since most drivers would probably opt for the FCV over a battery EV, given the FCV's superior range. But the sales of FCVs will also be impeded initially by the lack of hydrogen refueling facilities. The price elasticity curve drops very sharply as the FCV price rises, falling to only 0.1 percent of the ZEV available market if the FCV costs twice the battery EV or $50,000. This long tail on the elasticity curve reflects the "early adopters" -- those special few who will spend $50,000 to be the first on their block to own a new, ultra-clean technology.

The market share is also dependent on the price of hydrogen. The hydrogen market share multiplier (Figure 3) is less steep than the vehicle curve, on the assumption that fuel price will be less of an inhibitor than initial vehicle price. The default hydrogen price curve would cut market sales by one half, for example, if hydrogen cost twice as much (high range) or 1.5 times as much (low range) as gasoline per mile driven. As shown, this curve gives a slight boost to FCV sales if hydrogen costs less than gasoline, which we predict will occur at large sales volumes. The model also includes sales to 25% (default value) of the conventional (non-ZEV) car market, with a competitive price of $18,000 for gasoline internal combustion engine vehicles (ICEVs).

Cost Models

The model calculates the cost of hydrogen and the cost of fuel cell vehicles each year, based on cumulative sales of both through the previous year. In general prices fall with increased production volume. For example, Figure 4 shows the constant dollar price of the Model T Ford over its lifetime (Flavin and Lenssen 1994). The Model T price fell an average of 13.4% for every doubling of production, or a "progress ratio" of 86.6%. Figure 5 shows an analysis of the progress ratios for a wide variety of products, which tend to range between 70% to 90% (Dutton and Thomas 1984). These progress ratios include all forms of cost reduction, including labor productivity gains (called "learning curves"), other improvements in the product, the process, management, etc. within a given company. In addition, costs can be driven down by competing companies within an industry, sometimes called "experience curves." We do not assume industry-wide experience curves in this model, but assume that each company follows its own progress ratio curve. For example, the total number of FCVs sold is divided by the number of automobile companies (default value is three) before applying the progress ratio cost reduction calculation.

Fuel Cell Vehicle Component Costing

The preferred costing methodology does not, however, rely on estimation of arbitrary progress ratios for each component. Rather, we use the progress ratios to bridge current component prices with estimated future prices in mass production. For example, Directed Technologies, Inc. has worked with the Ford costing department to estimate the manufacturing cost of fuel cell stacks in large volume production (Lomax 1997), using the Design for Manufacturing and Assembly (DFMA) methodology used by industry both to select the lowest cost technique for manufacturing a given component, and to accurately estimate the large volume cost of each component. This detailed costing process scrutinizes every part, analyzing not only bulk material costs but also the least costly method of fabrication in large, automotive production volumes. As a result of this process, we estimate that the cost of PEM fuel cells could be reduced from about $1,500/kW today down to the neighborhood of $40/kW at the one million unit production level.

Given these initial and one-million production quantity prices, the model then calculates the progress ratio to tie these two values together -- in this case requiring a progress ratio of 82.1%.[1] Similar estimates were made for the other major components unique to the fuel cell vehicle, as summarized in Table 1. The third column of this table indicates the calculated price after the production of 110 transit buses, which is the main government/industry cost-shared project assumed in this model to drive down the initial cost of FCVs. The battery and motor/controller cost estimates were based on values in the literature, and the hydrogen storage tank estimates were estimated by DTI (James 1996).

Table 1. Baseline Fuel Cell Vehicle Pricing Parameters

	Price at Start Program (Input Data)	Price after 110 Buses (start of FCV Production) (calculated)	Progress ratio (calculated)	Price at One Million Production Level (Input Data)
Fuel Cell System ($/kW)	1,500	413	0.821	40
Peak Power Battery ($/kW)	80	34.9	0.881	7.8
Motor & Controller ($/kW)	490	133.6	0.819	12.7
Hydrogen Tank ($/kg of stored H_2)	510	316	0.929	133

[1]For production above the one million mark, the model switches the progress ratio to a default value of 0.98, which yields only two percent price reduction for each doubling after one million items are produced.

Hydrogen Costing

The cost of hydrogen was based on a detailed, industry-led costing project funded by the Ford Motor Company under a cost-shared contract with the Department of Energy's direct hydrogen fuel cell vehicle program (Thomas et al., 1997b). One major conclusion from this study is that hydrogen in a FCV could be competitive with gasoline even if the hydrogen were made in small scale, factory-built steam methane reformers or small scale electrolyzers. These small scale hydrogen fueling appliances are a key feature of this market penetration scenario. These inexpensive fueling systems can be installed at local bus garages and local fleet operators, avoiding the "chicken and egg" dilemma inherent with building large scale steam methane reformers and hydrogen pipelines or liquid hydrogen tanker trucks before fuel cell vehicles are plentiful.

The model estimates the number of FCVs within range of fueling stations each year in the California and opt-in ZEV states, assuming three miles between each station in the mature market. Four types of hydrogen fueling stations are assumed: those supporting less than 50 FCVs, 50 to 100, 100 to 300 and greater than 300 FCVs[2]. Electrolyzers are the only cost effective option for the smaller fueling stations. Steam methane reformers become more cost effective for the larger units. The initial cost estimates are summarized in Table 2. The electrolyzer costs were derived from a detailed DFMA type costing exercise with Electrolyser Corporation and Ford. We have not yet evaluated the large volume costs of factory-built steam methane reformers, but use an 85% progress ratio instead. The initial cost for the 272 kg/day steam methane reformer is based on the reformer that is part of the 200-kW stationary phosphoric acid fuel cell system manufactured by International Fuel Cells of South Windsor, Connecticut. We have assumed scaling factors for each of the major system components to extrapolate from the 272 kg/day unit down to the two smaller units. All costs include hydrogen compression to 6,000 psi, storage and dispensing into the vehicle tanks.

Investments

The model assumes that both government and industry make investments to bring the fuel cell vehicle to market. Initial cost-shared projects to supply 110 fuel cell buses and 232 fleet FCVs serve to bring costs down via the progress ratios described above. For example, the first FCVs cost $178,000. By the end of the bus project, costs have fallen to $55,300 per FCV. These lower costs then provide a small market for "early adopters," which in turn gradually increase market share in subsequent years, slowly driving down prices.

Government Investments

The model assumes that the federal government continues funding R&D in fuel cells for

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[2]The number of vehicles supported by a station is approximately eight times the number of vehicles actually refueling each day. Thus a fueling station supporting 300 FCVs would refuel about 38 vehicles on an average day.

transportation, and also initiates cost-shared projects to develop and demonstrate small scale electrolyzers and steam methane reformers for hydrogen fueling applications. The government is also assumed to 50% cost-share two vehicle demonstration projects: a 110-bus project ($113 million of government funds) extending the three fuel cell buses slated for Chicago, and also a smaller fleet vehicle program ($7.7 million government) that supports 232 FCVs. Total government investments are $432 million over the 1995-2008 time period, as summarized in Table 3.

Table 2. Cost Parameters for Small Scale Electrolyzers and Steam Methane Reformers

	Electrolyzers	Steam Methane Reformer Systems		
Nominal Hydrogen Production Rate (kg/day)	2.72	44.2	88.5	272
No. of FCVs Supported	2.7	50	100	375
Initial Capital Cost[3] ($)	15,500	221,900	256,000	447,000
Manufacturing Progress Ratio Factor[4]	0.819	.85	0.85	0.85
Capital Cost at 10,000 Quantity ($)	4,380	33,400	39,950	76,000
Cost/per Vehicle ($/FCV)	1,622	667	400	203

Industry Investments

The automobile industry is assumed to invest $3,125 per FCV annual production capacity, plus two percent of annual sales for capital replacement. Plant construction time is three years, so the model looks ahead and calculates increased capacity needed three years in the future. The model adds this investment incrementally, although the actual investments would be made in discrete steps as new production volume was added. This incremental as-needed investment optimizes capital utilization and overestimates return on investment compared to the real world, but this approximation will apply to all the vehicle options. Again, the relative comparisons between vehicle options should still be valid. Total industry investment over the 1997-2030 time period is projected at $16 to $20.6 (low range / high range) billion, split between three companies.

The model assumes that one electrolyzer company invests $20 million, plus four percent of electrolyzer sales. The steam methane reformer companies (three assumed) invest $15 million each and four percent of sales, or a total of $234 to $318 million over the full period. In addition,

[3]Initial capital cost for electrolyzers assumes production of 100 units minimum.

[4]Progress ratios varied for different components; values shown are approximate for the total system.

the fueling stations invest $7.5 to $14.4 billion to purchase the fueling appliances over this period.

Table 3. Government Investments (in 1996 U.S. Million Dollars) in Fuel Cell and Hydrogen Infrastructure Projects

Year	R&D			Technology Validation Demonstrations (Cost Shared with Industry)				Annual Totals
	Fuel Cell	Electrolyzer	Steam Methane Reformer	FC Buses	FC Vehicles	Electrolyzer Fueling Station	SMR Fueling Station	
1995	22			1.6				23.6
1996	25			0				25.0
1997	30	0.4	0.2	4.2	0.09			34.9
1998	35	0.5	0.4	7.2	0.08	5.33		48.5
1999	30	0.2	1.4	10	0.28	5.33		47.2
2000	25		2.5	40	1.64	0.33		69.5
2001	20			50	0.40			70.4
2002	20				2.43			22.4
2003	20				2.77			22.8
2004	15							15.0
2005	15							15.0
2006	10						7.5	17.5
2007	5						7.5	12.5
2008							7.5	7.5
Totals	272	1.1	4.5	113	7.69	10.99	22.5	431.8

Government Benefit/Cost Ratios

The model also calculates the societal benefits of replacing gasoline ICE vehicles with FCVs, including the reduced costs of importing oil, and the reduced costs of environmental degradation. Estimating environmental damage is highly speculative. Instead of damage costs, the model uses the lowest of several estimated avoided costs of alternative methods of reducing pollution, as summarized Table 4.

Table 4. Air Pollution Avoided Costs ($/ton)

Ref:	U.S.					Southern California		
	(Tellus 1990)	Mass. (EEI 1994)	Nev. (EEI 1994)	N.Y. (Mark 1996)	Used Here:	(Tellus 1990)	(Mark 1996)	Used Here:
VOC	5,300	6,140	6,190	17,300	**5,300**	29,000	18,000	**18,000**
CO	870	1,010	1,040	2,100	**870**	870	350	**350**
NOx	6,500	7,540	7,650	14,400	**6,500**	262,500	17,000	**17,000**
CO_2	22	26	25		**22**			

The environmental benefit/cost ratio is then the net present worth of avoided environmental costs over the 1997-2030 time period, divided by the present worth of the government investments, using a three percent societal discount rate. Similarly, the oil import benefit/cost ratio is the present worth of avoided oil purchases divided by the present worth of government investments, again using three percent discount rate for social effects.

Baseline Direct Hydrogen Fuel Cell Vehicle Results

The various time-lines for the direct hydrogen fuel cell vehicle industry are shown in Figure 6a, and for the hydrogen gas industry in Figure 6b, illustrating how increasing sales drive down costs over time. The investment curves show how relatively small government investments initially help to drive down prices, leading to dramatically larger industry investment once profitability has been demonstrated.

The basic results of the analysis for the direct hydrogen fuel cell vehicle are summarized in Table 5 for industry return on investment, and in Table 6 for the government benefit/cost ratios. The automobile, gas and hydrogen retail suppliers all make over 17% returns on their investments. The electrolyzer business, however, never takes off in the baseline model. Although electrolyzers are essential to get the market started by providing low cost hydrogen fueling systems for just a few vehicles, the steam methane reformers produce lower cost hydrogen, and soon dominate the market.

The oil import benefit/cost ratio is between 28 and 61 to 1 -- oil imports savings exceed government investments by a factor of 28 to 61. The environmental avoided costs are 14 to 33 times greater than the government total investment of $432 million ($371 million net present worth at 3% discount rate) over the 1996-2008 time period.

Table 5. Industry Return on Investments (30-year Baseline Totals - High / Low Ranges)

	Investment ($U. S. Millions)	Return on Investment
Fuel Cell Vehicle Industry (36 / 21 Million FCVs)	20,570 / 16,050	21.8% / 17.2%
Hydrogen Production Industry:		
Electrolyzer Fueling Appliances	20.1 / 17.7	2.9% / 1.2%
Natural Gas Reformer Fueling Appliances	318 / 234	27.2% / 26.9%
Hydrogen Retail Suppliers	14,470 / 7,500	24.7% / 21.4%

Table 6. Government Benefit/Cost Ratios (30-year Totals)

	($ U. S. Millions)		Benefit/Cost Ratios @3% Discount
	Current $M	Present Worth @ 3%	
Total Government Investment	432	371	
Oil Import Savings (11.5 / 5.2 Quads)	54,750 / 26,380	22,650 / 10,400	61 / 28
Environmental Savings	29,200 / 13,400	12,200 / 5,300	33 / 14

Onboard Fuel Processors

The current model also includes fuel cell vehicles powered by methanol and by gasoline. The onboard chemical processors required to convert these liquid fuels into hydrogen change vehicle performance and cost. These fuel processors add weight to the vehicle, and also reduce the fuel cell peak power, which in turn requires larger fuel cells and slightly larger motors to maintain equal vehicle performance in terms of drive train power to vehicle weight ratio. The resulting extra weight in turn requires larger drivetrain components -- the weight compounding phenomenon.

Methanol Fuel Processor

The model assumes an onboard steam methanol reformer with water gas shift reactors to convert most of the carbon monoxide to hydrogen and water. Since CO poisons the anode catalyst of a PEM fuel cell, a gas cleanup device such as a preferential oxidizer is also required to reduce CO down to less than 10 ppm. The gas stream from this system will include approximately 25% CO_2 and 75% hydrogen (excluding water vapor). To avoid buildup of this CO_2 in the anode chamber, the fuel cell cannot be operated "dead-ended," which is possible with pure hydrogen. Rather, the anode must have a significant exhaust component, which also means that a significant fraction (10% to 20%) of the hydrogen will pass through the fuel cell unreacted. Some of this unreacted hydrogen can be returned to a boiler to preheat the methanol or to raise steam for the reaction, but only with a loss of efficiency in the burner and heat exchangers. Hence the fuel cell operating on reformate must necessarily have lower efficiency than the same fuel cell operating on pure hydrogen.

Furthermore, existing PEM fuel cell systems have lower performance operating on a dilute mixture of hydrogen. Figure 7 compares the polarization curves measured by the Los Alamos National Laboratory for an older Ballard fuel cell operating on pure and dilute hydrogen, with hydrogen content varying from 40% to 75% (Inbody 1996). The anode gas stream also included 2% air to reduce the deleterious effects of CO_2, which also reduces performance -- without this air bleed performance would have been worse. The measured drop in peak power was about 12% for the 75% hydrogen case characteristic of a methanol reformer output. The model assumes that the fuel cell size is therefore increased by 12% to maintain vehicle power to weight ratio.

Even after increasing fuel cell size, however, the system efficiency on 75% hydrogen is still slightly lower than that for pure hydrogen, as shown in Figure 8. The solid upper curve shows the fuel cell system efficiency as a function of net output power operating on pure hydrogen with variable air compressor power from 1.2 atmospheres at low power up to 3 atmospheres at full power. The three lower curves in Figure 8 show theoretical and experimental data from Los Alamos for 75% hydrogen mixtures. The two theoretical curves were generated from computer models of the anode performance (Gottesfeld 1996).

Given these efficiency data, the model estimates the weight of the vehicle after weight compounding, and a separate driving cycle simulation code estimates the fuel economy of the vehicle over the EPA combined urban/highway driving cycle with each velocity segment multiplied by 1.25 (a more realistic "real world" driving schedule). Two estimates are made for each methanol FCV parameter: a high range with optimistic assumptions, and a low range assuming fuel processor developments do not meet expectations. The parameters for the methanol processor are summarized in Table 7. The methanol FCV would have about 28% to 38% lower fuel economy than a direct hydrogen fuel cell vehicle. Since methanol production is also slightly less efficient than hydrogen production from natural gas (eg., 64% to 72%), greenhouse gas emissions will also be greater for methanol by at least 30% per vehicle.

Gasoline Fuel Processor

The model assumes that gasoline is processed with an onboard partial oxidation (POX) system combined with water gas shift reactors and gas cleanup. This system would be similar to the methanol processor, but with even lower performance. The hydrogen content would be only 40% instead of 75%, causing a measured drop of 36% in peak power with the old Ballard fuel cell stack, or a 21% drop using the optimistic LANL theoretical data. In addition, the POX processor will not need the excess thermal energy contained in the hydrogen in the anode exhaust. It may be more difficult to recover this wasted hydrogen energy. The overall gasoline processor parameters are summarized in Table 8. The estimated gasoline FCV fuel economy would be 38% to 57% less than that of a hydrogen FCV, although still 20% to 72% better than that of a gasoline-fueled ICEV.

Table 7. Characteristics of Low and High Range Methanol-Powered Fuel Cell Vehicles

	High Range	Low Range
Fuel Cell Size Increase w/r to H_2 FCV	-10%	-12%
Fuel Cell Efficiency Curve	LANL Theory (R_{CL}=0.025)	LANL Experimental
Hydrogen Utilization	90%	83.3%
CO_2 Degradation	None	(Included in exp. data)
Methanol Reformer Efficiency (H_2/MeOH -LHV)	84.5%	77%
Methanol Reformer Weight (kg)	46	60
Vehicle Weight Increase (kg)	110	135
Fuel Economy (1.25 X Combined Cycle) in km/l (mpg-equivalent)	20.7 (48.7)	17.8 (41.9)
Fuel Economy w/r to ICEV	1.98	1.70
Fuel Economy Decrease w/r to H_2 FCV	-28.6%	-38.5%

Table 8. Characteristics of Low and High Range Gasoline-Powered Fuel Cell Vehicles

	High Range	Low Range
Fuel Cell Size Increase(w/r to H_2 FCV)	1.21	1.36
Fuel Cell Efficiency Curve	LANL Theory (R_{CL}=0.025)	LANL Experimental
Hydrogen Utilization	90%	83.3%
CO_2 Degradation	None	(Included in exp. data)
Gasoline POX Efficiency (H_2/Gasoline -LHV)	75%	70%
Anode Gas Heat Recovery	70%	0
Gasoline POX Reformer Weight (kg)	55	87
Vehicle Weight Increase (kg)	109	186
Fuel Economy (1.25 X Combined Cycle) in km/l (mpg-equivalent)	17.9 (42.3)	12.5 (29.4)
Fuel Economy w/r to ICEV	1.72	1.20
Fuel Economy Decrease w/r to H_2 FCV	-38.3%	-56.9%

Comparison of Direct Hydrogen with Methanol and Gasoline Fuel Cell Vehicles

Vehicle Cost Comparison

The lower fuel cell performance and the added weight of the liquid-fueled FCVs also translates into added cost. Part of the additional cost is due to the requirement for larger fuel cell stacks, larger peak power batteries and larger motor controllers to maintain vehicle power to weight ratio, as summarized in Table 9 for methanol-powered FCVs and Table 10 for gasoline-powered FCVs. To a first approximation, the extra power train costs cancel the savings derived from eliminating the compressed hydrogen tank, leaving the cost of the onboard processor as a net addition to the hydrogen FCV cost. The estimated vehicle prices are shown in Figure 9, assuming that the base gasoline AIV Sable costs $18,000.

Table 9. Incremental Cost Estimates (1996 U.S. Dollars) for Methanol-Powered Fuel Cell Vehicle (High Volume Mass Production Costs)

	Direct Hydrogen FCV		Methanol FCV Cost		Cost Differential (MeOH FCV - H_2 FCV)	
	Size	Cost	High	Low	High	Low
Fuel Cell System ($40/kW)	50 kW	2000	2400	2440	400	440
Peak Power Battery ($7.8/kW)	40 kW	312	337	343	25	31
Motor/Controller ($12.7/kW)	79 kW	1000	1080	1100	80	100
Hydrogen Tank ($133/kg)	5.78 kg	768	0	0	-768	-768
Methanol Processor ($10/kW -High & $20/kW-Low)	-	0	540	1100	540	1100
Totals		4080	4357	4983	277	903

Table 10. Incremental Cost Estimates (1996 U.S. Dollars) for Gasoline-Powered Fuel Cell Vehicle (High Volume Mass Production Costs)

	Direct Hydrogen FCV		Gasoline-POX FCV Cost		Cost Differential (Gasoline FCV - H_2 FCV)	
	Size	Cost	High	Low	High	Low
Fuel Cell System ($40/kW)	50 kW	2000	2630	3120	630	1120
Peak Power Battery ($7.8/kW)	40 kW	312	337	355	25	43
Motor/Controller ($12.7/kW)	79 kW	1000	1080	1140	80	140
Hydrogen Tank ($133/kg)	5.78 kg	768	0	0	-768	-768
Gasoline-POX Processor ($10/kW -High & $20/kW-Low)	-	0	540	1140	540	1140
Totals		4080	4587	5755	507	1675

Fuel Economy Comparison

The fuel economies of the three vehicles are compared in Figure 10, in miles per gallon of gasoline equivalent (LHV) on the 1.25 times accelerated EPA combined driving schedule.

Emissions Comparison

The estimated local air pollution and global greenhouse gas emissions per vehicle for these three FCVs are compared with battery EVs and with a FCV storing liquid hydrogen onboard in Figure 11, all normalized to one for the gasoline ICE vehicle in the 2000^{+} time period. The most striking result is that the greenhouse gases associated with electrolytic hydrogen would be 65% greater than those from a gasoline ICEV. This results from the projected composition of the average U.S. marginal grid mix in the 2000^{+} time period -- 70% coal and 25% natural gas. Since the clean generators (nuclear and hydro-electric) are operated near capacity, any new power demand requires primarily additional coal consumption. As discussed earlier, however, the steam methane reformers rapidly take over most of the hydrogen market, providing greater greenhouse gas reductions than any other option.

Any of the FCVs nearly eliminate CO and NOx emissions. However, both methanol and gasoline will have significant evaporative emissions unless fueling systems and refueling procedures are modified for liquid fuels. Methanol is both less volatile and less photoreactive than gasoline vapors, so its impact on ozone smog is less than that of gasoline.

Market Penetration Comparisons

As shown in Figure 12, the market penetration of methanol- and gasoline-powered FCVs lags behind that of the direct hydrogen FCV, due to higher initial vehicle cost, even though hydrogen initially costs more per mile than methanol or gasoline. Only the high ranges for the liquid fueled FCVs show up on Figure 12. The low range cases never penetrate the market with the baseline parameters -- they remain too expensive to gain significant market share. Market penetration for the lower range hydrogen FCV case[5] is very similar to the methanol high range case -- the market share penalty as a result of the high initial cost of hydrogen nearly equals the market loss due to the higher initial purchase price of the methanol-powered FCV.

As a result of reduced market penetration, the return on investment is generally less for the methanol- and gasoline-powered FCVs (Figure 13), although the high range methanol case yields slightly higher returns than the low range hydrogen case. Again, only the high range estimates are shown on Figure 13 for methanol- and gasoline-FCVs -- there is no return for the low range assumptions for either liquid fueled FCV.

The government environmental benefit/cost ratios also decline for the FCVs with onboard reformers (Figure 14), due both to lower market penetration and also due to lower per vehicle

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[5]The low range hydrogen case assumes that the hydrogen cost market share multiplier falls to 50% when the cost of hydrogen is 1.5 times the cost of gasoline, compared to 2 times the cost of gasoline for the hydrogen high range case (See Figure 3.)

environmental benefits. In this case the high range methanol-FCV environmental benefit / cost ratio is only slightly less than the low range direct hydrogen FCV case.

Finally, Figure 15 shows the corresponding oil import benefit/cost ratios for these three FCV types.

Conclusions

This market penetration model shows a plausible scenario whereby small scale electrolyzers and small scale natural gas steam reformers could provide economic hydrogen to support a growing fuel cell vehicle market. Based on detailed assessment of fuel cell vehicle and hydrogen costs in mass production, the model illustrates that both the automotive industry and the hydrogen gas industry could make over 17% return on investment, provided that the federal government invested over $400 million between now and 2008 in the further development and demonstration of fuel cell vehicles and in hydrogen infrastructure development.

Electrolyzers, on the other hand, have mixed review: they are essential in the startup phases to provide very small fueling appliances to support early fleets of 2 to 50 vehicles. But the model indicates that electrolyzer manufacturers could not make adequate return on investment on the FCV market alone, since steam methane reformers would take over the market as fuel cell vehicle sales increased. In any case, electrolytic hydrogen would dramatically increase greenhouse gases with the projected marginal utility mix in the U. S. in the early 21st century. Thus both economic and environmental concerns impede mid term use of electrolytic hydrogen. Only substantial utility grid penetration of renewable electricity would make electrolytic hydrogen environmentally acceptable. Renewable electricity would have to saturate the grid during peak use, for example, in which case producing hydrogen from excess renewable electricity would reduce overall greenhouse gases. Otherwise, displacing fossil fuel electricity at any time of the day or night with renewable electricity would reduce greenhouse gases more than making hydrogen for use in a FCV.[6]

This model also indicates that methanol- or gasoline-powered FCVs would be less attractive in the marketplace, due primarily to an expected increase in vehicle costs. Although the onboard processor itself might be cost competitive with the compressed hydrogen tank it would replace, the lower peak power and lower efficiency of the fuel cell operating on dilute mixtures of hydrogen would require larger fuel cells and slightly larger drivetrain components, driving up the vehicle cost.

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[6]For example, wind or solar electricity that displaces the marginal U. S. utility generation mix would reduce greenhouse gas emissions by a factor of 1.8 times more than making hydrogen and displacing gasoline ICEVs with hydrogen FCVs.

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Figure 1. Major Functional Relationships for Programmatic Pathway Analysis

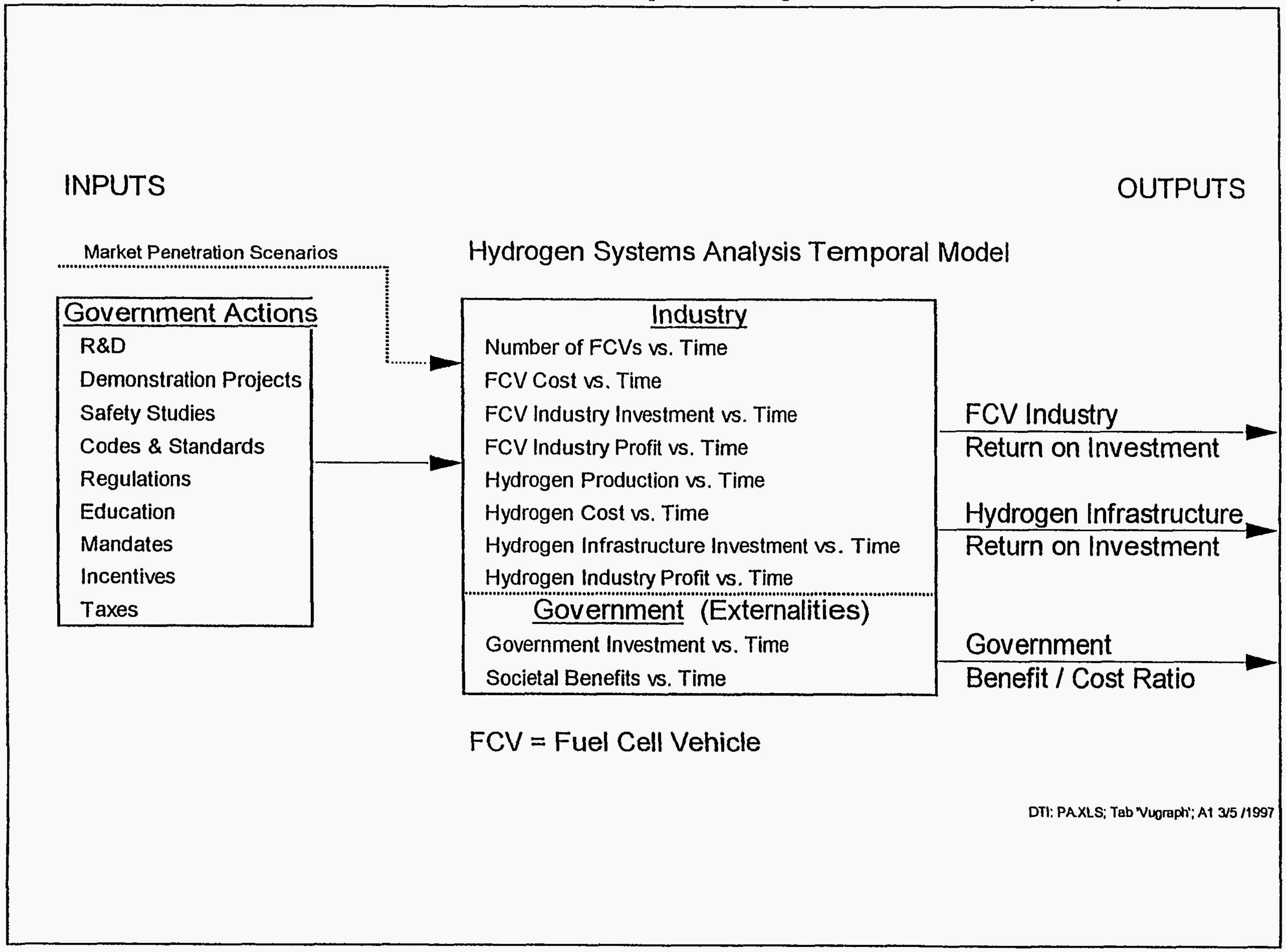

Figure 2. Fuel Cell Vehicle Market Share vs. Vehicle Price

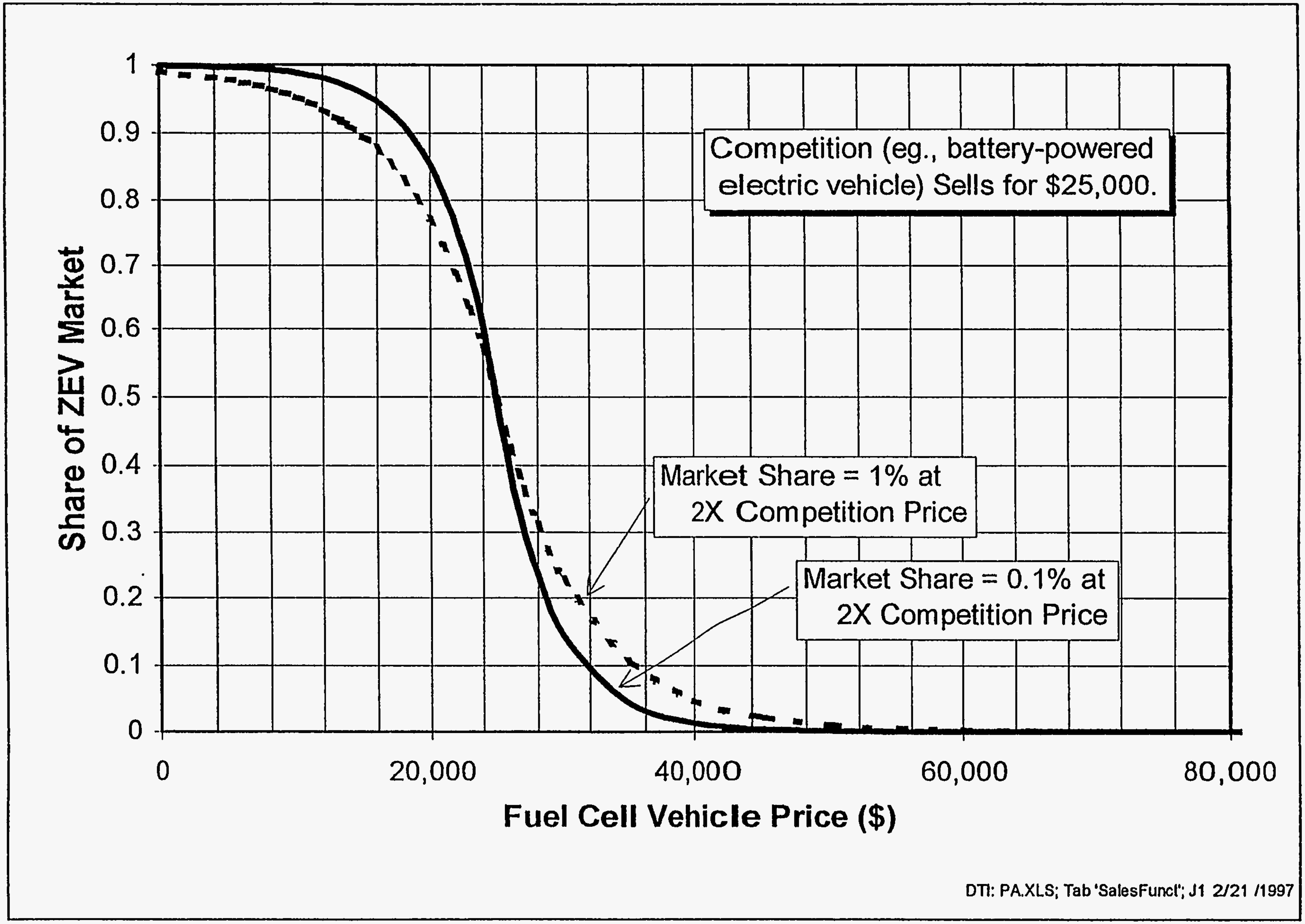

Figure 3. Hydrogen Price Market Share Multiplier

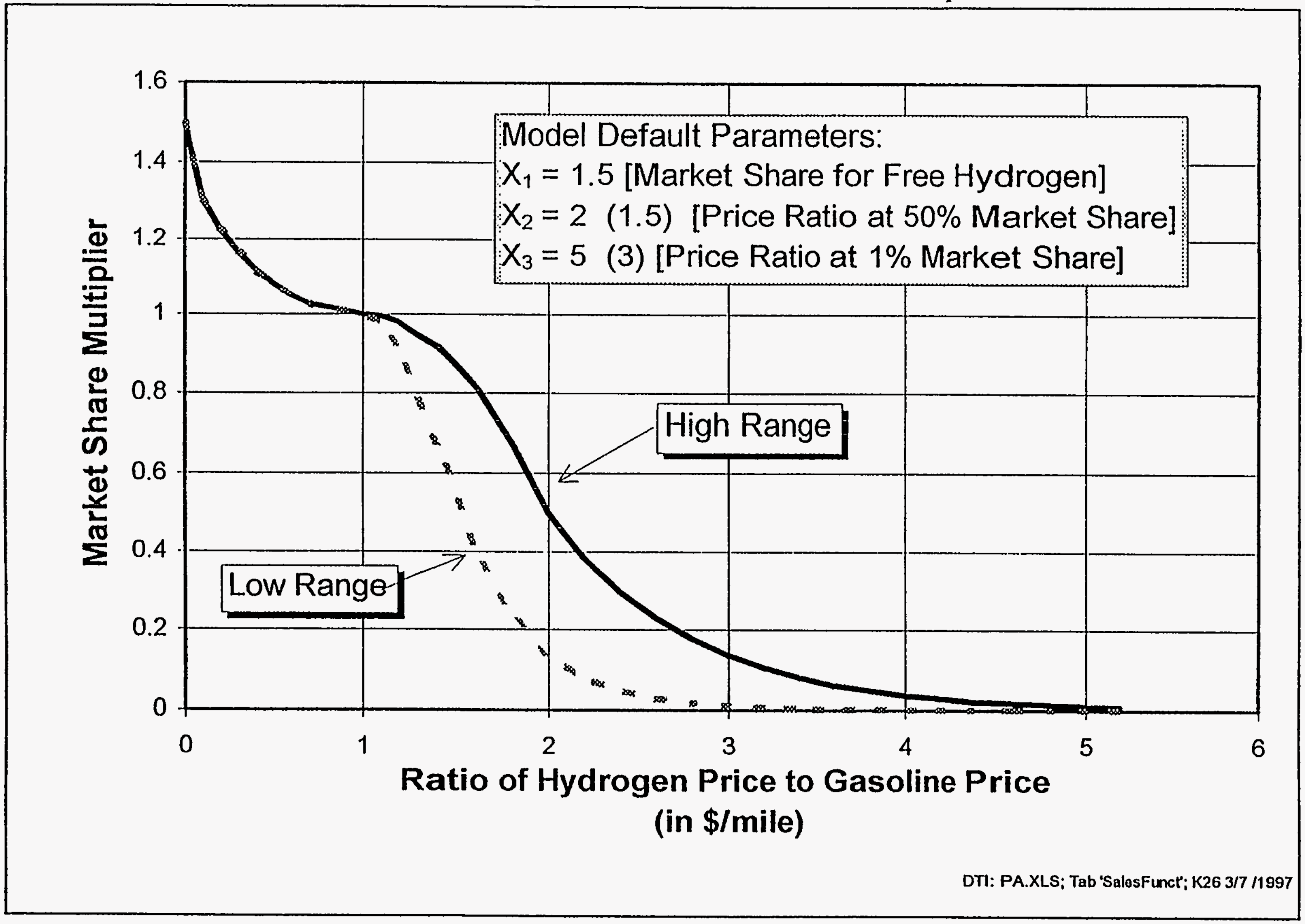

Figure 4. Ford Model T Price (Constant 1978 $) vs. Cumulative Production

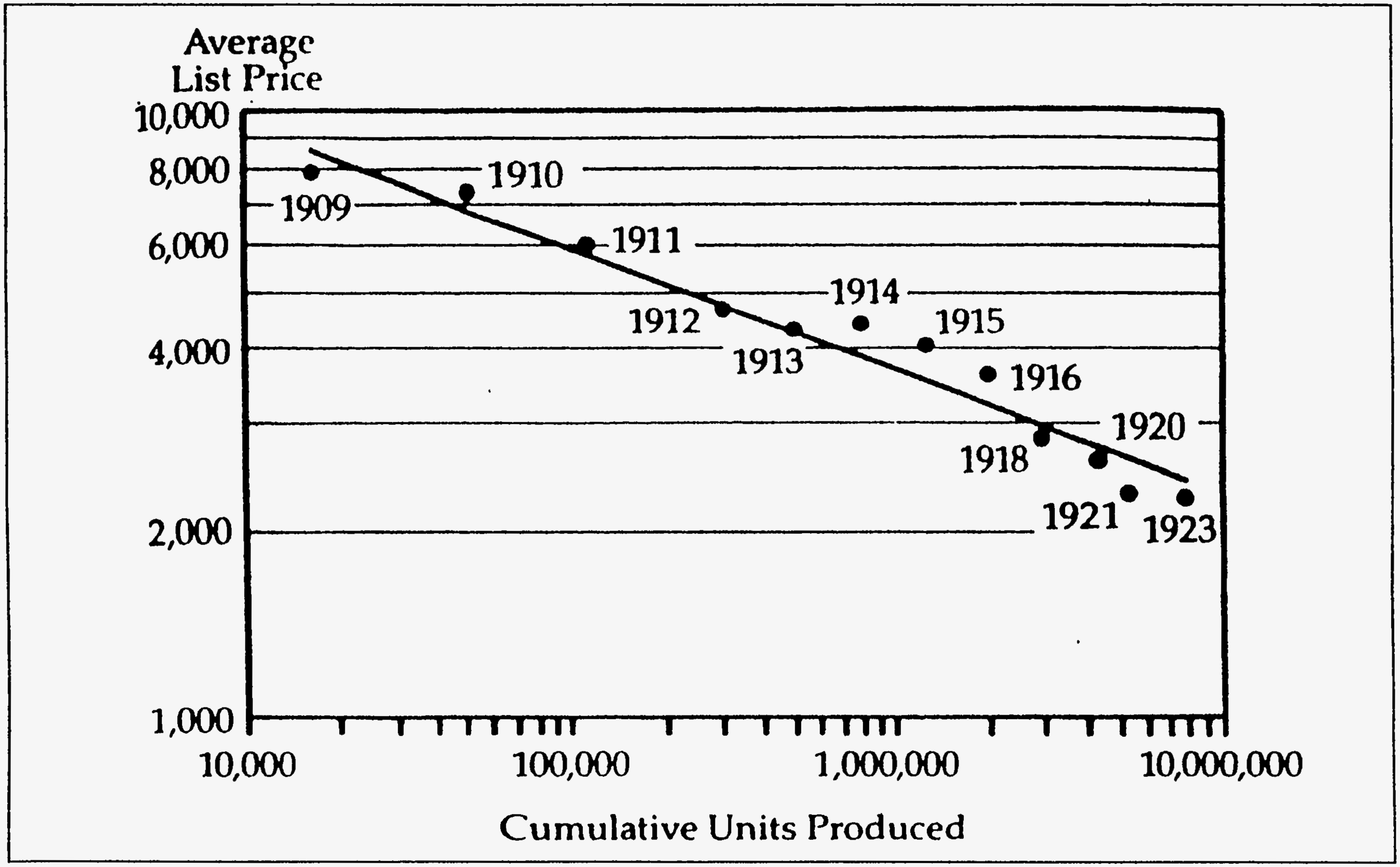

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Figure 5. Distribution of Progress Ratios Observed in 22 Field Studies

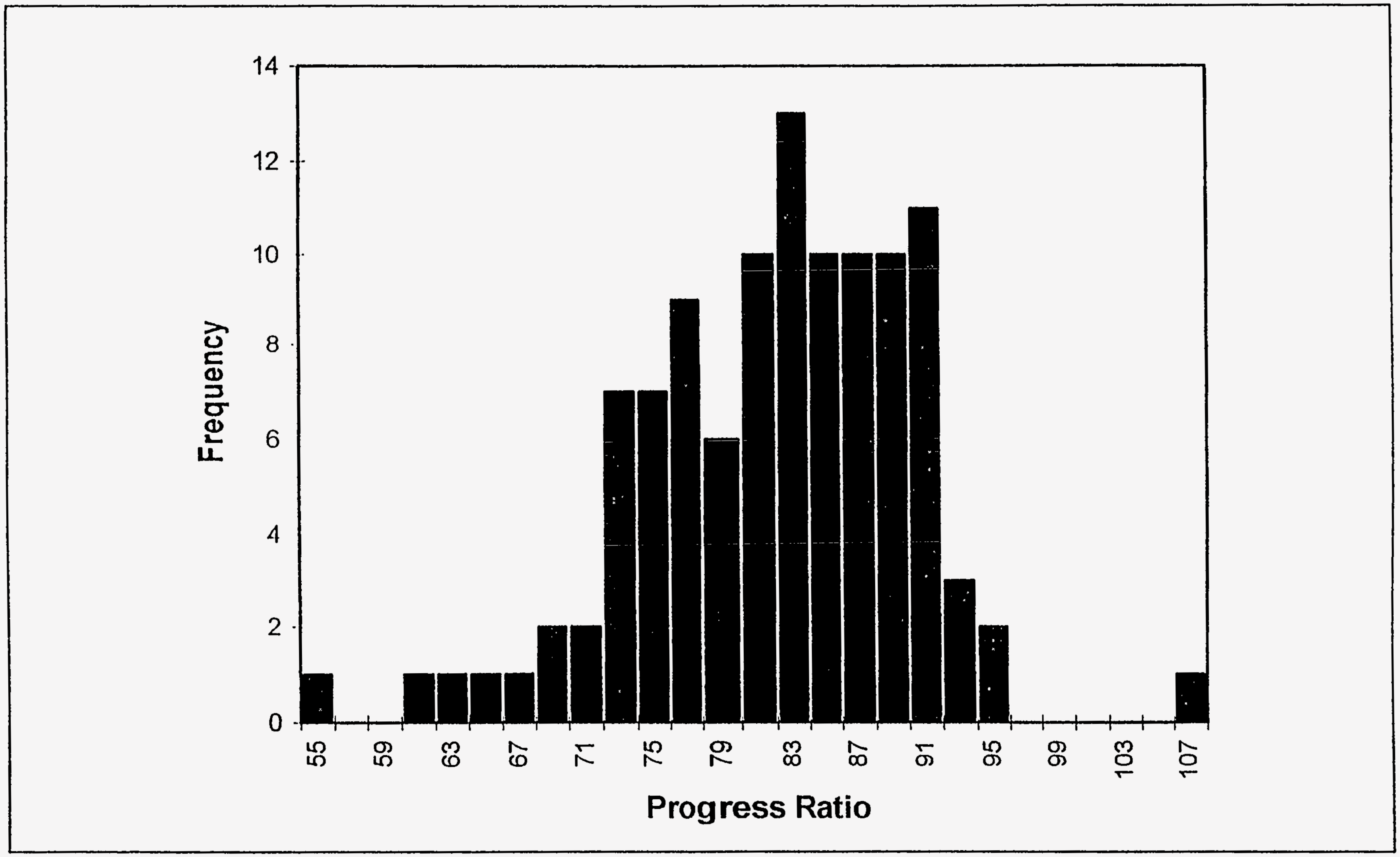

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Figure 6a. Example of Fuel Cell Vehicle Industry Programmatic Pathway Projections (All Costs in 1996 U. S. Dollars)

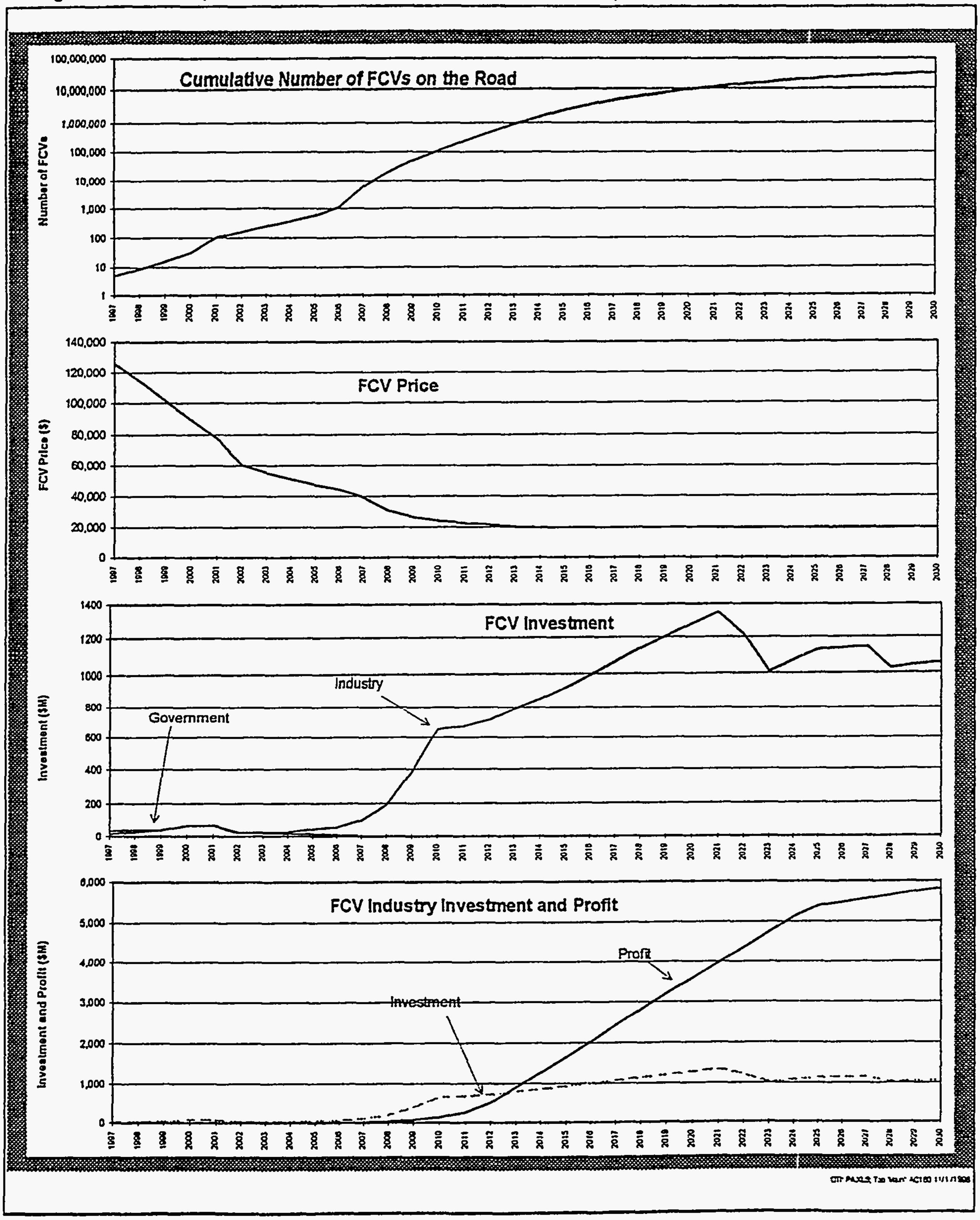


Figure 6b. Example of Hydrogen Industry Programmatic Pathway Projections (All Costs in 1996 U. S. Dollars)

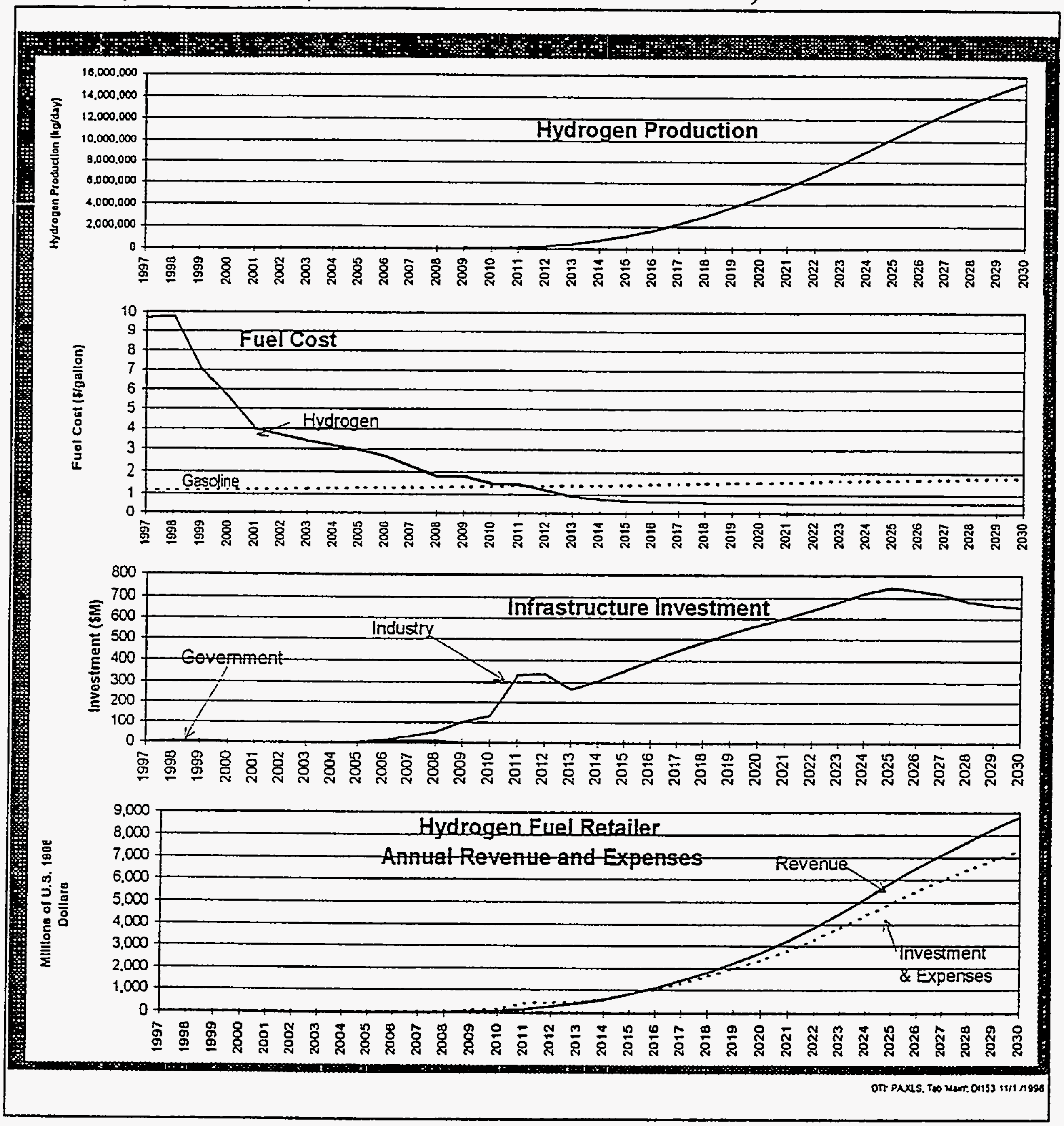
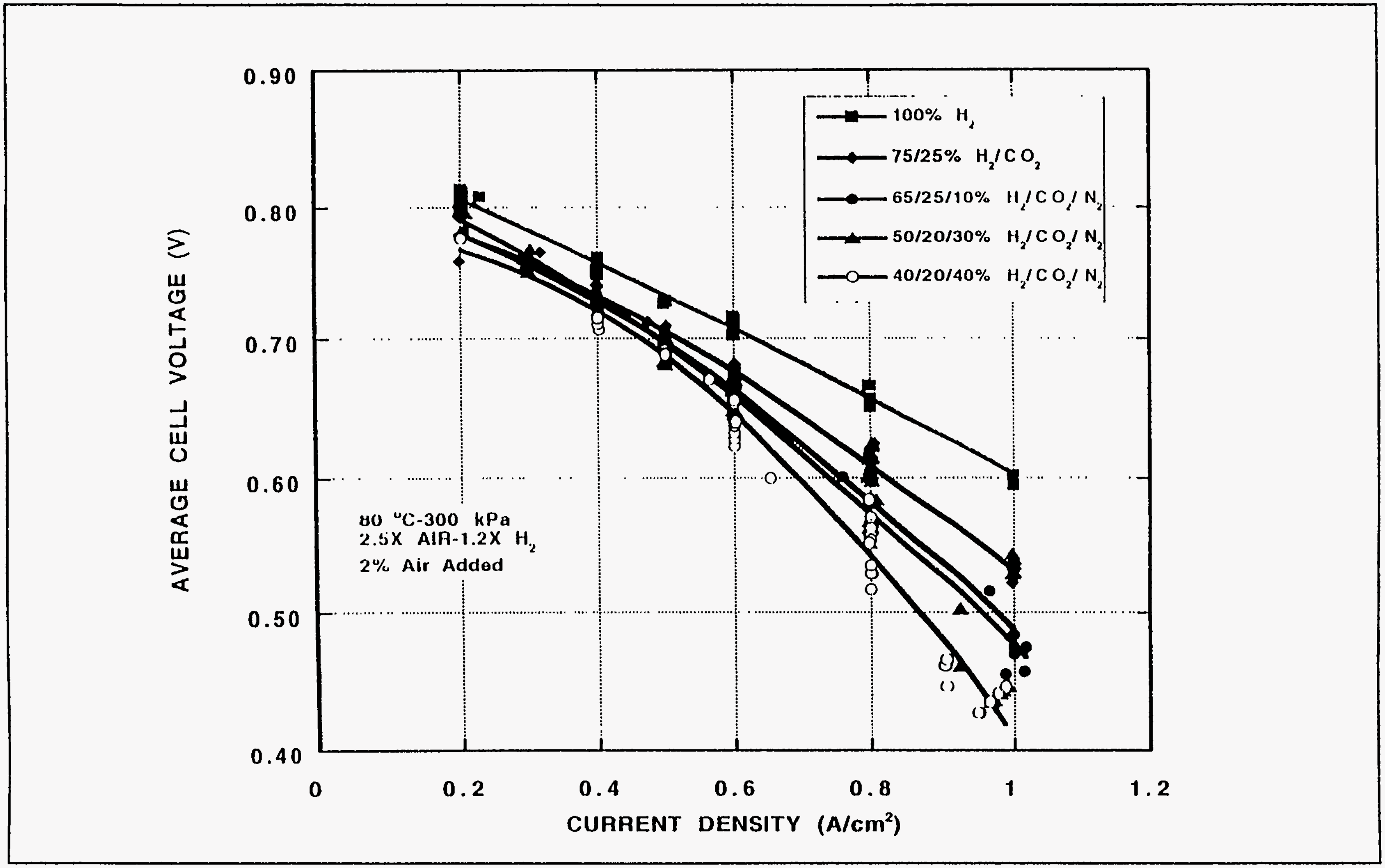


Figure 7. Measured Fuel Cell Polarization Curves with Dilute Mixtures of Hydrogen



Ref: Inbody, M., Tafoya, J., Hedstrom, J., Vanderborgh, N., "Fuel Cell Stack Testing at Los Alamos National Laboratory," *DOE Fuel Cells for Transportation Exploratory R&D Program*, Washington, D. C.: Los Alamos National Laboratory

Figure 8. Fuel Cell System Net Efficiency vs. Output Power for Pure Hydrogen and Simulated Methanol Reformate

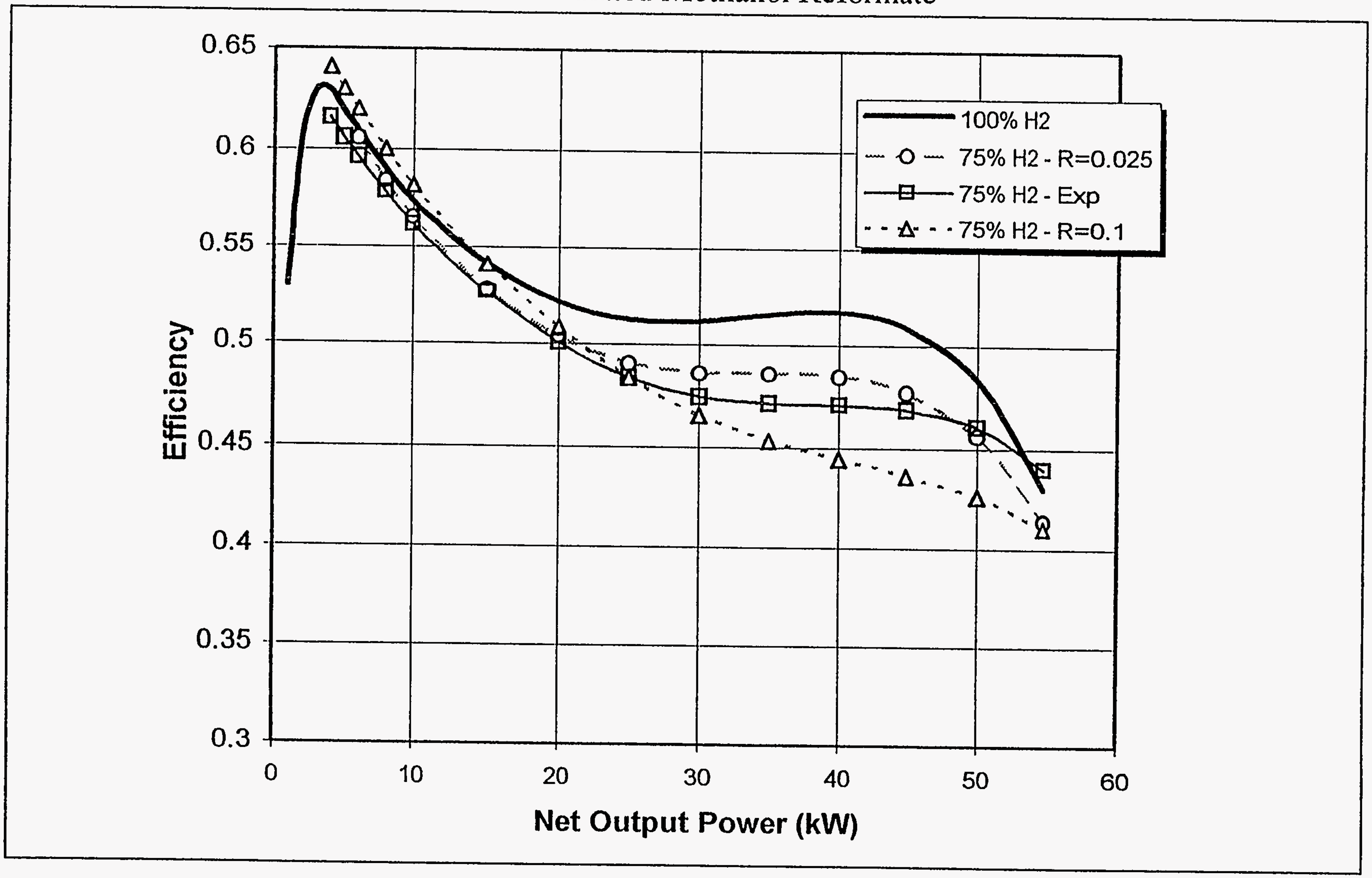


Figure 9. Estimated Vehicle Purchase Price in Large Volume Manufacturing

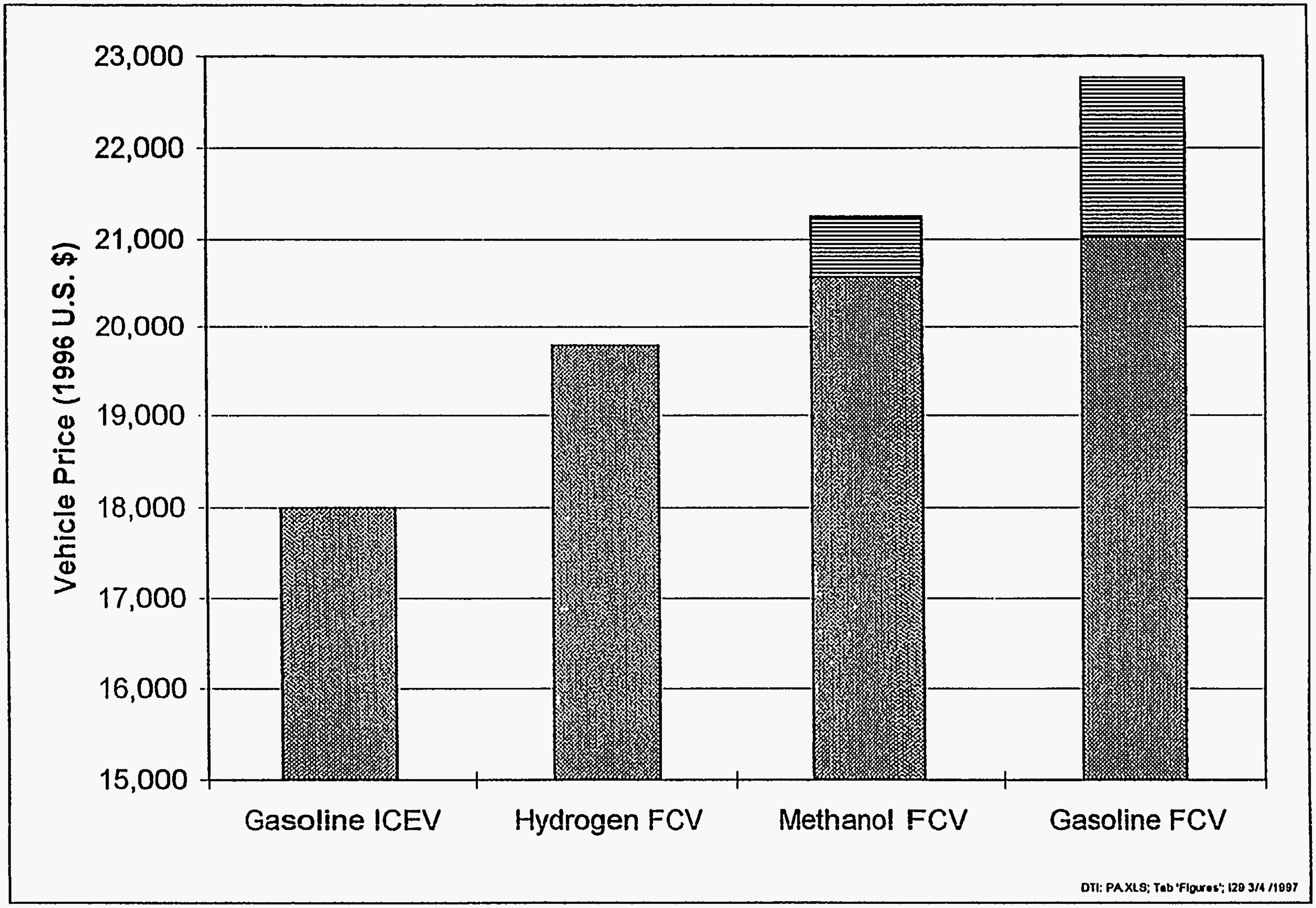


Figure 10. Onboard Fuel Economy for Fuel Cell Vehicles Compared to a Conventional Vehicle

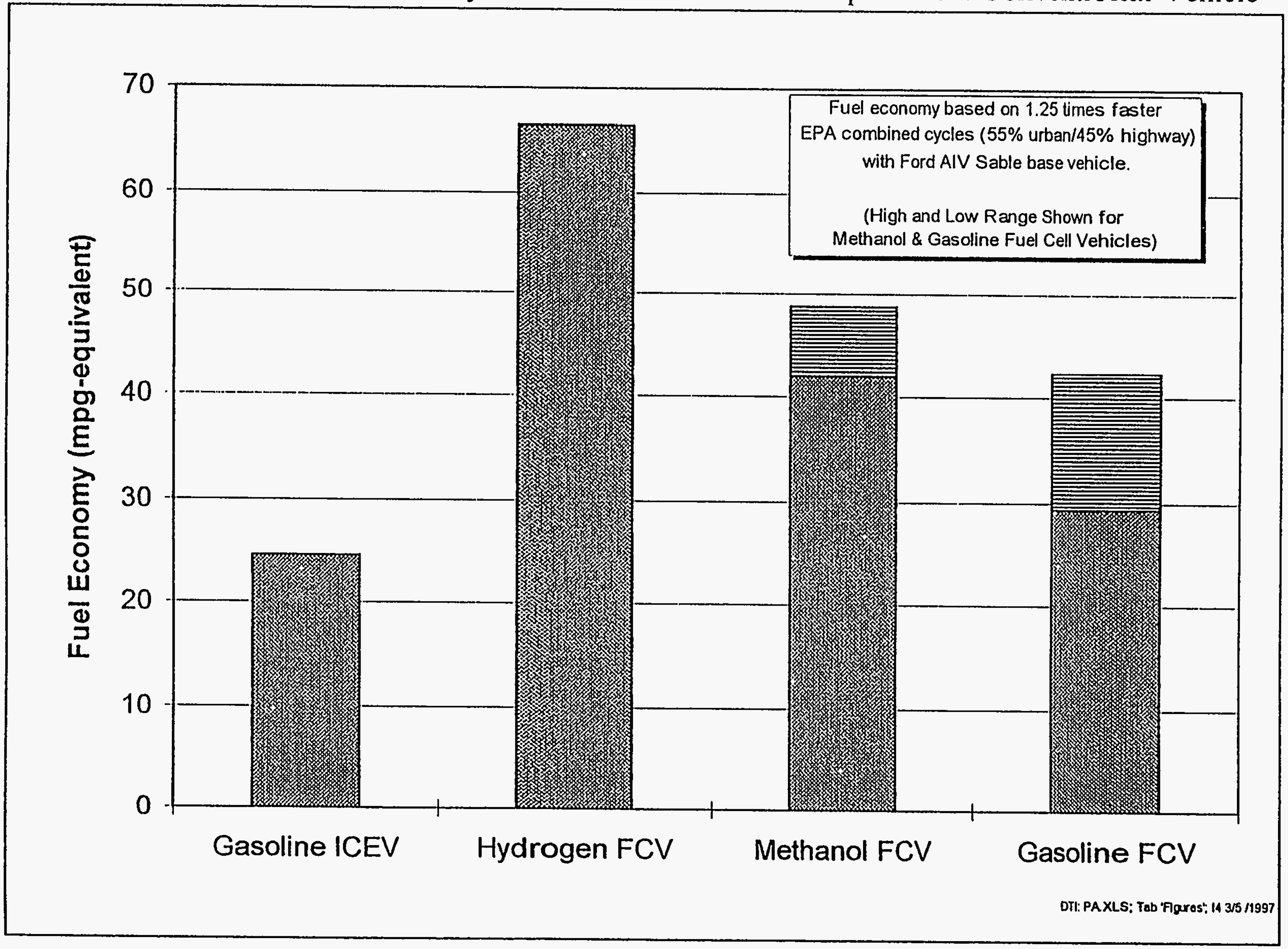


Figure 11. Fuel Cell Vehicle Emissions
Normalized to One for the Gasoline Internal Combustion Engine Vehicle

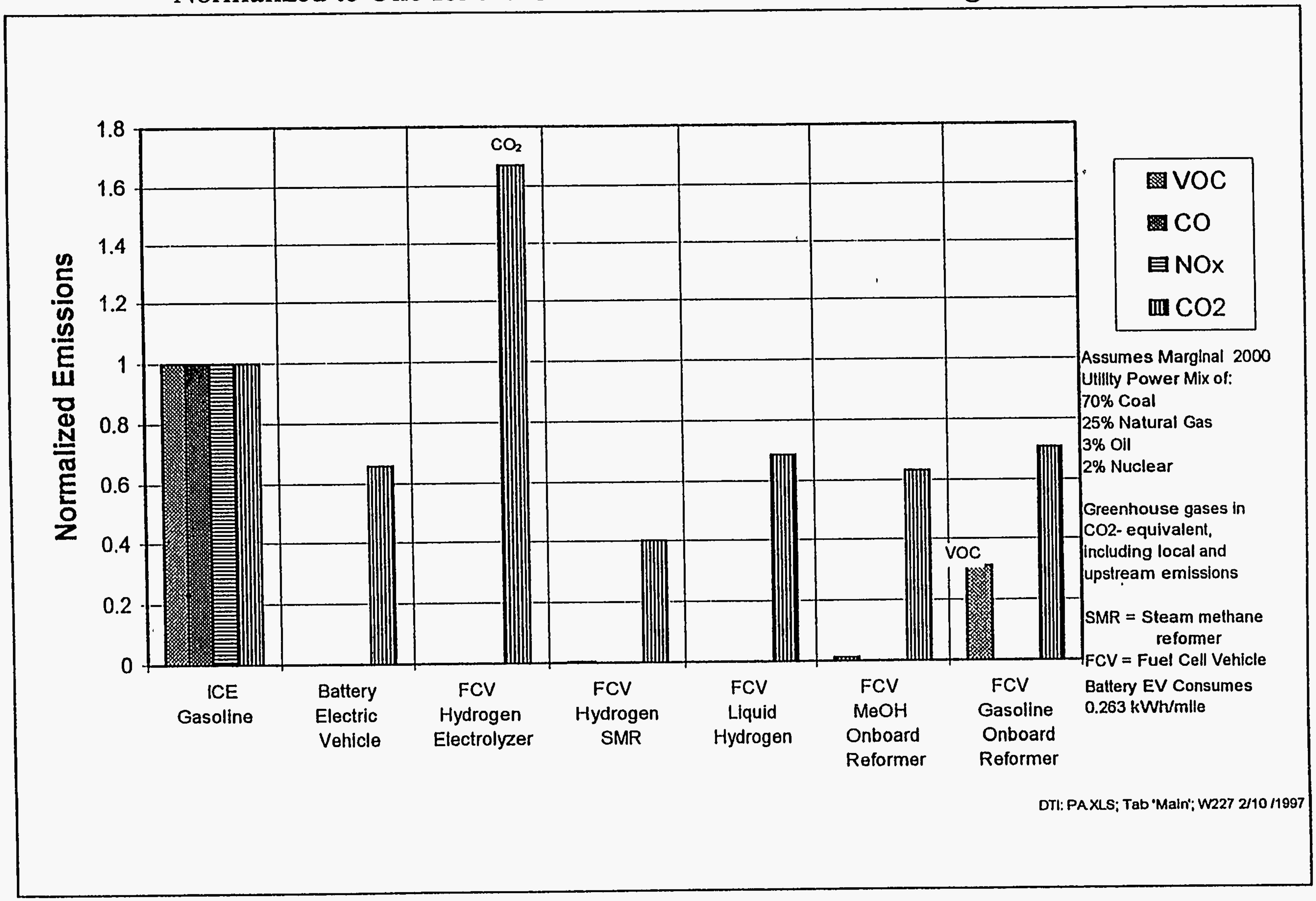


Figure 12. Fuel Cell Vehicle Market Penetration Projections

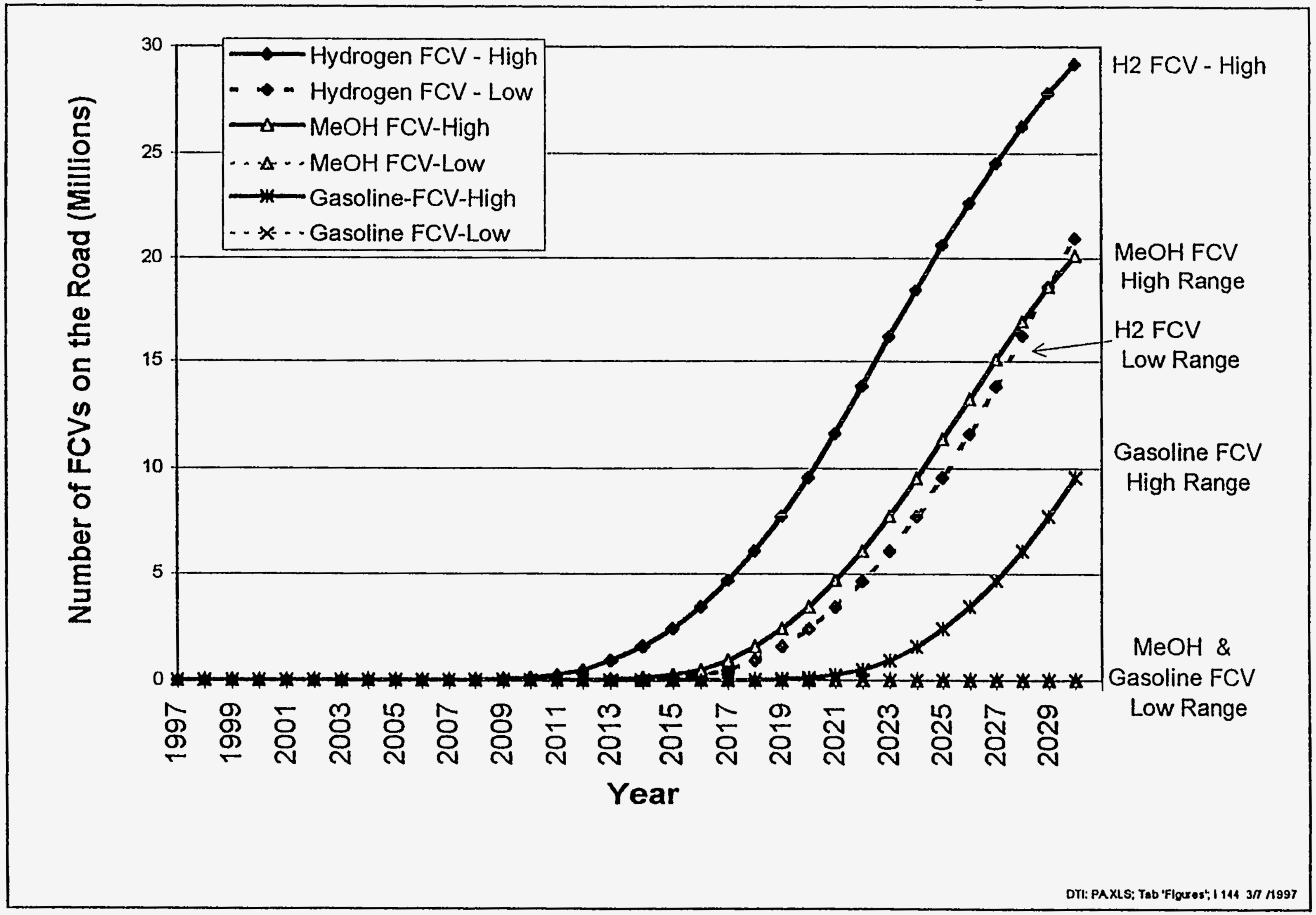


Figure 14. Environmental Benefit / Cost Ratios for Fuel Cell Vehicles

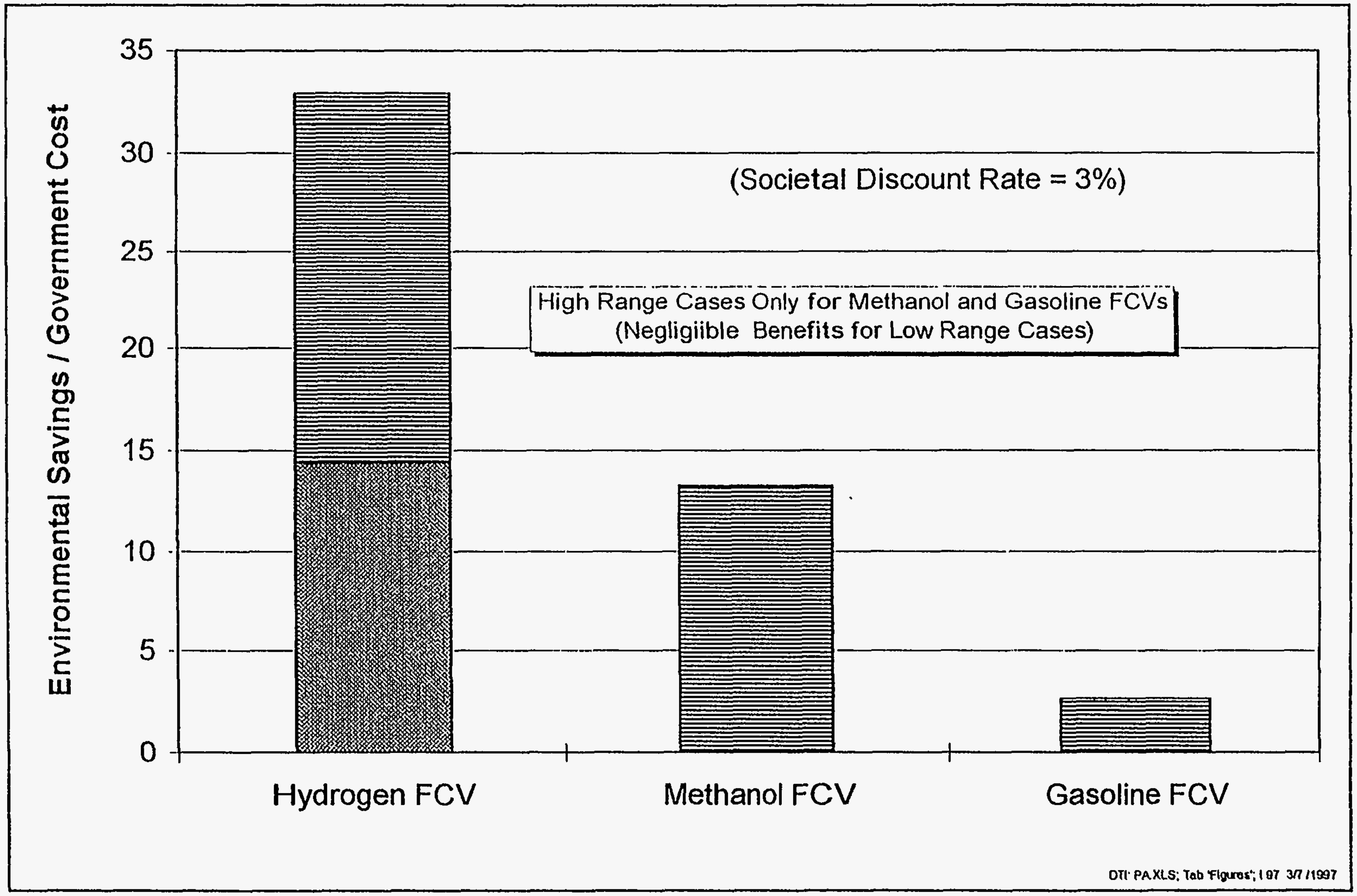
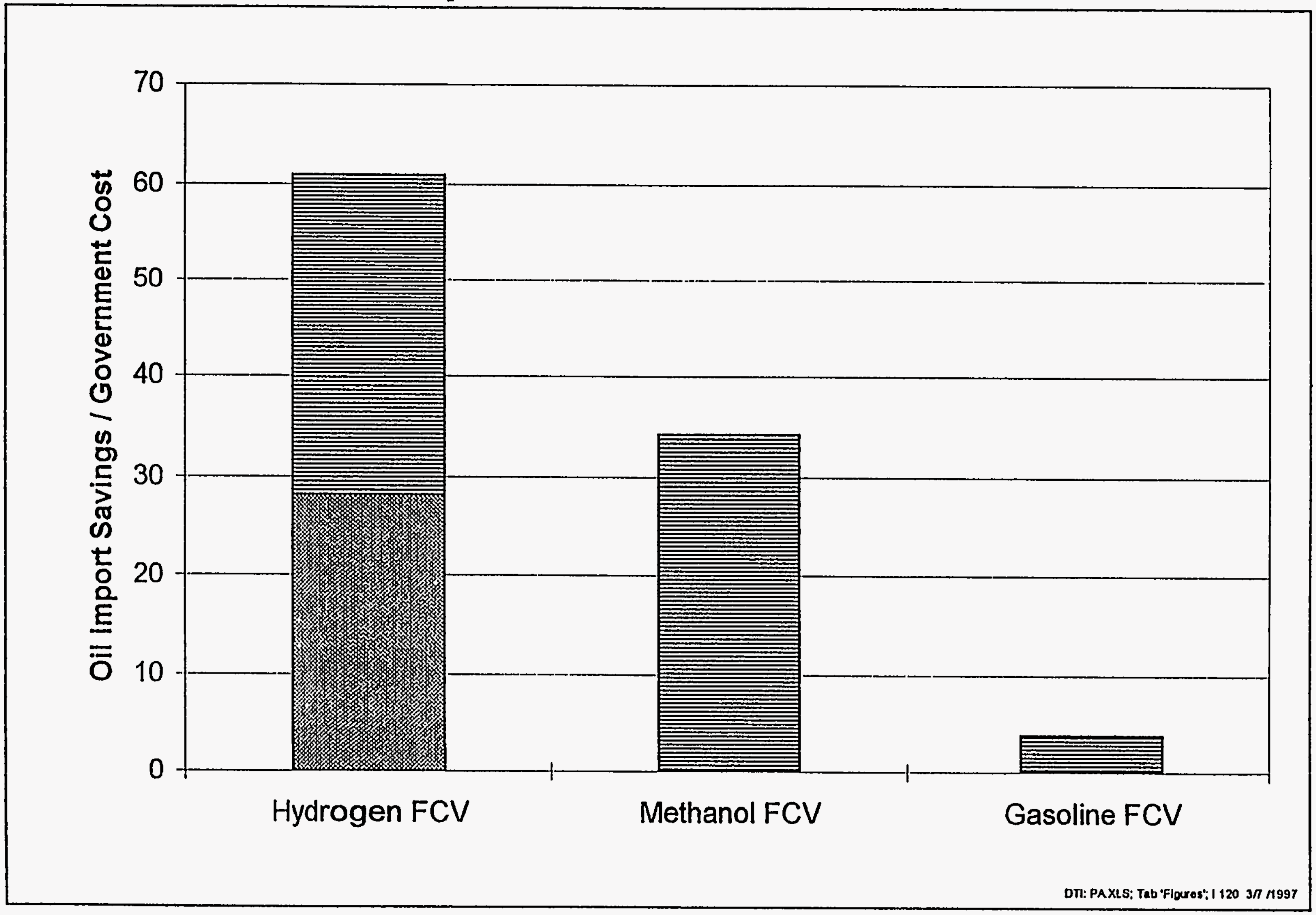


Figure 15. Oil Import Benefit / Cost Ratios for Fuel Cell Vehicles



SPEEDING THE TRANSITION: DESIGNING A FUEL-CELL HYPERCAR

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Abstract

A rapid transformation now underway in automotive technology could accelerate the transition to transportation powered by fuel cells.

Ultralight, advanced-composite, low-drag, hybrid-electric "hypercars"—using combustion engines—could be three- to fourfold more efficient and one or two orders of magnitude cleaner than today's cars, yet equally safe, sporty, desirable, and (probably) affordable. Further, important manufacturing advantages—including low tooling and equipment costs, greater mechanical simplicity, autobody parts consolidation, shorter product cycles, and reduced assembly effort and space—permit a free-market commercialization strategy.

This paper discusses a conceptual hypercar powered by a proton-exchange-membrane fuel cell (PEMFC). It outlines the implications of platform physics and component selection for the vehicle's mass budget and performance.

The high fuel-to-traction conversion efficiency of the hypercar platform could help automakers overcome the Achilles' heel of hydrogen-powered vehicles: onboard storage. Moreover, because hypercars would require significantly less tractive power, and even less fuel-cell power, they could adopt fuel cells earlier, before fuel cells' specific cost, mass, and volume have fully matured. In the meantime, commercialization in buildings can help prepare fuel cells for hypercars.

The promising performance of hydrogen-fueled PEMFC hypercars suggests important opportunities in infrastructure development for direct-hydrogen vehicles.

I. Introduction

The magnitude and severity of the impacts of burning petroleum products in vehicles range through all geographic scales, from local air quality to global climatic change, and require an understanding of many disciplines, from the natural sciences to health and welfare to national security, and beyond. Outstripping human population growth, global growth in transportation and demand for vehicles will continue as incomes rise and the majority of the world eyes OECD levels of mobility. Accommodating the equitable desires of non-OECD peoples with a petroleum-based transport system is clearly not sustainable. Further, even with rapid growth outside of the OECD, the magnitude of petroleum use by transportation inside the OECD will command the lion's share for decades to come.

All of this presents a chasm of challenges for transportation technology and energy policy to cross. Although humans, as a species, are excellent "rapid reactors" (Parkin, 1994), adaptive measures will be taxed to overcome these pressures, and a focus on long-term planning is needed. One important element in a such a planning strategy is the development and use of alternative fuel technologies to diminish petroleum dependence. One particularly promising group of such technologies is the hydrogen fuel cell.

Unfortunately, the uncertainty surrounding the development and commercialization of hydrogen-based transportation systems and their supporting infrastructure is conducive to "serialistic" (Black, 1994) or incremental tendencies that confound effective planning and radical change. Supported by powerful special interests, this incremental *modus operandi* forces us into small adaptations of existing systems and prevents the realization of the benefits of hydrogen-based transport. It tries to cross the chasm of challenges presented by petroleum-based transport in two leaps.

Fortunately, realizing the benefits of hydrogen-based transportation need not depend solely on successful government planning and regulation, nor on incremental adaptation of the status quo. A dramatic transformation now underway in automotive technology—toward ultralight, low-load, hybrid-electric "hypercars"—may rapidly accelerate the adoption of fuel cells for propulsion by making the automotive platform an attractive environment for these exciting technologies years, perhaps decades, sooner than previously believed.

Interestingly, widespread use of efficient and/or alternatively fueled vehicles could rapidly reduce growth in demand for petroleum products and hence more or less crash the world oil price by creating lasting disequilibrium between supply capacity and demand. Although it is beyond the scope of this exercise to explore such implications for fuel markets, it should be kept in mind that the success of hydrogen and fuel cell technologies should not depend on rising oil prices.

More generally, one could argue that strategic planning must not depend on the predictability of oil price. As shown by H.R. Holt of the U.S. Department of Energy (Figure 1), changes in the real price of crude oil on the world market satisfies every test of statistical randomness. Indeed, it followed a Brownian random-walk trajectory throughout 1881–1993, with a doubling of volatility since 1973 (the offscale excursion on both axes).

This paper conceptualizes a hypercar powered by a proton-exchange-membrane fuel cell (PEMFC hypercar). Section II describes the hypercar design philosophy and outlines autobody and component issues, and Section III presents the PEMFC hypercar modeling. The implications of fuel-cell hypercars for the transition to gaseous hydrogen fuel (Section IV) and the rapid commercialization of fuel cells (Section V) are presented. The Appendix provides detailed printouts of the three model scenarios.

By making the car attractive for new technologies, rather than exclusively the other way around, the hypercar concept provides an opportunity to leapfrog past both the undesirable state of dependence on government action or oil prices and the striking challenges facing transportation, to a future of automotive fuel cells powered by hydrogen fuel.

II. Hypercars

Concept

During 1991–93, Rocky Mountain Institute (RMI)—a nonprofit resource policy center devoted to resource productivity—explored a set of ideas that, if true, could transform the automotive industry. Working with electric utilities and innovative designers worldwide, RMI Research Director Amory Lovins had been showing for two decades how whole-system redesign of buildings, motors, and many other technical systems that use electricity could often achieve large energy savings more cheaply than small ones.

Rather than treating components in isolation and narrowly optimizing for energy savings in the face of diminishing returns (Figure 2), RMI had discovered that the artful combination of a number of strategies and technologies, many of which would be considered uneconomic, or which would not have been considered at all in the traditional framework, can allow "tunneling through the cost barrier" (Figure 3). RMI suspected that the same might be possible in cars—breaking through the component-oriented mentality that was leading automotive evolution into a cul-de-sac of stagnating efficiency at ever greater complexity and cost.

Calculations suggested that combining two proven approaches to car design—ultralight and low-load construction, plus "hybrid-electric" propulsion (the century-old concept of powering electric wheel-motors with a small fueled powerplant carried onboard, *e.g.*, Figure 4)—could simultaneously:

- improve modern family cars' fuel efficiency by about three- to sixfold;

- reduce their pollution by one or two orders of magnitude; yet also

- yield comparable or better comfort, refinement, safety, acceleration, and probably affordability.

A typical four- to five-passenger "hypercar," as RMI has dubbed these conceptual vehicles, would need only on the order of two liters of fuel per 100 km—perhaps ultimately only half as much. It could safely, cleanly, and comfortably carry a family 5,000 km across the United States on about 100 liters of virtually any liquid hydrocarbon fuel or its gaseous equivalent.

Figure 5 illustrates the dramatic benefits of load reduction and efficiency improvements. In the top diagram, losses compound as energy flows from the engine to the wheels in a typical vehicle. About 80% of the fuel energy never reaches the wheels: of the roughly one-fifth that does, roughly one-third heats the air through aerodynamic losses, one-third heats the tires and road, and one-third heats the brakes. Moreover, most of this propulsion energy is required to move the vehicle itself. The net result is that an ungratifying 1% of the fuel energy ends up moving the driver.

The bottom diagram in Figure 5, however, turns the compounding losses (from engine wheels) into compounding savings (from the wheels upstream to the engine). For each unit of reduction in load at the wheels, or improved efficiency along the way, the associated savings multiply along this chain, reducing by manyfold the amount of fuel that must be used or stored in the first place. Additionally, regenerative braking enables part of the otherwise irrecoverable braking losses to be captured for reuse—although the energy required for braking will also decrease in proportion to gross vehicle mass.

Such exemplary performance would clearly be hard to achieve. It would require highly integrated whole-system engineering, melding dozens of new technologies with meticulous attention to detail. The downsizing, simplification, and elimination necessary to reduce mass, cost, and complexity, and thus enable new options, are hard-won through recursive optimizations at the system level. However, RMI found that meeting this challenge could bring unexpected rewards. Ordinarily, hybrid-electric propulsion tends to make a car heavier, costlier, and more complex. But *prior* reductions both in weight and in air and road drag could turn hybrid drive's "vicious circles" into "virtuous circles," making the hybrid propulsion system lighter, simpler, and cheaper than it would be in a conventional platform. This in turn could trigger further simplification of many automotive systems and components, make most of them much smaller[1], and eliminate some entirely. That would make the car even lighter, further reinforcing the advantages of its hybrid-electric driveline. Repeating this process could make the weight savings snowball, yielding a better car with extremely light weight and probably lower total cost (Figure 6).

RMI found that the engineering principles required were well established; the technologies were demonstrated and some were commercially available. What was needed was an integrated design concept that would reoptimize the car into a new domain of behavior where, paradoxically, seeking to minimize the cost of the car rather than the fuel it consumed would actually lead to its saving even more fuel. Also needed was an equally integrated practical concept of how such a car could be made, sold, and used. By mid-1993, industry presentations, seminars, and technical publications had begun to confirm RMI's early hypotheses. In ever-increasing detail, the 1991 conjecture about the potential for a "leapfrog" in car design seemed to be taking shape.

Commercialization

Starting in mid-1993, RMI adopted an unusual way to speed the commercialization of this apparently promising idea—a way that relies not on governmental mandates or subsidies but on manufacturers' quest for competitive advantage and customers' desire for superior cars. Such a free-market approach appears feasible because hypercars' novel features extend strongly to their method of manufacture.

Making hypercars ultralight, yet also strong for safety, will probably depend on a shift from stamping and welding steel to molding advanced composites made of polymeric materials such as carbon fiber embedded in plastic resin. ("Advanced" means the composite is stronger or stiffer than glass-reinforced composites.) The new materials, and special manufacturing methods adapted from other fields (racecars, aerospace, boatbuilding, etc.) to achieve high volume and low cost, could completely change the way autobodies are made. These new methods could offer the manufacturer a much lower product cycle time, capital investment, assembly effort, and body parts count. The agility, cost, risk, and locality of production would greatly improve. Risks of and barriers to market entry could dramatically diminish.

RMI's commercialization strategy rests on the premise that such potentially decisive competitive advantages will reward early adopters and encourage rapid market entry. Rather than patenting and auctioning the intellectual property, therefore, RMI simply puts most of it into the public domain and seeks to maximize competition in exploiting it. As a result, by the end of 1996, about 25 firms—half current and half intending automakers (from car-parts, aerospace, electronics, and other industries)—were engaged in discussion or collaboration with RMI's Hypercar Center on a nonexclusive and compartmentalized basis.

Early success of this commercialization effort holds the promise of achieving the supposedly incompatible car-related public-policy goals for the economy, environment, and national security—simultaneously and robustly. However, this requires discontinuous technological changes in materials, manufacturing, and propulsion systems; re-integration of the automotive design process; and other major cultural changes in automaking and in wider engineering and commercial practice. It is not yet clear whether automakers can achieve these changes, or whether they might instead be displaced by new market entrants who have none of the automakers' vast physical and human capital trapped in established manufacturing modes, such as stamping and welding steel. Commercial developments remain extremely fluid, and which firms, or even which kinds of firms, will win the race cannot yet be anticipated.

Autobody Design Options

The body of a car currently accounts for one-fourth of its total curb (*i.e.*, empty) weight; is its largest single system; provides its structural integrity, safety, and comfort; and largely determines its look, feel, and market attraction. For an ultralight-hybrid hypercar, the body becomes even more important, because its structure and materials are the keys to making the whole car ultralight and low-drag.

The feasibility of hypercars as practical and profitable products therefore depends critically on making the body extremely light without compromising its basic requirements. It must also be cost-competitive. A hypercar might cost less than a standard car even if its body cost more, because the body would be so light that the rest of the car could become cheaper, but the case is more compelling if the ultralight body itself also costs less to make than the standard steel unibody. Several different but convergent kinds of designs appear able to achieve this. Among them, true "monocoques" (whose shell is the structure—much like the light, thin, but hard-to-break shell of a lobster) appear better able than spaceframe- or unibody-based alternatives to achieve maximum strength with the least weight.

Though certain innovative approaches with light metals, or even with advanced steel structures, may offer significant palliatives, it is highly advantageous to "leapfrog" autobody design directly to new ways of mass-producing the body-in-white (BIW) from advanced composites.

The benefits of this major shift in materials, design, and manufacturing could include:

- greatly reduced fuel consumption and emissions;
- unchanged or improved crashworthiness (partly because advanced-composite structures can absorb five times as much crash energy per kg as steel);
- more quiet and refined operation (because composites, especially foam cores, can suppress noise, vibration, and harshness better than metal bodies);
- increased stylistic flexibility and improved fit, finish, and aesthetics (such as the virtually invisible seams made possible by composites' tight molding tolerances);
- freedom from rust, greater resistance to minor dents and scratches, and generally greater durability, but at least comparable and perhaps better recyclability;
- an order of magnitude fewer body parts;
- safer, less polluting, and less wasteful methods of production; and
- more agile and less financially risky production and marketing with lower fixed costs, comparable or possibly lower total costs, small breakeven sales volumes, diversified model portfolios, rapid product cycles, and ability to respond quickly to changing markets.

Achieving these results reliably requires a challenging short-term reliance on highly integrated and often unfamiliar techniques, materials, and optimization methods. However, the initial costs would be such a small fraction of the roughly $1 billion required to tool up a new steel-car model (often nearer $4–6 billion for that model's total development investment) that automakers, whether large and risk-averse or smaller and perhaps more receptive to taking risks to get ahead, may find ample motivation. Those who act swiftly could be rewarded with competitive advantages as decisive as those Henry Ford achieved with his 1908 Model T.

Components

Components other than the body-in-white would account for about 70–80% of the hypercar's curb weight. About 40% of the total curb weight would be the miscellaneous nonpropulsion systems that are normally considered minor in today's cars. Many of these require special design attention to reduce mass and accessory loads, which could offset the hypercar's great propulsive efficiency if not reduced by at least severalfold, as today's best technologies appear to permit.

Many hypercar components would be similar to today's, but much smaller and lighter. The main differences would probably include:

- Some components, such as power steering and power brake booster, become unnecessary with ultralight construction, while others, such as the starter, alternator, axles, differentials, multispeed transmission, clutch, driveshaft, and universal joints, could be displaced by the hybrid drivesystem.

- Except in some early models that might use a small internal-combustion engine for convenience, the powerplant would probably range from modestly different (Stirling or gas-turbine) to profoundly different with no moving parts (fuel cell or thermophotovoltaic).

- Rather than hauling a half-tonne of batteries for driving range (Figure 7), buffer storage might entail a high-specific-power (>800 W/kg) nickel-metal-hydride or wound-foil lead-acid battery roughly three times heavier than today's cars' ordinary 14-kg lead-acid starting battery, but lasting about as long as the car. Later, carbon-fiber superflywheels, ultracapacitors, thin-film lithium batteries, or some combination of these technologies could be used.

- Power electronics could be far smaller in mass, size, and cost than for today's battery-electric cars, because the platform would be severalfold lighter (not requiring a large battery bank).

- Each component, subsystem, and system would require and receive rigorous and holistic design. Many subtle energy losses or mass accretions now considered negligible would become important and would be minimized.

Technologies identified as particularly attractive, though not essential, for a successful hypercar include advanced switched-reluctance motor/generators and power electronics, Stirling Thermal Motors' external-combustion engine (now completing several years' reliability testing), proton-exchange-membrane fuel cells, and a wide range of specific technologies related to suspension and steering, brakes, wheels, tires, glazings, interior climate control, seats, safety equipment, lights, electricals, instruments, and controls. More important than any of these will be a highly integrative whole-platform design process that fully exploits the potential of the hypercar's enlarged "design space."

III. Fuel-Cell Hypercars

Using the design philosophy described in the previous section, RMI has now undertaken the task of conceptualizing and modeling a hypercar powered by a proton-exchange-membrane fuel cell.

Modeling

To explore hypercar-optimization issues more quantitatively, RMI developed parametric spreadsheets[2] for use in combination with SIMPLEV—a second-by-second, component-matrix-based simulation tool (Cole 1993).

The spreadsheet model consists of a detailed mass budget for the vehicle as well as tools for estimating various aspects of vehicle performance and fuel economy. Using these heuristic tools to derive inputs for SIMPLEV, the conceptual vehicle was run through the U.S. Federal Urban Driving Schedule (FUDS) and the U.S. Federal Highway Driving Cycle. To represent more realistic driving conditions, the conceptual vehicle was also run through versions of those cycles with all second-by-second velocities multiplied by 1.3, as well as through the US06 Driving Cycle. (The "intensified" driving cycles, which simultaneously correct power, energy-storage, and emissions parameters, yield somewhat worse fuel economies than the correction factors applied to fuel-economy results by the U.S. Environmental Protection Agency.)

The adaptation of RMI spreadsheet models, and the outputs of SIMPLEV for three fuel-cell hypercar scenarios, are included in the Appendix. The three scenarios modeled were: a "base-case" scenario optimized in traditional hypercar fashion with a relatively high-power (36 kW) load-leveling device (LLD), a "min-LLD" scenario using considerably less LLD power capacity (12 kW), and a "no-LLD" scenario where the fuel-cell powerplant was sized to meet all performance criteria without the assistance of a high-power electrical storage device. The latter two scenarios were undertaken to try to take advantage of the fuel cell's excellent load-following capabilities due to its high efficiency at partial loads.

To assure the broad salability of any conceptual PEMFC hypercar modeled, demanding performance criteria were met in each of the three scenarios.

Design Criteria

Industry design criteria for efficient vehicles have tended to focus on limiting compromises in performance rather than on *improving* it. Marketability, however, probably dictates that new vehicles must be not only equivalent to those they displace but in some way *more* attractive to consumers. RMI's analyses suggest that hypercars would yield generally improved acceleration, handling, braking, safety, and durability. Since fuel economy and emissions are low on the list of criteria for most consumers today, and may be lower in the future (based on increased popularity of sport-utility vehicles and minivans), efficient vehicles must be better in other respects if they are to gain the large market share required to provide significant societal benefits. The following criteria (based in part on similar criteria developed by the U.S. Partnership for a New Generation of Vehicles, or PNGV) appear essential for the U.S. market, and were thus assumed for this analysis (all improvements are relative to current touring-class production sedans):

Key Component Assumptions

Based on previous RMI benchmarking to technologies that appear ready for high-volume production by ~2002-2004:

Body-In-White (BIW):

- Based on a major automaker's validated all-aluminum unibody BIW, a mass of 153 kg (with closures). Although carbon-fiber-dominated advanced-composite monocoque BIWs should be able to do better, this is a remarkable accomplishment for aluminum and should have no problem supporting the gross loadings of any of the three scenarios. Previous modeling assumed a 150-kg advanced-composite BIW (with closures).

Fuel Cell and Related Systems:

- 3.15 lb/gross kW bare stack (Ballard) + 1 lb/gross kW balance-of-system (~2004 estimate by James 1997) + 1 lb/gross kW radiator, coolant, deionizing fluid, pumps, filters, etc. (*id.*) = 2.34 kg/gross kW.

- 8-kg latent heat (phase-change) battery + 5 kg of insulation for fuel-cell freeze protection.

The time allowed for the fuel cell to ramp up to full power (based on estimates for an appropriate expander/compressor @ 3 atm) set at 1.55 seconds for all scenarios. Please see the discussion for more information.

Fuel Systems:

- 4.65 kg of hydrogen in a 34.4-kg, 345-bar (5,000-psia), filament-wound T-1000 carbon-fiber[3] tank lined with metalized polyester film[4] (Thomas 1997).

- 2 kg of fuel delivery, sensors, etc.

Motor:

- Unique Mobility SR218H permanent magnet motors, scaled from 42 kg to fulfill starting torque requirements.

Load-Leveling Device (LLD):

Three scenarios were modeled with varying sizes of LLD, based on available modules of the Bolder Technologies thin-foil lead-acid battery. In the "base-case" scenario, the fuel cell is sized to meet the gradability target (90 km/h) at gross mass on a 6.5% grade, and the LLD is sized for acceleration and acceptable capacity for multiple passes on a grade at gross mass (see the discussion for more information). In the "min-LLD" scenario, the fuel cell is sized to meet passing requirements on a grade at gross mass, and a small module of the Bolder Technologies battery is used to meet acceleration requirements and to allow for regenerative braking. In the "no-LLD" scenario, the fuel cell is sized to meet all acceleration and gradability requirements.

The LLD increments modeled, based on available modules, were:

- Base-case: 42-kg, 36-kW Bolder Technologies thin-foil lead-acid.
- Min-LLD: 14-kg, 12-kW Bolder Technologies thin-foil lead-acid.

Control Strategy

The following methods were used to represent appropriate vehicle control strategy:

- The minimum operating power fraction for the fuel cell was set at 0.04, yielding a minimum operating power of 1.2 kW, 2.2 kW, and 2.6 kW for the base-case, min-LLD, and no-LLD scenarios, respectively.
- In the base-case and min-LLD, the lead-acid battery was allowed to move between 50% and 65% state of charge (SOC).
- DC to DC conversion was accounted for in the base-case and min-LLD scenarios by doubling the internal resistance of the lead-acid battery.

Results

The three PEMFC hypercar scenarios were designed and optimized using RMI spreadsheets (Table 3), and were modeled in SIMPLEV[5] over several driving cycles (Table 4).

Table 3. Performance Results

Scenario	Curb Mass	0-100 km/h @ test mass (M_{test})	0-100 km/h @ gross mass (M_{gross})	Speed on 6.5% grade @ M_{gross}
Base-case	712 kg	7.2 s	10.2 s	90 km/h
Min-LLD	772 kg	7.9 s	11.0 s	140 km/h
No-LLD	790 kg	8.2 s	11.4 s	155 km/h

All times were calculated with 500W of accessories turned on.

Table 4. SIMPLEV Fuel-Efficiency Results

Scenario	Curb Mass kg	Intensified FUDS mpg_{equiv} (km/kg)	Intensified 55/45 FUDS/Highway mpg_{equiv} (km/kg)	US06 mpg_{equiv} (km/kg)
Base-case	712	124 (205)	120 (199)	100 (166)
Min-LLD	772	117 (194)	115 (190)	96 (159)
No-LLD	790	102 (169)	109 (180)	91 (151)

Discussion

Fuel Cell Efficiency and Driving Work: A Good Match

To match zones of highest efficiency to typical use patterns, designers of powerplants, load-leveling devices, and power electronics need to know the relative distribution of *cumulative* energy throughput at various power levels over representative driving cycles. A simple graph showing cumulative energy throughput at various power levels for a base-case PEMFC hypercar over the duration of a complete intensified FUDS cycle is shown in Figure 8. On top of that graph is drawn a representative efficiency-vs.-power curve for a PEMFC (scaled from a DTI representation, Thomas 1997). The relative conformity of the high-efficiency zones of this curve to the areas of largest cumulative energy throughput suggest an elegant match between fuel-cell efficiency and typical driving conditions. This match is significantly superior to that achievable by combustion engines, which generally increase steadily from low efficiency at low power to higher efficiency (although still low relative to the fuel-cell) at full power.

This match suggests that, even in a hybrid-electric configuration *with* a load-leveling device, the fuel cell has tremendous potential to follow most driving loads while maintaining high efficiencies. To the extent that the region of high cumulative energy throughput is significantly higher than (shifted to the right of) the power fraction at which the fuel cell operates at highest efficiency, however, the load-leveling device will still play an important role in the overall control strategy. This and other factors that determine the sizing of the LLD are discussed in the next subsection.

Sizing the Load-Leveling Device

The high part-load efficiencies of a fuel cell (Figure 8) argue that a large fuel cell should be used, and that only minimal load-leveling is required. Although the fuel cell has tremendous load-following capabilities, other important consequences of downsizing the high-specific-power load-leveling device are highlighted by a comparison of the three scenarios modeled. Among these consequences are:

- mass compounding (712 kg vs. 772 or 790 kg);
- overall fuel economy reduction (120 mpg_{equiv} vs. 115 or 109 mpg_{equiv});
- poorer 0–100 km/h acceleration (7.2 seconds vs. 7.9 or 8.2 seconds).

Because a larger fuel-cell APU is used, however, the minimum-LLD and no-LLD scenarios have much better gradability (90 km/h on a 6.5% grade at gross mass vs. 140 or 155 km/h), although all three meet the PNGV design targets. Also, the no-LLD scenario actually shows *increased* fuel economy for highway driving, The is because the cruising loads at highway speeds are well suited to a large APU, and because fewer hard transients and opportunities for regenerative braking exist under these conditions.

Number of Passes on a Grade

Built into the control strategy for the base-case scenario is the very gradual reduction in power available to the driver as LLD charge is depleted when passing repeatedly on a hill at gross mass (see Moore 1996a for more detail). On the performance spreadsheet for this scenario, a simple calculation has been included to indicate the number of 60–100 km/h passes (currently five) that are available to the driver on a 6.5% grade at gross mass, using only 40% of the LLD's charge. This does *not* include any contribution from regenerative braking or from the fuel cell, which is sized to maintain a 90 km/h speed indefinitely at gross mass on a 6.5% grade. Estimates indicate that the fuel cell would typically add at least one pass per eight LLD passes. A greater contribution would result from LLD charging if the vehicle spent any significant time below 90 km/h.

Performance Sensitivity and Fuel-Cell Ramp-Up Time

A somewhat arbitrary total time of 1.55 seconds was chosen to allow the fuel cell to ramp up to full power, based on estimates of the part-load behavior of an appropriate three-atmosphere compressor. To test the sensitivity of vehicle performance to this assumption, a base-case scenario PEMFC hypercar was allowed 3.8 seconds to ramp up to full power (based on estimates including some allowance for a cold start). Given this assumption, the model predicted a 0–100 km/h time of 7.9 seconds at test mass, rather than the 7.2 seconds presented in the results subsection. Although this comparison is not rigorous, it can be seen that even a conservative assumption for fuel-cell ramp-up would still allow the performance target of 8.5 seconds to be met, by a considerable margin, in the base-case scenario.

IV. Fuel Shifting

"Hydrogen is a logical choice because it doesn't pollute. But hydrogen tanks are huge and heavy."
—*USA Today,* 24 February 1997

A shift to hydrogen fuel could greatly reduce both the air pollution and the climatic effects of cars, but there is a widespread misconception that hydrogen storage must be prohibitively bulky. Except in special fleet-vehicle cases, gaseous fueling is seldom seen as attractive today because:

- the cars themselves are so inefficient that large, heavy, and costly tanks are needed to carry enough fuel for substantial range;
- their more frequent refueling may require more ubiquitous and hence more costly refueling infrastructure;
- they would consume significant amounts of a costlier fuel; and
- the fuel-cell stack (the ideal way to convert energy from gases to electricity) required to propel such heavy cars would itself be excessively heavy, bulky, and expensive.

However, in a 1994 conceptual study for Argonne National Laboratory, Directed Technologies, Inc. (DTI) concluded that a Ford Taurus converted into a proton-exchange-membrane fuel cell (PEMFC) hybrid, and fueled with a strong, safe, compressed-hydrogen tank weighing less than a filled gasoline tank, could provide range comparable to that of the original gasoline-fueled Taurus if a severalfold larger tank could be accommodated (James *et al.* 1994). DTI also found that if the hydrogen were made by splitting water with cheap offpeak retail electricity in mass-produced electrolyzers, the hybrid's fuel would be cost-competitive on a per-kilometer basis with American taxed gasoline (Thomas and Kuhn 1995).

These impressive findings result from the severalfold higher efficiency of converting gaseous hydrogen rather than gasoline into tractive energy: the electricity used to make the hydrogen is a costlier energy carrier[6], but hydrogen's efficient use, via the hydrogen-fuel-cell cycle, more than compensates. (Specifically, the fuel cell is nearly twice as efficient as the *peak* efficiency of an ordinary spark-ignition, gasoline-fueled, internal-combustion engine, and over three times as efficient as the *average* efficiency of such an engine in a non-hybrid car, integrating over a typical driving cycle.) DTI's conceptual Taurus conversion, however, did not assume the significant improvements in platform physics posited by the hypercar concept.[7]

Hypercars Make Compressed Gaseous Fuels Practical

According to preliminary modeling, a PEMFC hypercar would convert hydrogen into traction about four to six times more efficiently than today's cars convert gasoline into traction. Hypercars should thus need so little fuel that a small, light, cheap tank of compressed hydrogen gas or natural gas could take them a very long distance—thereby largely or wholly offsetting hydrogen gas's low energy content per liter. Moreover, PEMFCs have net peak efficiencies of over 60% when fueled with hydrogen, and achieve high efficiency over a wide range of partial loads well matched to common driving conditions. Requiring so little fuel for a given range, hypercars could thus afford to use relatively costly fuel, such as hydrogen reformed from natural gas or electrolyzed from water. (For example, if the car uses only a sixth as much fuel, the fuel will cost the same per *kilometer* even if it costs six times as much per *megajoule*.) Hypercars could achieve these results without compromising performance. This does an end-run around the fuel-price-elasticity debate, and makes rapid market success much more probable.

Additionally, hypercars would make fuel cells—the ideal way to use hydrogen—a far more robust vehicular powerplant option by reducing the kilowatt output capacity, physical size, mass, and cost of the fuel cells *required to run* the car, thus providing generous safety margins and multiple technological backstops to fuel-cell development (see Section V); more good eggs in the compressed-methane-or-hydrogen basket.

In short, hypercars could:

- make hydrogen's success as the main fuel for road vehicles significantly less dependent on decreasing fuel-cell cost, size. and weight;
- accommodate a more gradual phase-in of a hydrogen refueling infrastructure;
- ensure the competitiveness of gaseous automotive fuels even if fuel cells fail to meet their design goals and another form of APU must be substituted (in other words, they diversify the APU portfolio suitable for gaseous fuels);
- rely for their success on consumers' demand for superior performance and features, not on cleanliness or efficiency, and on automakers' pursuit of competitive advantage, not on government mandates like ZEV or CAFE; and
- by these means make achievement of a hydrogen road transport sector far more likely.

Depending on how sanguine one is about the chances of hydrogen becoming a cheap, convenient, and widely available fuel, this complementary approach from the other direction—making the car ideal for hydrogen, not just the other way around—could be considered a selling tool, a vital foundation, or an insurance policy. Either way, it is a sound investment, adding yet another motivation to the commercialization of hypercars.

Onboard Storage: Hydrogen's Achilles' Heel?

An important feature of pressurized-hydrogen fuel-cell hypercars worth highlighting is their modest tankage requirements. Although DTI claims that volumes up to five times greater than the original gasoline tank could be accommodated in a vehicle with careful packaging (James *et al.* 1994), they recognize that tankage much more comparable in size to a gasoline tank is usually required. To illustrate the onboard storage requirements for a PEMFC hypercar, consider such a car fueled with 4.65 kg of hydrogen stored onboard in a carbon-fiber tank like the one described in the component assumptions in Section III. Integrated into a vehicle, such a tank design, suggested by Fred Mitlitsky of Lawrence Livermore National Laboratories (LLNL) and described by DTI, could provide greater safety than conventionally packaged gasoline.[8]

Table 1 illustrates that, if the tank described above were put into the base-case PEMFC hypercar, it would only be about 2.5 times larger—and about 50% *lighter*[9]—than the gasoline tank required to give a conventional vehicle the same driving range (about 925 km).

Even using the presently required U.S. tank safety factor (ratio of rupture to design pressure) of 2.25, these results are impressive. But though the reasons for regulatory conservatism are understandable, that safety factor appears to reflect traditional understanding of metal tanks prone to fatigue, embrittlement, corrosion, and considerable manufacturing variability. Greater experience may well persuade the safety authorities that the advanced-composite tanks analyzed here lack these drawbacks, and that a safety factor of around 2.0 is very reasonable with careful quality assurance (including non-destructive testing) in materials and mass production, perhaps supplemented by embedded damage or stress sensors.

The exceptional driving range offered by a hypercar with just 4.65 kg of hydrogen is an attractive feature, particularly while the hydrogen refueling infrastructure is young. But it is important to note that the extra onboard storage capacity could be partly traded away for better packaging, reduced pressurization levels, or savings in tank and vehicle mass. This design-space "breathing room,"—a result of first optimizing the vehicle loads and efficiency—is also an important aspect of determining vehicular requirements for fuel cells. This flexibility makes the success of PEMFC hypercars more likely.

comparable to its ICE counterpart. When configured with a 45 kW load-leveling device, only 40 net kW would be required, and those fuel cells could compete in capital cost with the Taurus's internal-combustion-engine mechanical driveline if they cost about $37/kW. But a Taurus-class PEMFC hypercar, needing only 29 net kW of fuel cells, would therefore be competitive using PEMFCs that cost 38% more.

It is important to note that Table 2 is only a rough, side-by-side comparison of one or two components, and it does not fully capture the economic incentive for using fuel cells in low-load cars. A more rigorous analysis would no doubt uncover increasing benefits as the vehicle were optimized at a system level. Depending on vehicle priorities, the additional degrees of freedom, or design-space breathing room, earned by up-front load reduction and efficiency improvement could be "cashed in" for an improved commercialization scenario for the automotive fuel cell. As previously mentioned, reducing the PEMFC hypercar's range to that of a conventional car would result in even more modest tankage requirements and the associated savings in mass, cost, and packaging could be factored into the optimization. More directly, reducing the acceleration capabilities of the conceptual hypercar from a touring-class vehicle to that of a peppy standard-class vehicle could significantly advance the date of automotive adoption of fuel cells (within marketing constraints) by further lowering the price hurdle that this promising young contender must overcome.

The difficulty of accommodating new technologies in conventional cars is presumably why, despite otherwise demanding requirements, the PNGV target for 0–60 mi/h is a doggish 12 seconds. One might also argue that PEMFCs should be introduced first in smaller, lighter, four- to five-passenger car models in order to build PEMFC production volumes and cut costs. Our modeling of the PNGV five- to six-passenger platform thus understates hypercars' full potential to accelerate fuel-cell commercialization.

Cheap PEM Fuel Cells Could Widely Displace Thermal Power Stations

Even with comparatively greater price tolerance, hypercars still require fuel cells that cost substantially less than they do today. However, important opportunities exist in many building applications that can build fuel-cell volumes and cut cost.

Fueled with reformed natural gas, PEMFCs should be able to undercut the short-run marginal cost of generating power from even the most efficient thermal power stations. For example, the net electrical output efficiency of a stationary PEMFC using reformed methane is often quoted at about 40% (LHV) with neither heat recovery from the stack to the reformer nor pressure recovery from the stack's hydrogen input and stack output to the air compressor. With both, the best technology is now typically closer to 50%. Natural gas at $3.70/GJ or $4/1000 ft^3 (the average U.S. price to CNG fleet-vehicle refueling stations in 1992–93) would thus produce electricity at 3.0¢/kWh: 2.7¢/kWh for the fuel plus 0.3¢/kWh for the cost of a fuel cell at ~$200/kW.[11] Note that this is the delivered electricity price, not busbar: it avoids all grid costs and losses, making three-cent power easily competitive with almost every utility's short-run marginal cost, even from the newest ~60%-efficient, but centrally located, combined-cycle gas turbines. In effect, the PEMFC is about as efficient as those turbines, but far smaller and more modular, easier to mass-produce, and probably cheaper per delivered kW even at modest production volumes.

However, this comparison neglects one of the fuel cell's most valuable benefits: it continuously produces not only electricity but also waste heat with a useful temperature of about 80°C, ideal for heating and cooling buildings or for heating domestic water. Such waste heat is valuable, because it can displace heat otherwise produced from furnaces or boilers that have their own costs and losses, both valuable to avoid. Each kWh (3.6 MJ) of fuel used by the PEMFC will yield about

1.8 MJ of electricity plus up to 1.8 MJ of waste heat[12], which when timely (needed approximately when produced) can displace up to 2.6 MJ of fuel normally used by a typical ~70%-efficient commercial boiler. The avoided boiler fuel is thus worth a fraction of the fuel cell's fuel cost (about 2.6/3.6), multiplied by the duty factor of the local heat requirements. For a typical commercial building requiring substantial heating or cooling at virtually all times of the day and year, this waste-heat credit (plus an estimated 3% allowance for displacing the capital and maintenance costs of the boiler) would offset three-fourths of the fuel cell's natural-gas costs, reducing the effective net cost of the electricity to only 1.0¢/kWh. Fuel, operation, maintenance, and major-repair costs of a typical central power plant is about 2.5¢/kWh. And, delivering the average kilowatt-hour costs 2.3¢/kWh.

To be sure, the actual site-specific comparison is far more complex, because persistent temporal imbalances—the less efficient the buildings, probably the greater the imbalances—are likely between the supply of and the demand for both heat and electricity. But real-time electricity pricing, the relative ease of storing heat, and the prospect that cheap superflywheel or ultracapacitor electrical storage will enter the market in the late 1990s (also stimulated by the vehicular market) all suggest that these details will not materially change the conclusion: cheap PEMFCs could economically and practically displace any thermal power station in circumstances that occur widely—wherever there is natural gas and a moderately frequent market (even as small as kilowatt-scale) for the waste heat.

Buildings use two-thirds of U.S. electricity. In principle, such a formidable competitor could put a significant portion of thermal power plants out of business. But the competitive prospect does not stop with buildings. The current U.S. private fleet of some 150 million cars, excluding other motor vehicles, and averaging 20 continuously rated kW of onboard fuel-cell APU capacity per vehicle, would represent a generating capacity about five times that of all U.S. electric utilities. The fuel cells could be run silently, very cleanly, and at low marginal capital cost (since they are already paid for and promise to be durable) when plugged into both the electric and the natural-gas grids, assuming a simple reformer to produce hydrogen at, or sufficiently near, the plug-in site. The average American car is parked ~96% of the time, usually in habitual sites such as the home or workplace. Although the electric-and-gas connection would have a capital and metering cost, it would typically be in sites already served, or nearly served, by both grids, and the cost of the electric hookup would probably be less than the "distributed benefits" (Lovins and Yoon 1993) of onsite generation to support local electric distribution.[13]

In these circumstances, one might expect gas companies or third-party entrepreneurs to start providing hookups. A simple credit-card swipe when plugging in the car would automatically handle the gas billing and electricity credit, both at real-time prices. These plus a profit for the entrepreneur could well repay a significant fraction of the depreciation and finance costs of owning the car—together accounting for ~64% of the total cost of the typical American family's second-biggest asset.[14] If even a modest fraction of car-owners took advantage of this opportunity to earn significant profit from that otherwise idle asset, they could well displace a significant portion of fossil-fueled power generation most or all of the time. To utilities now expecting to sell a lot of their surplus electricity to battery-electric cars, and already concerned about stranded generating assets exposed to wholesale competition from combined-cycle gas turbines, such widespread competition from a potentially ubiquitous and flexible power source is hardly a welcome prospect.

The prospect of beating power plants (starting in niche markets with costly electricity or bottlenecked grids but cheap gas) could inspire entrepreneurs to aggregate PEMFC markets for microscale combined-heat-and-power until the fuel cells become cheap enough to use in cars. These two enormous markets could then play off each other: commercialization in buildings will certainly help ensure that hypercars will follow. As in electrical storage, this greatly heightens the likelihood that both will happen. Both are very good news for the environment. Together, displacement of fossil-fueled power plants plus fuel-cell hypercars could reduce by more than half all present climate-threatening emissions from an industrialized nation like the United States.

To help illustrate this conservative scenario for fuel-cell commercialization, Figure 9 illustrates cost reductions as a function of doubling production, given a progress ratio of 82% (Thomas 1997) and an initial cost of $1,500/kW.

Implications for Further Development: Pursuing the Leapfrog to Hydrogen-Fueled Transportation

This analysis argues that the hypercar concept's low-drag, low-load, efficient platform enables the use of gaseous hydrogen fuel and direct-hydrogen fuel cells in passenger vehicles significantly earlier than would otherwise be possible by enlarging the design space in which to use these exciting technologies. Other reasons exist for rigorously pursuing a direct-hydrogen development path. Among these reasons (most of which will be thoroughly described in an upcoming report by DTI for the National Renewable Energy Lab) are:

- Direct-hydrogen operation minimizes the required platinum loadings, and thus cost. Low cost allows greater latitude when sizing the fuel cell to maximize efficiency.

- Reformers and reformate gases would reduce the efficiency of fuel-cell vehicles due to low reformer efficiency, greater vehicle mass, and lower fuel-cell efficiency (which is due, in turn, to hydrogen dilution, low hydrogen utilization, and anode-gas recirculation complexity).

- Fuel-cell vehicles with onboard reformers would also be inferior to direct-hydrogen in other, related ways, including overall mass, cost, complexity, and, importantly, responsiveness.

- When considering the load factors of onboard vs. offboard reformers, the resulting economics clearly favor the offboard application, potentially by one or two orders of magnitude.

Given the potential attractiveness of using pure hydrogen as a transportation fuel, the development of appropriate infrastructures, such as the use of small-scale, mass-produced electrolyzers or reformer "appliances" (Berry 1996, Thomas *et al.* 1996) or the development of hydrogen corridors or regions (Princeton University's analysis of the LA basin, Ogden *et al.* 1996), should be more aggressively pursued.

Accordingly, government and industry funding must not be based on an arbitrary system boundary drawn around the vehicle shell; infrastructure cannot be treated separately from vehicle development, because of the interconnectedness of the two. If narrow system boundaries can be overcome and integrated funding priorities can be achieved, then perhaps, with a little help from hypercars, the realization of the many benefits of hydrogen-powered transportation will come to pass—widely, rapidly, responsibly, and profitably.

Notes

[1] Smaller generally means cheaper. Surprisingly, however, RMI has found that cheaper does not necessarily mean less efficient. In other words, *price* and *efficiency* are not necessarily correlated in technological markets.

[2] Examples of previous Hypercar Center analyses using these tools, for scenarios where a Stirling engine coupled to a generator provides the onboard electrical power, include Moore (1996a) and Moore (1996b).

[3] Although the choice of fiber is still up for debate: "The performance factor of a bladder lined tank using lower strength/less expensive carbon fibers (such as T700S or Panex 33) can match the performance factor of similar tanks with thick liners using higher strength/more expensive carbon fiber (such as T1000G). This is important because tank cost is dominated by fiber cost and the fiber cost per tank for T1000G is currently a factor of three–four times that of T700S or Panex." (Mitlitsky *et al.* 1996)

[4] James *et al.* (1994) show that this novel feature, while preserving excellent safety in rigorous tests, raises the tank's performance figure (burst pressure x internal volume / tank mass) from 1.3 to 1.95 megainches or to 49.5 km—some 13 times normal the performance for steel or nearly nine times that for aluminum tanks. Substituting the film for a solid aluminum liner in a wound-carbon tank cuts total tank mass by 50% and materials cost by 36% (James *et al.* 1994).

[5] SIMPLEV modeling correlates closely with vehicle test data (Burke 1994) and shows very slightly worse fuel economy than CarSim (Cuddy 1995), a proprietary hybrid-electric vehicle simulator developed at AeroVironment (Monrovia CA) for GM.

[6] Electricity at 4¢/kWh contains the same enthalpy (heat content) as oil at $68/barrel—over four times the recent world crude-oil price, or 1.3 times a nominal U.S. taxed gasoline price of $1.25/gal ($0.33/l), but much lower than motor-fuel prices in almost all other industrial countries.

[7] A ~10% reduction in mass and in aerodynamic drag (to $C_D = 0.28$, $A = 2.14\ m^2$), accompanied by a high $r_0 = 0.0135$ and inefficient accessories were assumed.

[8] This is largely because the hydrogen tanks fail gracefully (leak-before-break), hydrogen is buoyant, and its low-emissivity flame has no incandescent soot to radiate infrared and cause burns at a distance. Kuhn (1995) states that in extensive tests, lightweight composite tanks were crashed, crushed, dropped, shot, burned, and blown up, but failed to produce any consequences as bad as those resulting from comparable assaults on ordinary gasoline tanks.

[9] Indeed, normalized to the same driving range, the filled hydrogen tank would weigh less than the filled gasoline tank of the conservatively designed hypercars simulated in Moore and Lovins (1995).

[10] These figures are not directly comparable not only because the proper comparison is in tractive power delivered to the wheels, but also because the fuel-cell rating is continuous, while the IC engine is designed to produce its rated output for only three minutes at sea level at 20°C.

[11] Assuming, for illustration, a 10%/y real fixed charge rate and a 75% capacity factor, such as might be characteristic of an efficient building with fairly long occupied hours.

[12] This heat would otherwise need to be dissipated in some other way, so the cost of a heat exchanger cannot be avoided except at extremely small scale.

[13] The new Edison EV subsidiary expects to install present-technology Hughes inductive-paddle rechargers, whose electric capacity is broadly comparable, for about $1,000 each, or ~$50/kW. This is a small fraction of the typical value of distributed benefits.

[14] For illustration, a 20-kW "mobile power plant" earning an average of, say, 5¢ gross or 2¢ net of fuel cost per kWh—remember, the car would often generate during peak hours, earning real-time pricing premia—for an average of, say, 15 h/d, or 65% of its nominal parking time, would return $2,000 net per year, or over 50% of the total depreciation and financing cost of the average MY1994 U.S. passenger car (AAMA 1994, p. 56).

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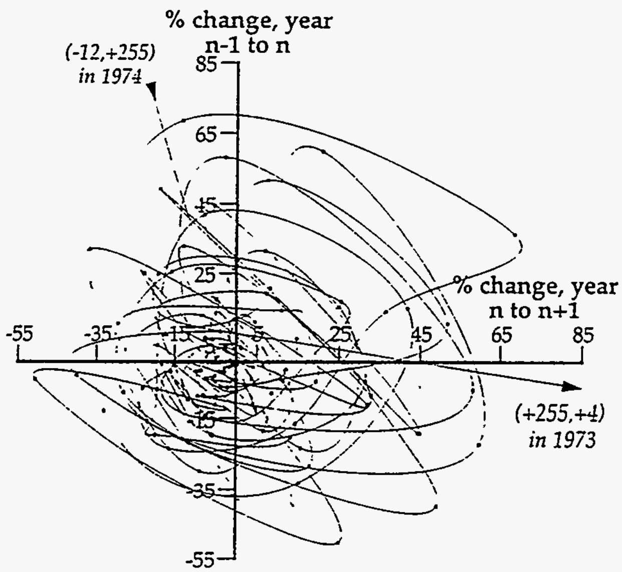
Figures

Figure 1. The Random Walk Of World Real Crude-Oil Price, 1881–1993



Worldwatch Institute data cited to British Petroleum, *BP Statistical Review of World Energy* (London 1993) and electronic database (London 1992); Worldwatch estimates, based on *id.* and on U.S. DOE'S *Monthly Energy Review* February 1994.

Figure 2. Incrementalism and Diminishing Returns

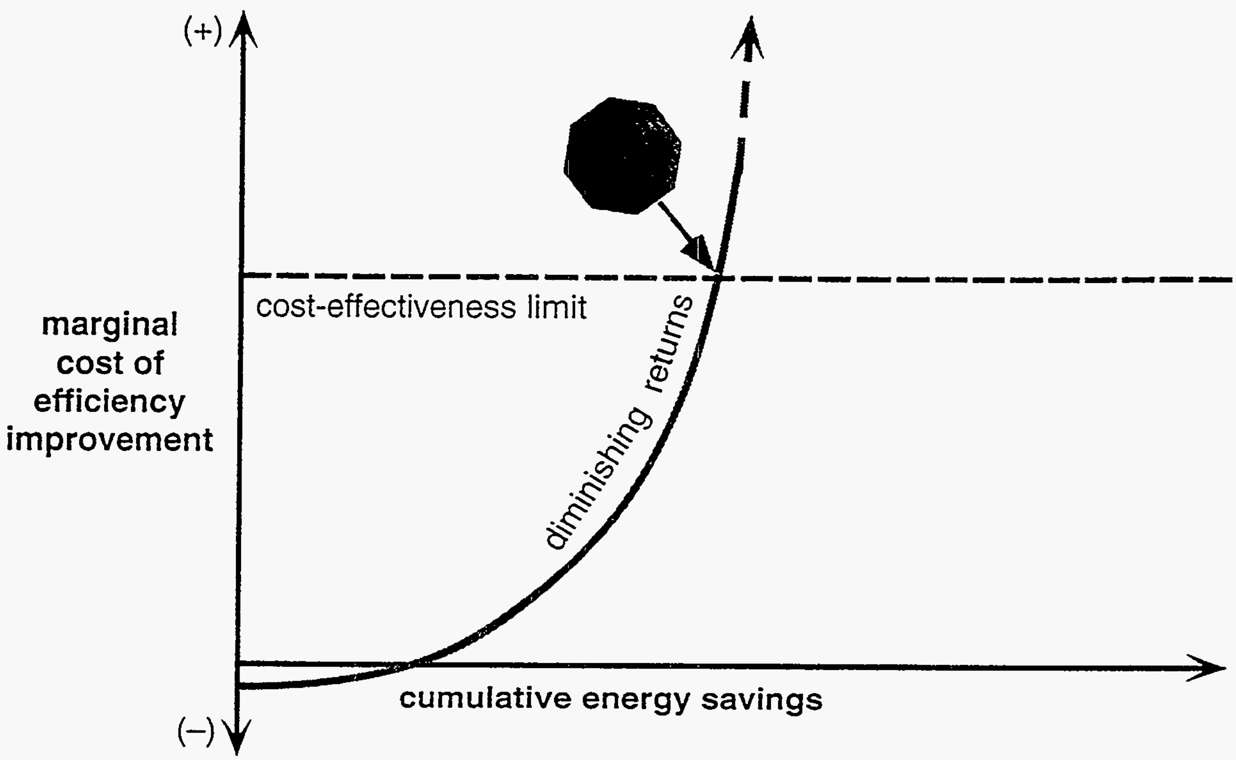


Figure 3. Systems Approach and Leapfrog

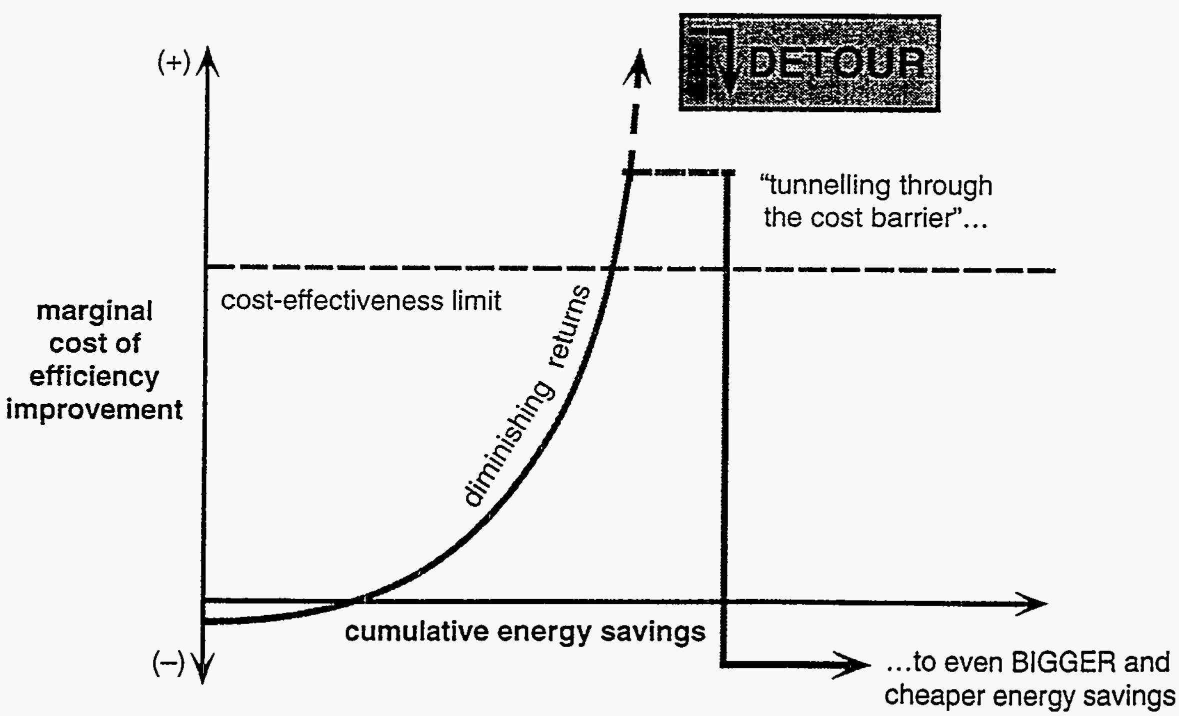


Figure 4. Energy Flow in a Series Hybrid

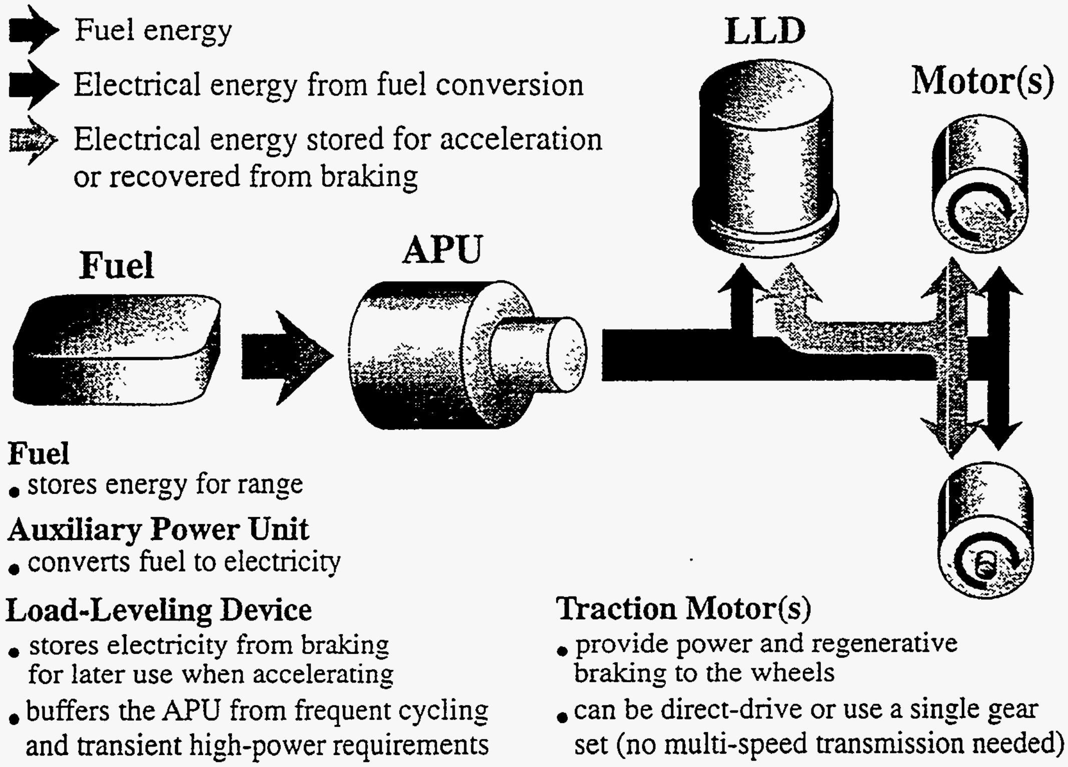


Figure 5. Two Ways to Drive: The End-Use Approach to Reducing Loads

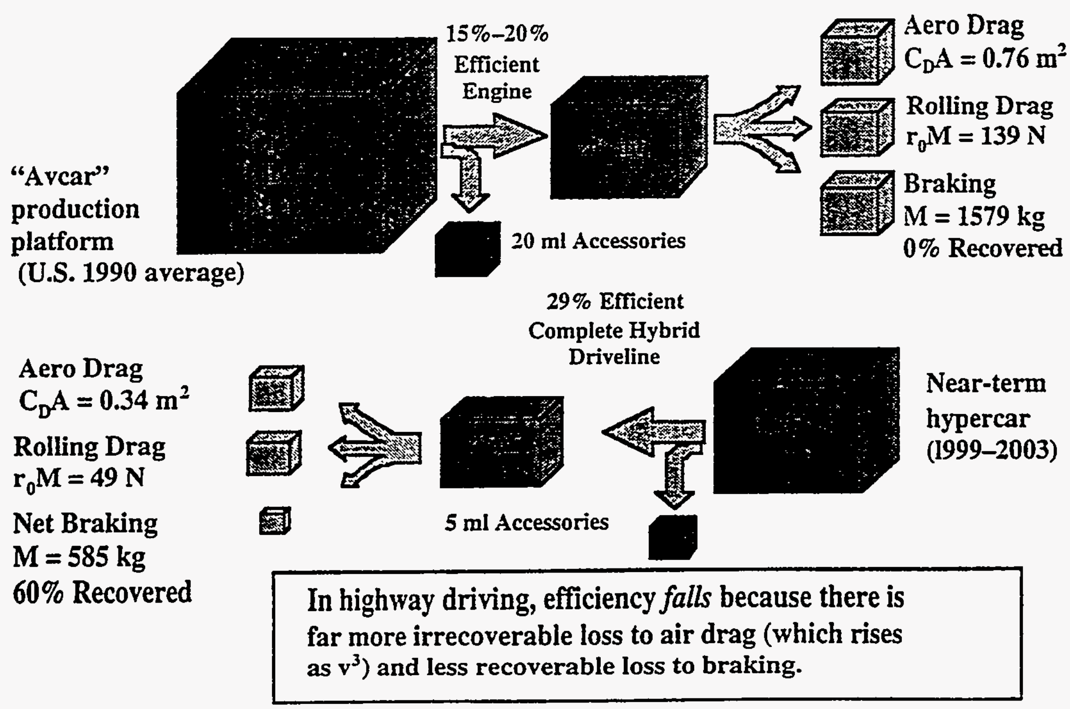
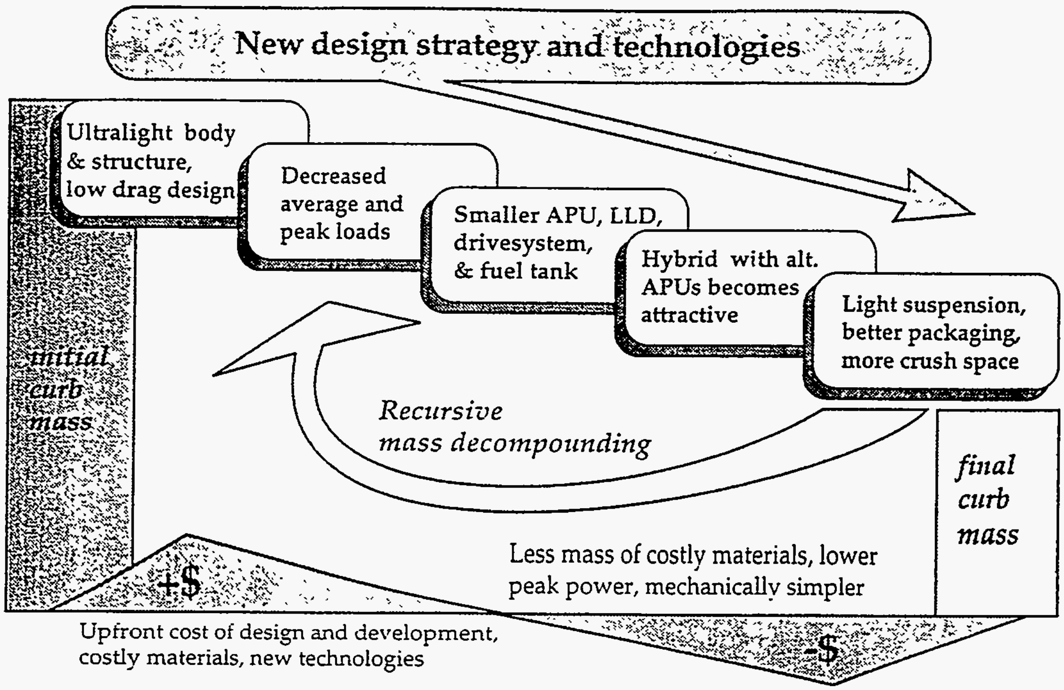
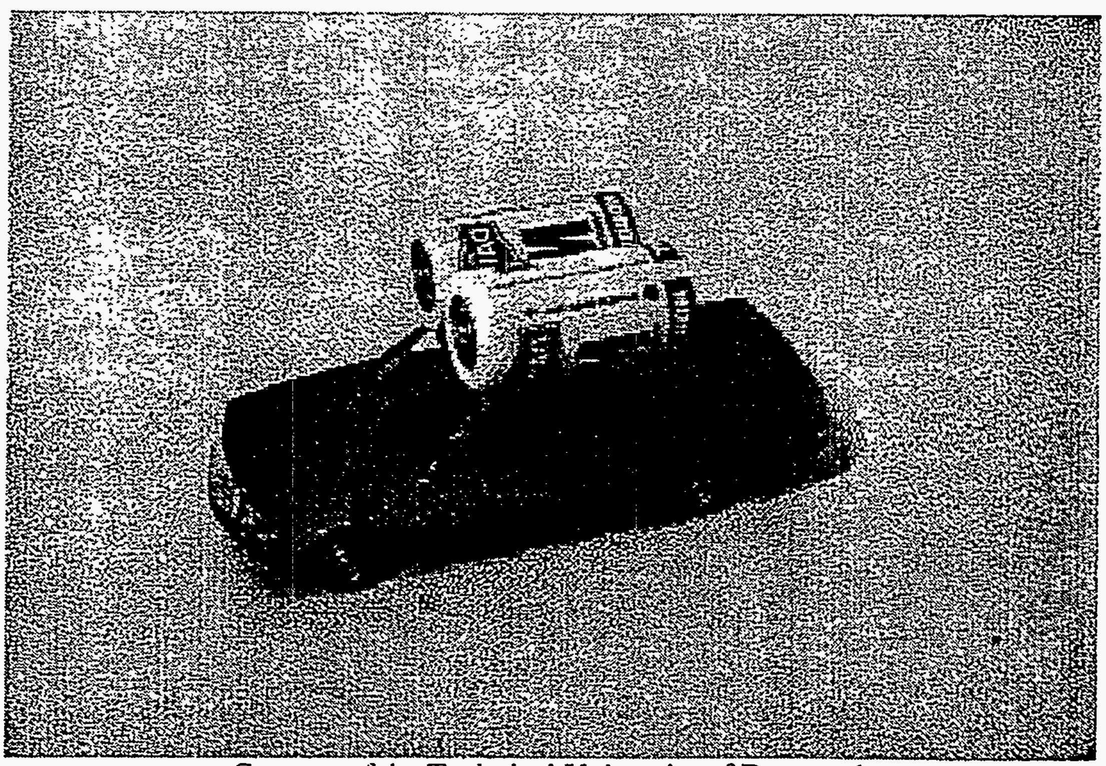


Figure 6. Recursive Mass and Cost Decompounding



Adapted from Behrens 1995.

Figure 7. The Battery Car



Courtesy of the Technical University of Darmstadt.

Figure 8. Fuel-Cell Efficiency and Driving-Cycle Work

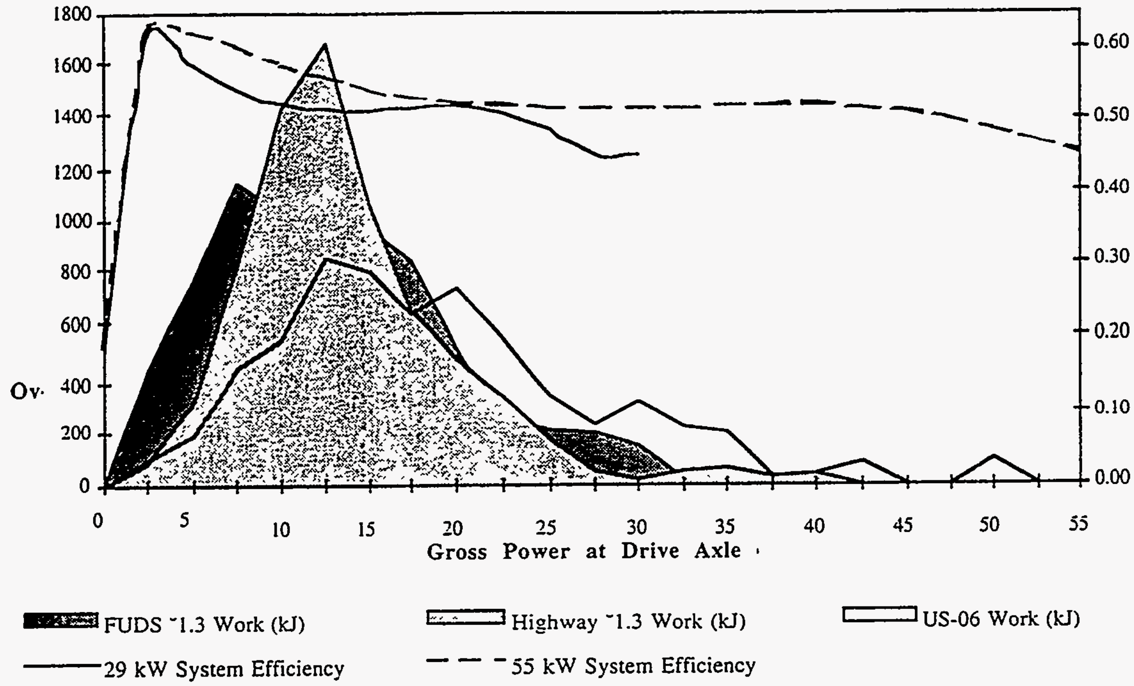
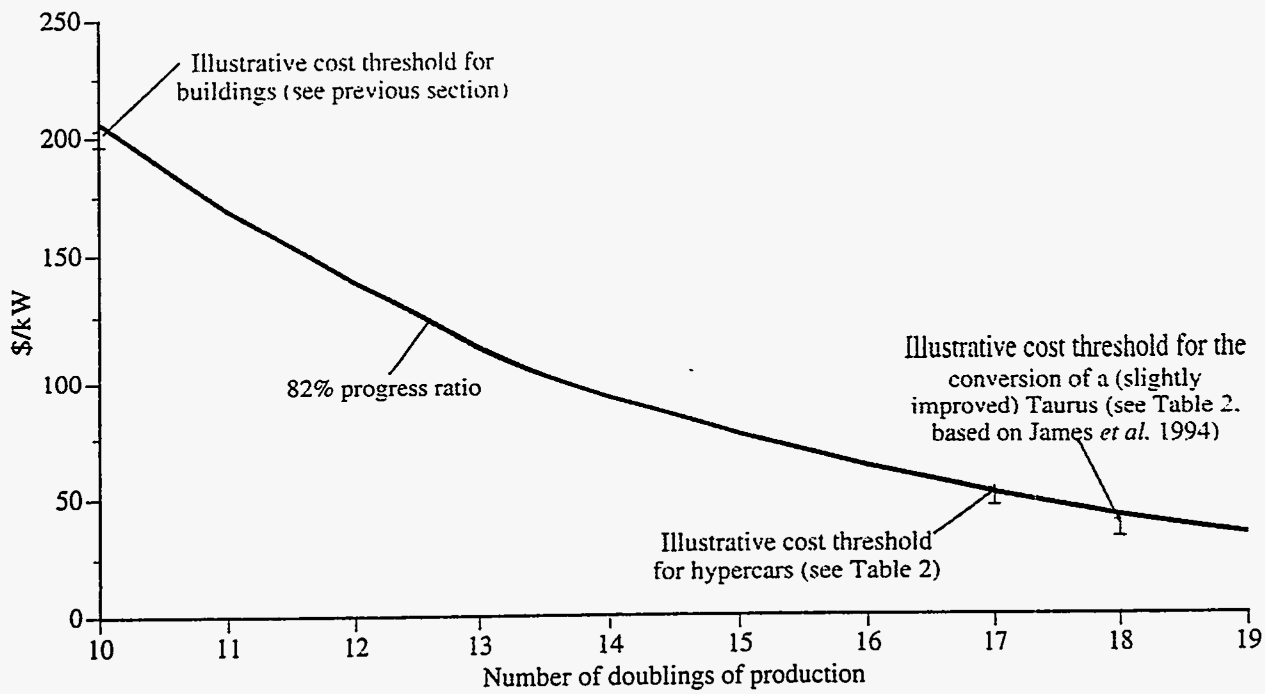


Figure 9. Illustrative Fuel-Cell Cost Reduction



Appendix: Modeling Printouts

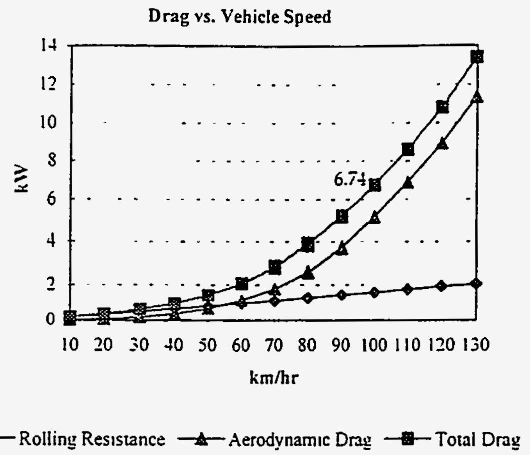
Tractive Loads: 5–6 Occupant PNGV Design Scenario

M_{curb} (kg)	$r_{0\,tires}$	$u_{brngs/brks}$ (Nm)	f_{r0-u} (N)	C_D	A (m^2)	C_DA (m^2)
712	0.0056	1.36	56.49	0.2	2.00	0.40

M_{test} (kg) = 848 r_0 with toe-in on road = 0.0062 Grade = 6.5%

Velocity (km/h)	Velocity (m/s)	Rolling R (kW)	Aero Drag* (kW)	Av. Drag (kW)	Total Drag (kW)	@ Grade (kW)
10	2.78	0.16	0.01	0.08	0.16	1.66
20	5.56	0.31	0.04	0.26	0.36	3.35
30	8.34	0.47	0.14	0.48	0.61	5.11
40	11.12	0.63	0.33	0.78	0.96	6.96
50	13.90	0.79	0.65	1.19	1.43	8.93
60	16.68	0.94	1.12	1.74	2.06	11.05
70	19.46	1.10	1.77	2.46	2.87	13.37
80	22.24	1.26	2.64	3.39	3.90	15.90
90	25.02	1.41	3.77	4.54	5.18	18.67
100	27.80	1.57	5.16	5.96	6.74	21.73
110	30.58	1.73	6.87	7.67	8.60	25.10
120	33.36	1.88	8.93	9.71	10.81	28.80
130	36.14	2.04	11.35	12.10	13.59	32.88

9.08	Current baseline Aerodynamic Drag (kW @ 100 km/hr)
43%	Reduction of Aero Drag from current baseline values
4.50	Current baseline Rolling Resistance (kW @ 100 km/hr)
65%	Reduction of Rolling Resistance from current baseline values
13.58	Current baseline Tractive Load (kW @ 100 km/hr)
50%	Reduction of Tractive Load from current baseline values



*Assumes density of ambient air to be 1.202 kg/m³

See Also: Tractive Loads for Baseline Vehicle below

Zoom view to fit selection of cells A1 to P32 (or 76% at 1024 x 768

Blue text = user input cell
Magenta = input from another sheet
Dark red text = intermediate output
Red text = final output or result

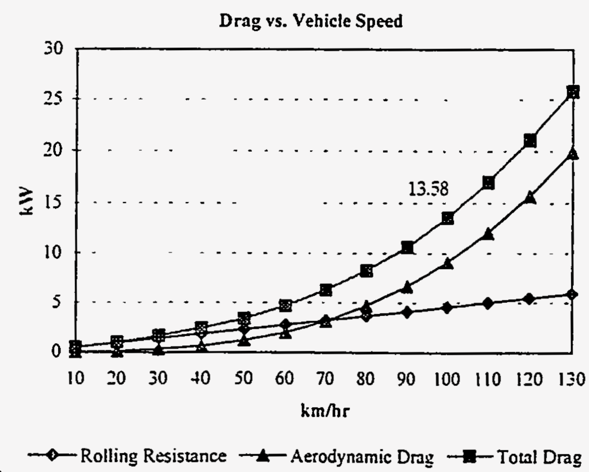
Minimum of 15" monitor @ 1024 x 768 pixels recommended for use of this model

Tractive Loads: Baseline Average 1995 Sedan

M_{curb} (kg)	$r_{0\,tires}$	$u_{brngs/brks}$ (Nm)	f_{r0-u} (N)	C_D	A (m^2)	C_DA (m^2)
1423.00	0.009	2.6	161.97	0.33	2.13	0.70

M_{test} (kg) = 1559 r_0 tires with toe-in on concrete/asphalt = 0.010

Velocity (km/h)	Velocity (m/s)	Rolling R (kW)	Aero Drag* (kW)	Total Drag (kW)
10	2.78	0.45	0.01	0.46
20	5.56	0.90	0.07	0.97
30	8.34	1.35	0.25	1.60
40	11.12	1.80	0.58	2.38
50	13.90	2.25	1.13	3.39
60	16.68	2.70	1.96	4.66
70	19.46	3.15	3.11	6.27
80	22.24	3.60	4.65	8.25
90	25.02	4.05	6.62	10.67
100	27.80	4.50	9.08	13.58
110	30.58	4.95	12.08	17.03
120	33.36	5.40	15.68	21.09
130	36.14	5.85	19.94	25.79



*Assumes density of ambient air to be 1.202 kg/m³

Hill Definition and Cruising-Speed Optimization for Acceleration and Gradability spreadsheet

Cd	0.2	r_0	0.0062	Grade	6.5%
A(m^2)	2.00	r_1	0.000005	θ (grade angle)	0.06490869
Test Mass (kg)	848	APU cont. P_{max} (W)	27920	g (m/s^2)	9.81
Gross Mass (kg)	1211	$\eta_{drivesystem}$	91%	= Motor/controller efficiency @ 55–65 mph and continuous Pmax	

Lookup Answer:	Velocity (km/hr)	Velocity (m/s)	Lookup Answer:	Velocity (km/hr)	Velocity (m/s)
@ Test Mass =	112	31	@ Gross Mass =	90	25

Base-case scenario PEMFC hypercar PNGV sedan with 5–6 occupant seating

Vehicle Components	Moment of rotational inertia (*I*) (kgm^2)	Mass (kg)	Current technology* or basis for mass estimate — "Base-case" scenario PEMFC hypercar PNGV sedan with 5–6 occupant seating
			*Other than the fuel cell system, technologies in this scenario appear ready for at least pilot production by ~1998 and high-volume production by ~2000-2002.
Total Curb Mass and Sum of Inertial Moments (incl. gear ratio)	2.0	712	<—700 kg = 51% curb mass reduction from the 1994 Ford Taurus @ 1419 kg
Monocoque body in white w/closures (*opt. for crashworthiness*)		153.0	Based on major automaker's validated all-Al BIW, with closures. Benchmarks: GM Ultralite=191kg; 152kg = 50% of IBIS baseline steel 4–5 seat BIW (RMI 1995)
Hardpoint mounting brackets			Aluminum or magnesium brackets, mechanically fastened and adhesive bonded to chassis (included above in all-Al. BIW, but seperate line item if composite).
Paint or molded color coat		8.0	Estimate for lay-in-the-mold class A finish or other light weight surface coatings
Extra crash absorption materials, structures, bumpers		18.0	Multi-stage materials and reaction members for collision partners of varying mass or for stationary objects, providing crashworthiness beyond regulatory req
Collapsable steering column		2.0	Like VRI Viking 6, incl. upholstered, spread-aluminum crush basket section, mount, bearings, and u-joints
Foam bolsters		3.0	PP foam, as in 5-mph bumpers and helmets, for dash, doors, "B"&"C" pillars, including upholstery
Air bag sys. (4x front & side)		12 0	Morton complete driver-side module = 1.2kg (for car w/long crush stroke) x 5 (1 driver, 4 side) + 2 rear @ 1.5x mass + 1 passenger @ 2x mass
Belts & force limiters — Body & crash-protection = 201.00		5.0	Estimate based on VRI Viking 6 equipment and TRW safety belts and force limiters now being developed for production vehicle applications (for all passengers)
Motors(s): 28 kW cont.@~6,000rpm 58 kW peak	0.118	47.2	42kg UNIQ SR218H PM = 0.95 kW/kg continuous (40kW) @ 6krpm, 305Vnom; 1.7–1 9 kW/kg peak @ 4–8krpm, 240–360V, 226Nm intermittent starting torque
Starting torque [specified/scaled manually] (Nm)= 254			UNIQ SR218H scaled to 112% peak power and starting torque, 112% mass
Reduction gear(s) and/or diff. Required ratio = 6.61	0 055	8.0	Based on Mg housing, integrated with motor, metal-matrix composite Al gears (no diff , more gears if more than one motor)
Axles and CV joints	0 009	7.0	Large dia., hollow, carbon-fiber axle shafts; smaller CV joints for reduced gross vehicle weight; 0kg if motors are in wheels
Auxiliary Power Unit (PEMFC) 32 gross cont. kW		45 6	Bare Ballard PEM FC stack @ 3 15 lb/gross kW (Gross = net+10% (for parasitic losses) = 32 kW
PEMFC balance of system		14 5	Water tank, humidifiers, piping, heat exchanger, expander/compressor (to 3 atm), air filter, etc. @ 1 lb/gross kW. Estimate by B James (DTI) 12 Feb. 1997.
APU cooling		14.5	Radiator, coolant, deionizing fluid, circulation pump @ 1 lb/gross kW. "Production-level", 2004-2006 technology estimate by B. James (DTI) 12 Feb 1997.
Latent heat battery for PEMFC freeze prevention		8.0	Rough estimate using a vacuum-insulated phase-change-material (eutectic salt) heat exchanger, heating element, plumbing, and coolant loop
PEMFC insulation for freeze prevention		5 0	1L/gross kW bare stack + 0 5l /gross kW ancilliaries = 48l.
Fuel tank (full)		39.1	Based on 4 65 kg H2 @ 5,000 psia in a conceptual 34 4 kg T-1000 carbon wrapped tank with aluminized polymer liner (Thomas (DTI) personal commun. 17 Feb 1997)
Fuel delievery, valves, safety features.		2.0	Tank valve included above. 1 or 2 solenoids, sensors, and piping
Lubricating oil		1.0	No oil required fuel cell, but some for gears plus possible differential
Drivesystem cooling with coolant		9.0	Fuel cell coolant included above; ~2 liters for motor(s) and controller(s)
Load Leveling Device (LLD) Wh/kg = 30 36 kW peak		42.0	1.08-kWh of 30Wh/kg Pb-A @ 1000W/kg + 6kg connectors, *etc.* ; 63kg for 630-Wh ultracap @ 10Wh/kg; 20-kg for 600-Wh EMB @ 30 Wh/sys. kg (incl. 5-kg ctrlr.)
Controllers (3) matched to motor, APU, and LLD peak power		32.6	UNIQ CR40 (150A 53-kW [100 kW *peak*] 100–420VDC) = 13.6kg (mass scaled with motor, APU, and LLD power: 1.12, 0.60, and 0.68 respectively)
Wiring — Drivesystem = 282.3		7 0	5m @ 0 6kg/m high-temp , high-power (silver plated strands and teflon/polypropylene ins) + 60m @ 0 05kg/m low power = 5 7–10.2kg (varies w/no. of motors)
Wheels (no spare needed)	0 280	14.0	2kg VRI, carbon; 3.5kg Esoro, aluminum; 3.9kg GM Impact, aluminum; assumed 3.5 Mg or Al metal-matrix composite
Tires (self sealing)	1.321	22.0	4kg Michelin tires for Esoro; 5.7kg Goodyear tires for GM Impact (5 5kg each assumed with kevlar belts, higer load, and better performance than for Esoro)
Brakes (pads, calipers & rotors)	0.179	14 0	14kg Al, Esoro, 4-passenger; C/CSiC rotors w/metal-matrix-composite calipers assumed for 5-6 pass.; *inboard* @ front to save mass/unsprung mass, use ducted air
Pedals, brake master cylinder, hydro./electr. lines, hand brake		4 0	Fiber-composite pedals with magnesium brackets and an aluminum or magnesium brake master cylinder
Steering (rack & pinion, tie rods, all-electric assist)		8 8	Estimate, based on composite housing and tie rods with Mg or Al MMC gears (steering column & wheel included elsewhere)
Suspension (springs, dampers, ctrl. arms, anti-sway)		26.0	18kg for Esoro using glass spring/arms; more at higher *gross* mass; perhaps less if TCAM; more if active electric (TCAM with some active control assumed)
Hub carriers and wheel bearings — Unsprung = 67.98	0 001	9.0	Al or Mg metal-matrix composites (partially incl. in motor mass if integrated with hub-mounted motors; if shared, bearings must take shock *and* lateral loads.)
Sprung to unsprung ratio (≥10 desireable) = 9.47			
Glazing, including window mechanisms		30.0	25kg Esoro (glass windshield + polymer glazings); 40kg 1994 AAMA Avcar—30% savings with GM-tested bi-layer
Wiper system and washer fluid		3.0	1.5 kg motor, mechanism, arms, blades + 1 kg (~1.2 l) fluid
HVAC		16 0	16kg Nartron all-polymer 18–21kBTU/hr HVAC/heat pump ~0 75 if 50% less load (12kg), plus supplement. PTC heater core (1kg) and small thermal battery (3kg)
Rear view mirrors		0 6	Estimate assuming use of polymer composites
Door, hood, & hatch hinges, struts, locks, latches, & handles		7.0	Estimate based on extensive use of aluminum and polymers for those components
Door, hood, and hatch seals		8.0	Estimate based on OTA mass budget for 1994 Ford Taurus
Seats		28.0	Estimate based on 11.8-kg Mg-frame seats for GM EV1 large, free-standing, adjustable part, must support in crash (incl. folding rear seats supported by BIW)
Steering wheel		0 5	Estimate assuming use of polymer composites
Instrument panel substrate (primary structure incl. with BIW)		5.0	Rough estimate based on similar semi-structural part
Interior trim, substrates, bolster skins		7.5	Minimized trim, otherwise class-A finish on interior of structure plus fabric bolster skins
Carpet & sound absorption		8.0	Using hollow-fiber carpet, as developed by Toyota, to save 30% of weight
Lighting (including fiber optics)		5.0	2 high-intensity discharge lamps, large fiber-optic headlights, sin. f/o running, fluorescent b/u, LED brake
Instruments, controls, multiplex fiber		5 5	Similar to a couple of notebook computers on board
Entertainment systems		3.4	Using neodymium-iron-boron speaker magnets
Miscellaneous hardware & fasteners		3.0	Rough estimate to cover excluded miscellaneous small hardware parts

Acceleration Time, Gradability, and Regenerative Braking for a Hybrid Drivesystem and Fixed-Ratio Transmission
"Base-case" scenario PEMFC hypercar PNGV sedan with 5–6 occupant seating

Curb mass (kg) =	712	Rotating inertia (kgm^2) =	2.0	$M_{effective}$ (kg) =	872	Desired maximum starting grade =	30%
Test mass (curb + 136 kg) =	848	Rot. inertia coeff. (e)=	1.03	$M_{effect. gross}$ (kg) =	1246	Desired acceleration grade =	5.0%
Max number of adult occupants =	6					Desired cruising grade =	6.5%
M_{gross} incl. all occupants + lugg. (kg) =	1211			LLD	Bolder Thin-foil Pb-A	Desired maximum vehicle speed (km/hr) =	129
				LLD P_{max} (kW) =	36.00		
APU	PEM Fuel Cell			APU+LLD absolute P_{max} w/o HVAC (kW) =	64.42	Traction motor starting torque [scaled] (Nm) =	254
APU continuous P_{max}** (kW) =	29.00			APU+LLD 0–100 km/hr accel. P_{max} (kW) =	63.92	Traction motor maximum speed (rpm) =	8000
Average generator η over operating range =	98%			Motor(s)	Unique SR218H	Wheel radius with tire (m) =	0.283
APU generator continuous P_{max} (kW) =	28.42			Motor system peak η **@ P_{max} =	96%		
$P_{accessories}$ or HVAC "hotel load" (kW) =	0.50			Motor system average η **@ accel. P_{max} =	91%	Minimum gear ratio (per starting grade) =	6.61
APU continuous P_{max} for gradability (kW) =	27.92			Absolute motor P_{max} requirement (kW) =	61.84	Maximum gear ratio (per max. veh. speed) =	6.62
APU accel. P_{max}: 0–100 km/hr from off (kW) =	27.92			0–100 km/hr accel. motor P_{max} req. (kW) =	58.17	Max. vehicle speed @ min. ratio (km/hr) =	129

Velocity (km/hr)	v_1 (m/s)	v_2 (m/s)	$M_{test}\Delta E$ (kJ)	$M_{gross}\Delta E$ (kJ)	$P_{max\ APU}$ **(kW)	$P_{max\ APU+LLD}$ **(kW)	$P_{max\ motor}$ **(kW)	$P_{av\ drag}$ (kW)	$P_{available}$ (kW)	$P_{avail.\ @grade}$ M_{test} (kW)	$P_{avail\ @grade}$ M_{gross} (kW)	Time M_{test} (s)	Time M_{gross} (s)	$Time_{@grade}$ M_{test} (s)	$Time_{@grade}$ M_{gross} (s)
0–10	0.00	2.78	3.370	4.813	0.00	36.00	6.55	0.08	6.47	5.32	4.82	0.52	0.74	0.63	1.00
10–20	2.78	5.56	10.110	14.440	11.45	47.45	17.27	0.26	17.01	14.70	13.72	0.59	0.85	0.69	1.05
20–30	5.56	8.34	16.851	24.067	25.13	61.13	38.94	0.48	38.46	34.99	33.51	0.44	0.63	0.48	0.72
30–40	8.34	11.12	23.591	33.694	27.92	63.92	58.17	0.78	57.38	52.77	50.79	0.41	0.59	0.45	0.66
40–50	11.12	13.90	30.331	43.320	27.92	63.92	58.17	1.19	56.97	51.20	48.73	0.53	0.76	0.59	0.89
50–60	13.90	16.68	37.071	52.947	27.92	63.92	58.17	1.74	56.42	49.50	46.54	0.66	0.94	0.75	1.14
60–70	16.68	19.46	43.811	62.574	27.92	63.92	58.17	2.46	55.70	47.63	44.17	0.79	1.12	0.92	1.42
70–80	19.46	22.24	50.552	72.201	27.92	63.92	58.17	3.39	54.78	45.55	41.60	0.92	1.32	1.11	1.74
80–90	22.24	25.02	57.292	81.827	27.92	63.92	58.17	4.54	53.63	43.24	38.80	1.07	1.53	1.32	2.11
90–100	25.02	27.80	64.032	91.454	27.92	63.92	58.17	5.96	52.21	40.67	35.73	1.23	1.75	1.57	2.56

60–100 km/h ΔE (kJ) = 308 | Acceleration P_{av} (kW) = 46.99 | **Total time from 0 to 100 km/hr (sec)** = 7.2 | 10.2 | 8.5 | 13.3

60–100 km/h ΔE (kWh) = 0.086 | 60–100 km/h acceleration time with running start = 4.0

Passes at gross mass = 5 | Speed maintained (km/hr) with continuous power on a grade of 6.5% @ M_{test} and @ M_{gross} = 112 | 90

(using 40% of LLD w/o APU) | (mi/h) = 69 | 56

APU time to full power (s) = 1.55 | Hard braking from 100 km/h is typically 0.6 to 0.75 g

Deceleration via regenerative braking (LLD limited) from 100 km/h @ M_{test} and @ M_{gross} (g) = 0.15 | 0.11

Power required at wheel for 0.30 g deceleration from 50 km/h @ M_{test} and @ M_{gross} (kW) = 36 | 51

**Based on performance and efficiency maps for specified components

Fuel Economy*** (ROUGH approximations of fuel economy for RELATIVE comparison of changes in vehicle parametrics)

"Base-case" scenario PEMFC hypercar PNGV sedan with two-row, 5–6 occupant seating (M_{test} includes two 68-kg occupants)

Curb Mass	712	kg
Test Mass: M_{test}	848	kg
Aero Drag coefficient: C_D	0.20	
Frontal Area: A_f	2.00	m^2
$C_D A_f M_{test}$	339	$m^2 kg$
Rolling Resistance: r_0	0.0062	
Velocity dispersion: r_1	0.000005	s/ft
Bearing and brake drag μ	1.36	Nm
Accessory Load	500	W
Av. H_2 consumption	0.132	lb/kWh
APU average η	0.50	
APU controller av. η	0.98	
APU system average η	0.49	
Gasoline-equiv. $BSFC_{average}$	171	g/kWh

Urban

LLD av. in/out η**	0.92	
Energy % via LLD	0.60	
Motor sys. +gear av. η	0.86	
HEV drivesystem av. η	0.82	
Mechanical braking	0.25	
Regen braking av. η	0.60	
Brake energy recovery	0.45	
Equiv. Fuel Econ.* =**	1.89	l/100km
Equiv. Fuel Econ.* =**	125	mpg_{equiv}
Eq EPA Fuel Econ*=**	112	mpg_{equiv}
H_2 Economy =	186	km/kg

Highway

LLD av. in/out η***	0.90	
Energy via LLD	0.50	
Motor sys. +gear av. η	0.87	
HEV drivesystem av. η	0.83	
Mechanical braking	0.30	
Regen braking av. η	0.45	
Brake energy recovery	0.32	
Equiv. Fuel Econ.* =**	1.68	l/100km
Equiv. Fuel Econ.* =**	140	mpg_{equiv}
Eq. EPA Fuel Econ.* =**	109	mpg_{equiv}
H_2 Economy =	180	km/kg

Urban/Highway 55/45 Composite

1.79	l/100km
131	mpg_{equiv}
218	km/kg
EPA "Corrected"	
111	mpg_{equiv}
183	km/kg

Range	
843	km
524	mi

*All numbers without specified units are fractions of a total or maximum of 100%.
**LLD efficiency at charge and discharge rate typical in urban or highway traffic.
***Closely correlated with second-by-second SIMPLEV results for *some* variable sets (not highly accurate).

Blue text = user input cell
Magenta = input from another sheet
Dark red text = intermediate output
Red text = final output or result

User Notes:

1) Average H_2 consumption is based on a single-cell average voltage of 0.83 V caluculated by DTI over the FUDS cycle for a 50 kW stack (James, Baum, and Kuhn 1994) minus a 10% parasitic load: 0.1 lb/gross kWh - 10% = 0.111 lb/net kWh.

2) APU efficiency of 51.3% is based on a 10% parasitic reduction from the 57% average efficiecy estimated by DTI as being representative over the FUDS cycle (see above). The controller efficiency of ~97% is an estimate for a controller with zones of highest efficiency matched to the most used APU load range.

3) **City** HEV drivesystem efficiency of **82%** is based on average efficiencies of **86%** for traction motor(s), incl. reduction gear, and controller(s), and **95%** for Pb-A or Ni-MH battery energy storage with electronics (round-trip LLD efficiency of **92%** applied to **60%** of energy flow from APU to traction motors).

4) **Highway** HEV drivesystem efficiency of **83%** is based on average efficiencies of **87%** for traction motor(s), incl. reduction gear, and controller(s), and **95%** for Pb-A or Ni-MH energy storage with electronics (round-trip LLD efficiency of **90%** applied to **50%** of energy flow from APU to traction motors).

5) U.S. EPA correction factors to match urban and highway estimates to typical user experience are **0.90** and **0.78** respectively.

Vehicle Components	Moment of rotational inertia (*I*) (kgm^2)	Mass (kg)	Current technology* or basis for mass estimate ("Minimum LLD" scenario PEMFC hypercar PNGV sedan with 5–6 occupant seating)
			*Other than the fuel cell system, technologies in this scenario appear ready for at least pilot production by ~1998 and high-volume production by ~2000–2002
Total Curb Mass and Sum of Inertial Moments (incl gear ratio)	2.1	772	<---700 kg » 51% curb mass *reduction* from the 1994 Ford Taurus @ 1419 kg
Monocoque body in white w/closures (*opt. for crashworthiness*)		153.0	Based on major automaker's validated all-Al BIW, with closures Benchmarks. GM Ultralite=191kg; 152kg = 50% of IBIS baseline steel 4–5 seat BIW (RMI 1995)
Hardpoint mounting brackets			Aluminum or magnesium brackets, mechanically fastened and adhesive bonded to chassis (included above in all-Al BIW, but seperate line item if composite).
Paint or molded color coat		8.0	Estimate for lay-in-the-mold class A finish or other light weight surface coatings
Extra crash absorption materials, structures, bumpers		18.0	Multi-stage materials and reaction members for collision partners of varying mass or for stationary objects, providing crashworthiness beyond regulatory req.
Collapsable steering column		2.0	Like VRI Viking 6, incl. upholstered, spread-aluminum crush basket section, mount, bearings, and u-joints
Foam bolsters		3.0	PP foam, as in 5-mph bumpers and helmets, for dash, doors, "B"&"C" pillars, including upholstery
Air bag sys. (4x front & side)		12.0	Morton complete driver-side module = 1.2kg (for car w/long crush stroke) x 5 (1 driver, 4 side) + 2 rear @ 1.5x mass + 1 passenger @ 2x mass
Belts & force limiters Body & crash-protection = 201.00		5.0	Estimate based on VRI Viking 6 equipment and TRW safety belts and force limiters now being developed for production vehicle applications (for all passengers)
Motors(s): 53 kW cont.@~6,000rpm 60 kW peak	0.124	49.6	42kg UNIQ SR218H PM = 0.95 kW/kg continuous (40kW) @ 6krpm, 305Vnom; 1.7–1.9 kW/kg peak @ 4–8krpm, 240–360V, 226Nm intermittent starting torque
Starting torque [specified/scaled manually] (Nm)= 267			UNIQ SR218H scaled to 118% peak power and starting torque, 118% mass
Reduction gear(s) and/or diff. Required ratio = 6.60	0.059	8.6	Based on Mg housing, integrated with motor, metal-matrix composite Al gears (no diff , more gears if more than one motor)
Axles and CV joints	0.009	7.5	Large dia , hollow, carbon-fiber axle shafts; smaller CV joints for reduced gross vehicle weight, 0kg if motors are in wheels
Auxilliary Power Unit (PEMFC) 60.5 gross cont. kW		86.4	Bare Ballard PEM FC stack @ 3.15 lb/gross kW Gross = net+10% (for parasitic losses) = 32 kW.
PEMFC balance of system		27.4	Water tank, humidifiers, piping, heat exchanger, expander/compressor (to 3 atm), air filter, etc. @ 1 lb/gross kW. Estimate by B. James (DTI) 12 Feb 1997.
APU cooling		27.4	Radiator, coolant, deionizing fluid, circulation pump @ 1 lb/gross kW. "Production-level", 2004-2006 technology estimate by B. James (DTI) 12 Feb. 1997.
Latent heat battery for PEMFC freeze prevention		15.2	Rough estimate using a vacuum-insulated phase-change-material (eutectic salt) heat exchanger, heating element, plumbing, and coolant loop
PEMFC insulation for freeze prevention		7.7	1L/gross kW bare stack + 0.5L/gross kW ancilliaries = 91L.
Fuel tank (full)		39.1	Based on 4.65 kg H2 @ 5,000 psia in a conceptual 34.4 kg T-1000 carbon wrapped tank with aluminized polymer liner (Thomas (DTI) personal commun. 17 Feb 1997)
Fuel delivery, vavles, and safety features		2.0	Tank valve included above. 1 or 2 solenoids, sensors, and piping.
Lubricating oil		1.0	No oil required fuel cell, but some for gears plus possible differential
Drivesystem cooling with coolant		9.5	Fuel cell coolant included above; ~2 liters for motor(s) and controller(s)
Load Leveling Device (LLD) Wh/kg = 30 12 kW peak		14.0	1.08-kWh of 30Wh/kg Pb-A @ 1000W/kg + 6kg connectors, *etc.* ; 63kg for 630-Wh ultracap @ 10Wh/kg; 20-kg for 600-Wh EMB @ 30 Wh/sys. kg (incl. 5-kg ctrlr.)
Controllers (3) matched to motor, APU, and LLD peak power		34.7	UNIQ CR40 (150A 53-kW [100 kW *peak*] 100–420VDC) = 13.6kg (mass scaled with motor, APU, and LLD power: 1.18, 1.14, and 0.23 respectively)
Wiring Drivesystem = 337.1		7.0	5m @ 0.6kg/m high-temp., high-power (silver plated strands and teflon/polypropylene ins.) + 60m @ 0.05kg/m low power = 5.7–10.2kg (varies w/no. of motors)
Wheels (no spare needed)	0.300	15.0	2kg VRI, carbon; 3.5kg Esoro, aluminum; 3.9kg GM Impact, aluminum; assumed 3.5 Mg or Al metal-matrix composite
Tires (self sealing)	1.414	23.6	4kg Michelin tires for Esoro; 5.7kg Goodyear tires for GM Impact (5.5kg each assumed with kevlar belts, higer load, and better performance than for Esoro)
Brakes (pads, calipers & rotors)	0.192	15.0	14kg Al, Esoro, 4-passenger; C/CSiC rotors w/metal-matrix-composite calipers assumed for 5–6 pass.; *inboard* @ front to save mass/unsprung mass, use ducted air
Pedals, brake master cylinder, hydro./electr. lines, hand brake		4.0	Fiber-composite pedals with magnesium brackets and an aluminum or magnesium brake master cylinder
Steering (rack & pinion, tie rods, all-electric assist)		8.8	Estimate, based on composite housing and tie rods with Mg or Al MMC gears (steering column & wheel included elsewhere)
Suspension (springs, dampers, ctrl. arms, anti-sway)		27.8	18kg for Esoro using glass spring/arms; more at higher *gross* mass; perhaps less if TCAM; more if active electric (TCAM with some active control assumed)
Hub carriers and wheel bearings Unsprung = 72.68	0.001	9.6	Al or Mg metal-matrix composites (partially incl. in motor mass if integrated with hub-mounted motors; if shared, bearings must take shock *and* lateral loads.)
Sprung to unsprung ratio (≥10 desireable) = 9.63			
Glazing, including window mechanisms		30.0	25kg Esoro (glass windshield + polymer glazings); 40kg 1994 AAMA Avcar—30% savings with GM-tested bi-layer
Wiper system and washer fluid		3.0	1.5 kg motor, mechanism, arms, blades + 1 kg (~1.2 l) fluid
HVAC		16.0	16kg Nartron all-polymer 18–21kBTU/hr HVAC/heat pump ˜0.75 if 50% less load (12kg), plus supplement. PTC heater core (1kg) and small thermal battery (3kg)
Rear view mirrors		0.6	Estimate assuming use of polymer composites
Door, hood, & hatch hinges, struts, locks, latches, & handles		7.0	Estimate based on extensive use of aluminum and polymers for those components
Door, hood, and hatch seals		8.0	Estimate based on OTA mass budget for 1994 Ford Taurus
Seats		28.0	Estimate based on 11.8-kg Mg-frame seats for GM EV1 large, free-standing, adjustable part, must support in crash (incl. folding rear seats supported by BIW)
Steering wheel		0.5	Estimate assuming use of polymer composites
Instrument panel substrate (primary structure incl. with BIW)		5.0	Rough estimate based on similar semi-structural part
Interior trim, substrates, bolster skins		7.5	Minimized trim, otherwise class-A finish on interior of structure plus fabric bolster skins
Carpet & sound absorption		8.0	Using hollow-fiber carpet, as developed by Toyota, to save 30% of weight
Lighting (including fiber optics)		5.0	2 high-intensity discharge lamps, large fiber-optic headlights, sm. f/o running, fluorescent b/u, LED brake
Instruments, controls, multiplex fiber		5.5	Similar to a couple of notebook computers on board
Entertainment systems		3.4	Using neodymium-iron-boron speaker magnets
Miscellaneous hardware & fasteners		3.0	Rough estimate to cover excluded miscellaneous small hardware parts

Acceleration Time, Gradability, and Regenerative Braking for a Hybrid Drivesystem and Fixed-Ratio Transmission
Minimum LLD scenario PEMFC hypercar PNGV sedan with 5–6 occupant seating.

Curb mass (kg) = 772
Test mass (curb + 136 kg) = 908
Max number of adult occupants = 6
M_{gross} incl. all occupants + lugg. (kg) = 1271

Rotating inertia (kgm²) = 2.1
Rot. inertia coeff. (e) = 1.03

$M_{effective}$ (kg) = 935
$M_{effect.gross}$ (kg) = 1308

Desired maximum starting grade = 30%
Desired acceleration grade = 5.0%
Desired cruising grade = 6.5%
Desired maximum vehicle speed (km/hr) = 129

LLD: Bolder Thin-foil Pb-A
LLD P_{max} (kW) = 12.00

APU: PEM Fuel Cell
APU continuous P_{max}** (kW) = 55.00
Average generator η over operating range = 98%
APU generator continuous P_{max} (kW) = 53.90
$P_{accessories}$ or HVAC "hotel load" (kW) = 0.50
APU continuous P_{max} for gradability (kW) = 53.40
APU accel. P_{max}: 0–100 km/hr from off (kW) = 53.40

APU+LLD absolute P_{max} w/o HVAC (kW) = 65.90
APU+LLD 0–100 km/hr accel. P_{max} (kW) = 65.40
Motor(s): Unique SR218H
Motor system peak η **@ P_{max} = 96%
Motor system average η **@ accel. P_{max} = 91%
Absolute motor P_{max} requirement (kW) = 63.26
0–100 km/hr accel. motor P_{max} req. (kW) = 59.51

Traction motor starting torque [scaled] (Nm) = 267
Traction motor maximum speed (rpm) = 8000
Wheel radius with tire (m) = 0.283

Minimum gear ratio (per starting grade) = 6.60
Maximum gear ratio (per max. veh. speed) = 6.62
Max. vehicle speed @ min. ratio (km/hr) = 129

Velocity (km/hr)	v_1 (m/s)	v_2 (m/s)	$M_{test}\Delta E$ (kJ)	$M_{gross}\Delta E$ (kJ)	$P_{max\ APU}$ **(kW)	$P_{max\ APU+LLD}$ **(kW)	$P_{max\ motor}$ **(kW)	$P_{av.\ drag}$ (kW)	$P_{available}$ (kW)	$P_{avail\ @grade}$ M_{test} (kW)	$P_{avail\ @grade}$ M_{gross} (kW)	Time M_{test} (s)	Time M_{gross} (s)	$Time_{@grade}$ M_{test} (s)	$Time_{@grade}$ M_{gross} (s)
0–10	0.00	2.78	3.611	5.055	11.21	23.21	4.22	0.09	4.14	2.90	2.41	0.87	1.22	1.24	2.10
10–20	2.78	5.56	10.834	15.164	32.57	44.57	16.22	0.27	15.95	13.48	12.49	0.68	0.95	0.80	1.21
20–30	5.56	8.34	18.057	25.273	53.40	65.40	41.66	0.51	41.15	37.44	35.96	0.44	0.61	0.48	0.70
30–40	8.34	11.12	25.279	35.382	53.40	65.40	59.51	0.82	58.69	53.75	51.77	0.43	0.60	0.47	0.68
40–50	11.12	13.90	32.502	45.491	53.40	65.40	59.51	1.24	58.27	52.09	49.62	0.56	0.78	0.62	0.92
50–60	13.90	16.68	39.725	55.600	53.40	65.40	59.51	1.80	57.71	50.30	47.33	0.69	0.96	0.79	1.17
60–70	16.68	19.46	46.947	65.709	53.40	65.40	59.51	2.53	56.98	48.33	44.87	0.82	1.15	0.97	1.46
70–80	19.46	22.24	54.170	75.818	53.40	65.40	59.51	3.46	56.05	46.16	42.21	0.97	1.35	1.17	1.80
80–90	22.24	25.02	61.393	85.927	53.40	65.40	59.51	4.63	54.89	43.76	39.31	1.12	1.57	1.40	2.19
90–100	25.02	27.80	68.615	96.036	53.40	65.40	59.51	6.05	53.46	41.10	36.16	1.28	1.80	1.67	2.66

60–100 km/h ΔE (kJ) = 323
60–100 km/h ΔE (kWh) = 0.090
Acceleration P_{av} (kW) = 47.87
Total time from 0 to 100 km/hr (sec) = 7.9 | 11.0 | 9.6 | 14.9
60-100 km/h acceleration time with running start = 4.2
Speed maintained (km/hr) with continuous power on a grade of 6.5% @ M_{test} and @ M_{gross} = 158 | 140
(mi/h) = 98 | 87

0–100 km/h accel. times with dead LLD (sec)

M_{test}	M_{gross}	M_{test}	M_{gross}
9.4	13.1	12.0	19.1

Hard braking from 100 km/h is typically 0.6 to 0.75 g
Deceleration via regenerative braking (LLD limited) from 100 km/h @ M_{test} and @ M_{gross} (g) = 0.05 | 0.03
Power required at wheel for 0.095 g deceleration from 50 km/h @ M_{test} and @ M_{gross} (kW) = 12 | 17
APU time to full power (s) = 1.55

*To account for APU lag during accel. (enter 0 if using H19–H28 for available APU power) **Based on performance and efficiency maps for specified components

Acceleration Time, Gradability, and Regenerative Braking for a Hybrid Drivesystem and Fixed-Ratio Transmission
"Minimum LLD" scenario PEMFC hypercar PNGV sedan with 5-6 occupant seating. Peformance without LLD

Curb mass (kg) =	772	Rotating inertia (kgm^2) =	2.1	$M_{effective}$ (kg) =	935	Desired maximum starting grade =	30%
Test mass (curb + 136 kg) =	908	Rot. inertia coeff. (e)=	1.03	$M_{effect\ gross}$ (kg) =	1308	Desired acceleration grade =	5.0%
Max number of adult occupants =	6					Desired cruising grade =	6.5%
M_{gross} incl. all occupants + lugg. (kg) =	1271	LLD	Bolder Thin-foil Pb-A			Desired maximum vehicle speed (km/hr) =	129
				LLD P_{max} (kW) =	0.00		
APU	PEM Fuel Cell			APU+LLD absolute P_{max} w/o HVAC (kW) =	53.90	Traction motor starting torque [scaled] (Nm) =	266
APU continuous P_{max}** (kW) =	55.00			APU+LLD 0-100 km/hr accel. P_{max} (kW) =	53.40	Traction motor maximum speed (rpm) =	8000
Average generator η over operating range =	98%	Motor(s)	Unique SR218H			Wheel radius with tire (m) =	0.283
APU generator continuous P_{max} (kW) =	53.90			Motor system peak η **@ P_{max} =	96%		
$P_{accessories}$ or HVAC "hotel load" (kW) =	0.50			Motor system average η **@ accel. P_{max} =	91%	Minimum gear ratio (per starting grade) =	6.63
APU continuous P_{max} for gradability (kW) =	53.40			Absolute motor P_{max} requirement (kW) =	51.74	Maximum gear ratio (per max. veh. speed) =	6.62
APU accel. P_{max}: 0-100 km/hr from off (kW) =	53.40			0-100 km/hr accel. motor P_{max} req. (kW) =	48.59	Max. vehicle speed @ min. ratio (km/hr) =	129

Velocity (km/hr)	v_1 (m/s)	v_2 (m/s)	$M_{test}\Delta E$ (kJ)	$M_{gross}\Delta E$ (kJ)	$P_{max\ APU}$ **(kW)	$P_{max\ APU+LLD}$ **(kW)	$P_{max\ motor}$ **(kW)	$P_{av.\ drag}$ (kW)	$P_{available}$ (kW)	$P_{avail.\ @grade}$ M_{test} (kW)	$P_{avail.\ @grade}$ M_{gross} (kW)	Time M_{test} (s)	Time M_{gross} (s)	$Time_{@grade}$ M_{test} (s)	$Time_{@grade}$ M_{gross} (s)
0-10	0.00	2.78	3.611	5.055	21.89	21.89	3.98	0.09	3.90	2.66	2.17	0.93	1.30	1.36	2.33
10-20	2.78	5.56	10.834	15.164	48.06	48.06	17.49	0.27	17.22	14.75	13.76	0.63	0.88	0.73	1.10
20-30	5.56	8.34	18.057	25.273	53.40	53.40	34.02	0.51	33.51	29.80	28.32	0.54	0.75	0.61	0.89
30-40	8.34	11.12	25.279	35.382	53.40	53.40	48.59	0.82	47.77	42.83	40.85	0.53	0.74	0.59	0.87
40-50	11.12	13.90	32.502	45.491	53.40	53.40	48.59	1.24	47.35	41.17	38.70	0.69	0.96	0.79	1.18
50-60	13.90	16.68	39.725	55.600	53.40	53.40	48.59	1.80	46.79	39.38	36.41	0.85	1.19	1.01	1.53
60-70	16.68	19.46	46.947	65.709	53.40	53.40	48.59	2.53	46.06	37.41	33.95	1.02	1.43	1.25	1.94
70-80	19.46	22.24	54.170	75.818	53.40	53.40	48.59	3.46	45.13	35.24	31.29	1.20	1.68	1.54	2.42
80-90	22.24	25.02	61.393	85.927	53.40	53.40	48.59	4.63	43.97	32.84	28.39	1.40	1.95	1.87	3.03
90-100	25.02	27.80	68.615	96.036	53.40	53.40	48.59	6.05	42.54	30.18	25.24	1.61	2.26	2.27	3.81

60-100 km/h ΔE (kJ) = 323 | Acceleration P_{av} (kW) = 39.57 | Total time from 0 to 100 km/hr (sec) = 9.4 | 13.1 | 12.0 | 19.1

60-100 km/h ΔE (kWh) = 0.090 | 60-100 km/h acceleration time with running start = 5.2

Speed maintained (km/hr) with continuous power on a grade of 6.5% @ M_{test} and @ M_{gross} = 158 | 140

(mi/h) = 98 | 87

APU time to full power (s) = 1.56 | Hard braking from 100 km/h is typically 0.6 to 0.75 g

Deceleration via regenerative braking (LLD limited) from 100 km/h @ M_{test} and @ M_{gross} (g) = 0.00 | 0.00

Power required at wheel for 0.36 g deceleration from 40 km/h @ M_{test} and @ M_{gross} (kW) = 37 | 51

*To account for APU lag during accel. (enter 0 if using H19-H28 for available APU power) **Based on performance and efficiency maps for specified components

Vehicle Components	Moment of rotational inertia (*I*)	Mass	Current technology* or basis for mass estimate ("No LLD" scenario PEMFC hypercar PNGV sedan with 5–6 occupant seating)
	(kgm²)	(kg)	*Other than the fuel cell system, technologies in this scenario appear ready for at least pilot production by ~1998 and high-volume production by ~2000–2002
Total Curb Mass and Sum of Inertial Moments (incl. gear ratio)	2.1	790	<---700 kg » 51% curb mass *reduction* from the 1994 Ford Taurus @ 1419 kg
Monocoque body in white w/closures (*opt. for crashworthiness*)		153.0	Based on major automaker's validated all-Al BIW, with closures. Benchmarks: GM Ultralite=191kg; 152kg = 50% of IBIS baseline steel 4–5 seat BIW (RMI 1995)
Hardpoint mounting brackets			Aluminum or magnesium brackets, mechanically fastened and adhesive bonded to chassis (included above in all-AL BIW, but seperate line item if composite).
Paint or molded color coat		8.0	Estimate for lay-in-the-mold class A finish or other light weight surface coatings
Extra crash absorption materials, structures, bumpers		18.0	Multi-stage materials and reaction members for collision partners of varying mass or for stationary objects, providing crashworthiness beyond regulatory req.
Collapsable steering column		2.0	Like VRI Viking 6, incl. upholstered, spread-aluminum crush basket section, mount, bearings, and u-joints
Foam bolsters		3.0	PP foam, as in 5-mph bumpers and helmets, for dash, doors, "B"&"C" pillars, including upholstery
Air bag sys. (4x front & side)		12.0	Morton complete driver-side module = 1.2kg (for car w/long crush stroke) x 5 (1 driver, 4 side) + 2 rear @ 1.5x mass + 1 passenger @ 2x mass
Belts & force limiters — Body & crash-protection = 201.00		5.0	Estimate based on VRI Viking 6 equipment and TRW safety belts and force limiters now being developed for production vehicle applications (for all passengers)
Motors(s): 63 kW cont.@~6,000rpm 58 kW peak	0.125	50.0	42kg UNIQ SR218H PM = 0.95 kW/kg continuous (40kW) @ 6krpm, 305Vnom; 1.7–1.9 kW/kg peak @ 4–8krpm, 240–360V, 226Nm intermittent starting torque
Starting torque [specified/scaled manually] (Nm)= 269			UNIQ SR218H scaled to 119% peak power and starting torque, 119% mass
Reduction gear(s) and/or diff. Required ratio = 6.65	0.059	8.6	Based on Mg housing, integrated with motor, metal-matrix composite Al gears (no diff., more gears if more than one motor)
Axles and CV joints	0.009	7.5	Large dia., hollow, carbon-fiber axle shafts; smaller CV joints for reduced gross vehicle weight, 0kg if motors are in wheels
Auxilliary Power Unit (PEMFC) 71.5 gross cont. kW		102.2	Bare Ballard PEM FC stack @ 3.15 lb/gross kW (Gross = net + 10% (for parasitic losses) = 32 kW.
PEMFC balance of system		32.4	Water tank, humidifiers, piping, heat exchanger, expander/compressor (to 3 atm), air filter, etc. @ 1 lb/gross kW. Estimate by B. James (DTI) 12 Feb. 1997.
APU cooling		32.4	Radiator, coolant, deionizing fluid, circulation pump @ 1 lb/gross kW. "Production-level", 2004-2006 technology estimate by B. James (DTI) 12 Feb. 1997.
Latent heat battery for PEMFC freeze prevention		17.9	Rough estimate using a vacuum-insulated phase-change-material (eutectic salt) heat exchanger, heating element, plumbing, and coolant loop
PEMFC insulation for freeze prevention		8.5	1L/gross kW bare stack + 0.5L/gross kW ancilliaries = 91L.
Fuel tank (full)		39.1	Based on 4.65 kg H2 @ 5,000 psia in a conceptual 31.4 kg T-1000 carbon wrapped tank with aluminized polymer liner (Thomas (DTI) personal commun. 17 Feb 1997)
Fuel delievery, valves, and safety features		2.0	Tank valve included above. 1 or 2 solenoids, sensors, and piping.
Lubricating oil		1.0	No oil required fuel cell, but some for gears plus possible differential
Drivesystem cooling with coolant		9.5	Fuel cell coolant included above; ~2 liters for motor(s) and controller(s)
Load Leveling Device (LLD) Wh/kg = 0 0 kW peak		2.0	1.08-kWh of 30Wh/kg Pb-A @ 1000W/kg + 6kg connectors, *etc.*; 63kg for 630-Wh ultracap @ 10Wh/kg; 20–kg for 600-Wh EMB @ 30 Wh/sys. kg (incl. 5-kg ctrlr.)
Controllers (3) matched to motor, APU, and LLD peak power		35.0	UNIQ CR40 (150A 53-kW [100 kW *peak*] 100–420VDC) = 13.6kg (mass scaled with motor and APU power: 1.19 and 1.35, respectively)
Wiring — Drivesystem = 355.1		7.0	5m @ 0.6kg/m high-temp., high-power (silver plated strands and teflon/polypropylene ins.) + 60m @ 0.05kg/m low power = 5.7–10.2kg (varies w/no. of motors)
Wheels (no spare needed)	0.300	15.0	2kg VRI, carbon; 3.5kg Esoro, aluminum; 3.9kg GM Impact, aluminum; assumed 3.5 Mg or Al metal-matrix composite
Tires (self sealing)	1.414	23.6	4kg Michelin tires for Esoro; 5.7kg Goodyear tires for GM Impact (5.5kg each assumed with kevlar belts, higer load, and better performance than for Esoro)
Brakes (pads, calipers & rotors)	0.192	15.0	14kg Al, Esoro, 4-passenger, C/CSiC rotors w/metal-matrix-composite calipers assumed for 5–6 pass.; *inboard* @ front to save mass/unsprung mass, use ducted air
Pedals, brake master cylinder, hydro./electr. lines, hand brake		4.0	Fiber-composite pedals with magnesium brackets and an aluminum or magnesium brake master cylinder
Steering (rack & pinion, tie rods, all-electric assist)		8.8	Estimate, based on composite housing and tie rods with Mg or Al MMC gears (steering column & wheel included elsewhere)
Suspension (springs, dampers, ctrl. arms, anti-sway)		27.8	18kg for Esoro using glass spring/arms; more at higher *gross* mass; perhaps less if TCAM; more if active electric (TCAM with some active control assumed)
Hub carriers and wheel bearings — Unsprung = 72.68	0.001	9.6	Al or Mg metal-matrix composites (partially incl. in motor mass if integrated with hub-mounted motors; if shared, bearings must take shock *and* lateral loads.)
Sprung to unsprung ratio (≥10 desireable) = 9.87			
Glazing, including window mechanisms		30.0	25kg Esoro (glass windshield + polymer glazings); 40kg 1994 AAMA Avcar—30% savings with GM-tested bi-layer
Wiper system and washer fluid		3.0	1.5 kg motor, mechanism, arms, blades + 1 kg (~1.2 l) fluid
HVAC		16.0	16kg Nartron all-polymer 18–21kBTU/hr HVAC/heat pump ~0.75 if 50% less load (12kg), plus supplement. PTC heater core (1kg) and small thermal battery (3kg)
Rear view mirrors		0.6	Estimate assuming use of polymer composites
Door, hood, & hatch hinges, struts, locks, latches, & handles		7.0	Estimate based on extensive use of aluminum and polymers for those components
Door, hood, and hatch seals		8.0	Estimate based on OTA mass budget for 1994 Ford Taurus
Seats		28.0	Estimate based on 11.8-kg Mg-frame seats for GM EV1 large, free-standing, adjustable part, must support in crash (incl. folding rear seats supported by BIW)
Steering wheel		0.5	Estimate assuming use of polymer composites
Instrument panel substrate (primary structure incl. with BIW)		5.0	Rough estimate based on similar semi-structural part
Interior trim, substrates, bolster skins		7.5	Minimized trim, otherwise class-A finish on interior of structure plus fabric bolster skins
Carpet & sound absorption		8.0	Using hollow-fiber carpet, as developed by Toyota, to save 30% of weight
Lighting (including fiber optics)		5.0	2 high-intensity discharge lamps, large fiber-optic headlights, sm. f/o running, fluorescent b/u, LED brake
Instruments, controls, multiplex fiber		5.5	Similar to a couple of notebook computers on board
Entertainment systems		3.4	Using neodymium-iron-boron speaker magnets
Miscellaneous hardware & fasteners		3.0	Rough estimate to cover excluded miscellaneous small hardware parts

Acceleration Time, Gradability, and Regenerative Braking for a Hybrid Drivesystem and Fixed-Ratio Transmission
"No LLD" scenario PEMFC hypercar

Curb mass (kg) =	790	Rotating inertia (kgm²) =	2.1	$M_{effective}$ (kg) =	953
Test mass (curb + 136 kg) =	926	Rot. inertia coeff. (*e*) =	1.03	$M_{effect\ gross}$ (kg) =	1326
Max number of adult occupants =	6				
M_{gross} incl. all occupants + lugg. (kg) =	1289			LLD	None
				LLD P_{max} (kW) =	0.00
APU	PEM Fuel Cell			APU+LLD absolute P_{max} w/o HVAC (kW) =	63.70
APU continuous P_{max}** (kW) =	65.00			APU+LLD 0–100 km/hr accel. P_{max} (kW) =	63.20
Average generator η over operating range =	98%			Motor(s)	Unique SR218H
APU generator continuous P_{max} (kW) =	63.70			Motor system peak η **@ P_{max} =	96%
$P_{accessories}$ or HVAC "hotel load" (kW) =	0.50			Motor system average η **@ accel. P_{max} =	91%
APU continuous P_{max} for gradability (kW) =	63.20			Absolute motor P_{max} requirement (kW) =	61.15
APU accel. P_{max}: 0–100 km/hr from off (kW) =	63.20			0–100 km/hr accel. motor P_{max} req. (kW) =	57.51

Desired maximum starting grade =	30%
Desired acceleration grade =	5.0%
Desired cruising grade =	6.5%
Desired maximum vehicle speed (km/hr) =	129
Traction motor starting torque [scaled] (Nm) =	269
Traction motor maximum speed (rpm) =	8000
Wheel radius with tire (m) =	0.283
Minimum gear ratio (per starting grade) =	6.65
Maximum gear ratio (per max. veh. speed) =	6.62
Max. vehicle speed @ min. ratio (km/hr) =	128

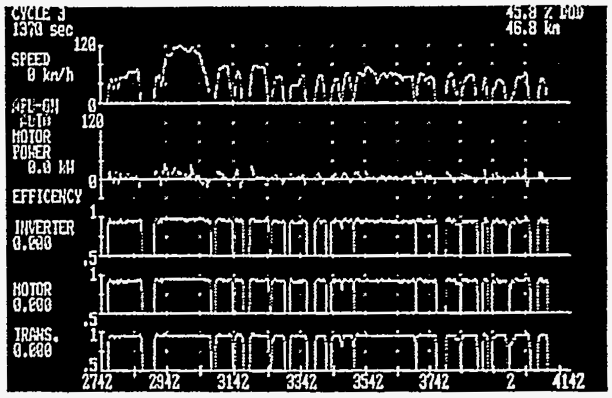
Velocity (km/hr)	v_i (m/s)	v_f (m/s)	M_{test}ΔE (kJ)	M_{gross}ΔE (kJ)	$P_{max\ APU}$ **(kW)	$P_{max\ APU+LLD}$ **(kW)	$P_{max\ motor}$ **(kW)	$P_{av.\ drag}$ (kW)	$P_{available}$ (kW)	$P_{avail\ @grade}$ M_{test} (kW)	$P_{avail\ @grade}$ M_{gross} (kW)	Time M_{test} (s)	Time M_{gross} (s)	$Time_{@grade}$ M_{test} (s)	$Time_{@grade}$ M_{gross} (s)
0–10	0.00	2.78	3.681	5.123	21.49	21.49	3.91	0.09	3.82	2.56	2.07	0.96	1.34	1.44	2.48
10–20	2.78	5.56	11.042	15.370	52.46	52.46	19.09	0.28	18.82	16.29	15.31	0.59	0.82	0.68	1.00
20–30	5.56	8.34	18.404	25.616	63.20	63.20	40.26	0.52	39.74	35.96	34.48	0.46	0.64	0.51	0.74
30–40	8.34	11.12	25.765	35.862	63.20	63.20	57.51	0.83	56.68	51.64	49.66	0.45	0.63	0.50	0.72
40–50	11.12	13.90	33.127	46.109	63.20	63.20	57.51	1.25	56.26	49.95	47.48	0.59	0.82	0.66	0.97
50–60	13.90	16.68	40.488	56.355	63.20	63.20	57.51	1.82	55.69	48.13	45.17	0.73	1.01	0.84	1.25
60–70	16.68	19.46	47.850	66.601	63.20	63.20	57.51	2.55	54.96	46.14	42.68	0.87	1.21	1.04	1.56
70–80	19.46	22.24	55.211	76.848	63.20	63.20	57.51	3.49	54.03	43.94	39.99	1.02	1.42	1.26	1.92
80–90	22.24	25.02	62.573	87.094	63.20	63.20	57.51	4.65	52.86	41.51	37.07	1.18	1.65	1.51	2.35
90–100	25.02	27.80	69.935	97.340	63.20	63.20	57.51	6.08	51.43	38.82	33.88	1.36	1.89	1.80	2.87

60–100 km/h ΔE (kJ) =	328	Acceleration P_{av} (kW) =	46.58	**Total time from 0 to 100 km/hr (sec) =**	8.2	11.4	10.2 / 15.9
60–100 km/h ΔE (kWh) =	0.091			60-100 km/h acceleration time with running start =	4.4		
APU time to full power (s) =	1.55	Speed maintained (km/hr) with continuous power on a grade of	6.5%	@ M_{test} and @ M_{gross} =	173	155	
				(mi/h) =	107	96	

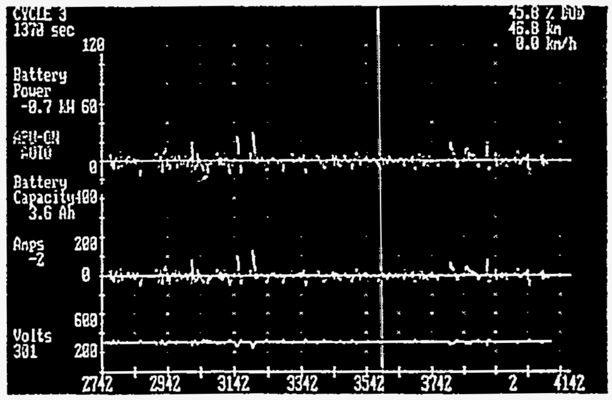
*To account for APU lag during accel. (enter 0 if using H19–H28 for available APU power) **Based on performance and efficiency maps for specified components

Vehicle speed, motor power, and efficiencies for the motor, power electronics, and single-speed transmission:

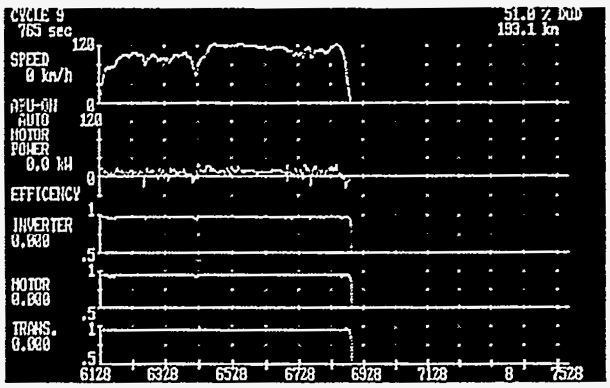
Power, current, and voltage for the load-leveling device (LLD):



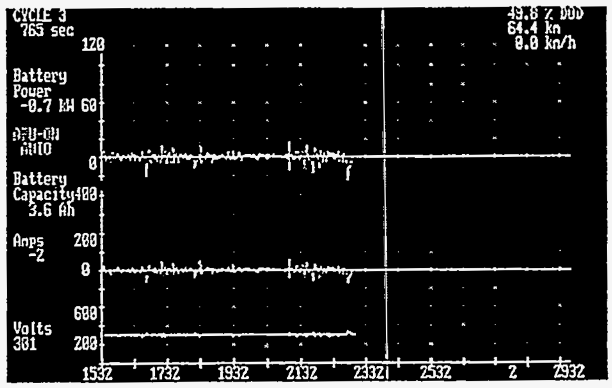
Intensified U.S. Federal Urban Driving Schedule
(all velocity inputs multiplied by a factor of 1.3).



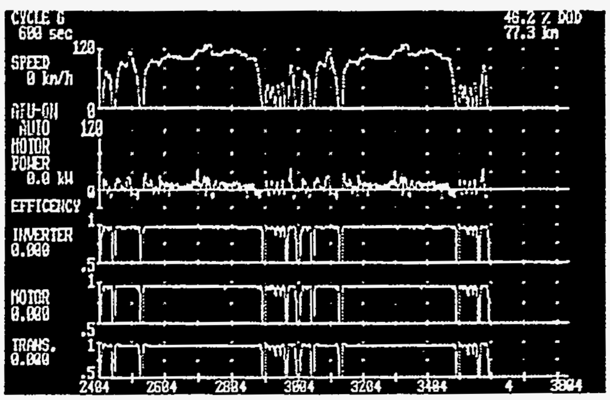
Fuel Economy: 123 mpg gasoline equivalent



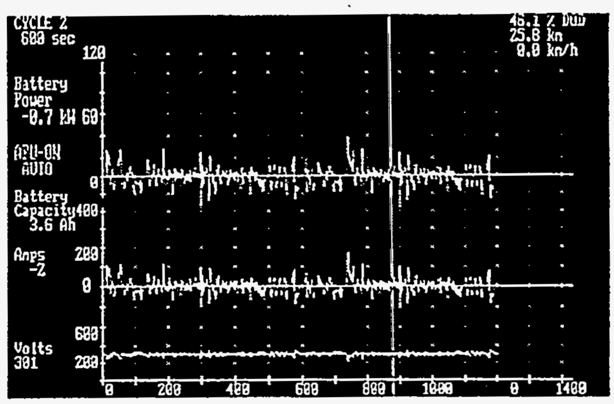
Intensified U.S. Federal Highway cycle
(all velocity inputs multiplied by a factor of 1.3).



Fuel Economy: 116 mpg gasoline equivalent



US-06 driving cycle
(High-speed and -acceleration cycle developed by the U.S. Environmental Protection Agency to augment the FTP for emissions assessment).



Fuel Economy: 100 mpg gasoline equivalent

Solar Hydrogen for Urban Trucks

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Abstract

The Clean Air Now (CAN) Solar Hydrogen Project, located at Xerox Corp., El Segundo, California, includes solar photovoltaic powered hydrogen generation, compression, storage and end use. Three modified Ford Ranger trucks use the hydrogen fuel.

The "stand-alone" electrolyzer and hydrogen dispensing system are solely powered by a photovoltaic array. A variable frequency DC-AC converter steps up the voltage to drive the 15 horsepower compressor motor. On site storage is available for up to 14,000 standard cubic feet (SCF) of solar hydrogen, and up to 80,000 SCF of commercial hydrogen. The project site is 3 miles from Los Angeles International airport.

The engine conversions are bored to 2.9 liter displacement and are supercharged. Performance is similar to that of the Ranger gasoline powered truck. Fuel is stored in carbon composite tanks (just behind the driver's cab) at pressures up to 3600 psi. Truck range is 144 miles, given 3600 psi of hydrogen. The engine operates in lean burn mode, with nil CO and HC emissions. NOx emissions vary with load and rpm in the range from 10 to 100 ppm, yielding total emissions at a small fraction of the ULEV standard. Two trucks have been converted for the Xerox fleet, and one for the City of West Hollywood.

A public outreach program, done in conjunction with the local public schools and the Department of Energy, introduces the local public to the advantages of hydrogen fuel technologies.

The Clean Air Now program demonstrates that hydrogen powered fleet development is an appropriate, safe, and effective strategy for improvement of urban air quality, energy security and avoidance of global warming impact. Continued technology development and cost reduction promises to make such implementation market competitive.

I - INTRODUCTION

Urban air pollution reduction, energy security and global warming concerns motivate us to use hydrogen as a vehicle fleet fuel. Clean Air Now (CAN), a California non-profit educational Corporation, has teamed with the South Coast Air Quality Management District (AQMD) and the White House Technology Reinvestment Project to fund and install renewable hydrogen generation and a fleet of hydrogen fueled trucks at a Xerox Corporation facility near Los Angeles International Airport.[a]

A primary goal is to demonstrate technical feasibility of hydrogen as a clean fuel, leading to corporate and public acceptance of hydrogen technologies.

Herein we first describe the hydrogen generation and storage, then the truck conversions to use the hydrogen as a fuel. Public health benefits are analyzed, in comparison to present experience in Los Angeles. The role of Xerox Corporation, safety and economic acceptance will also be discussed.

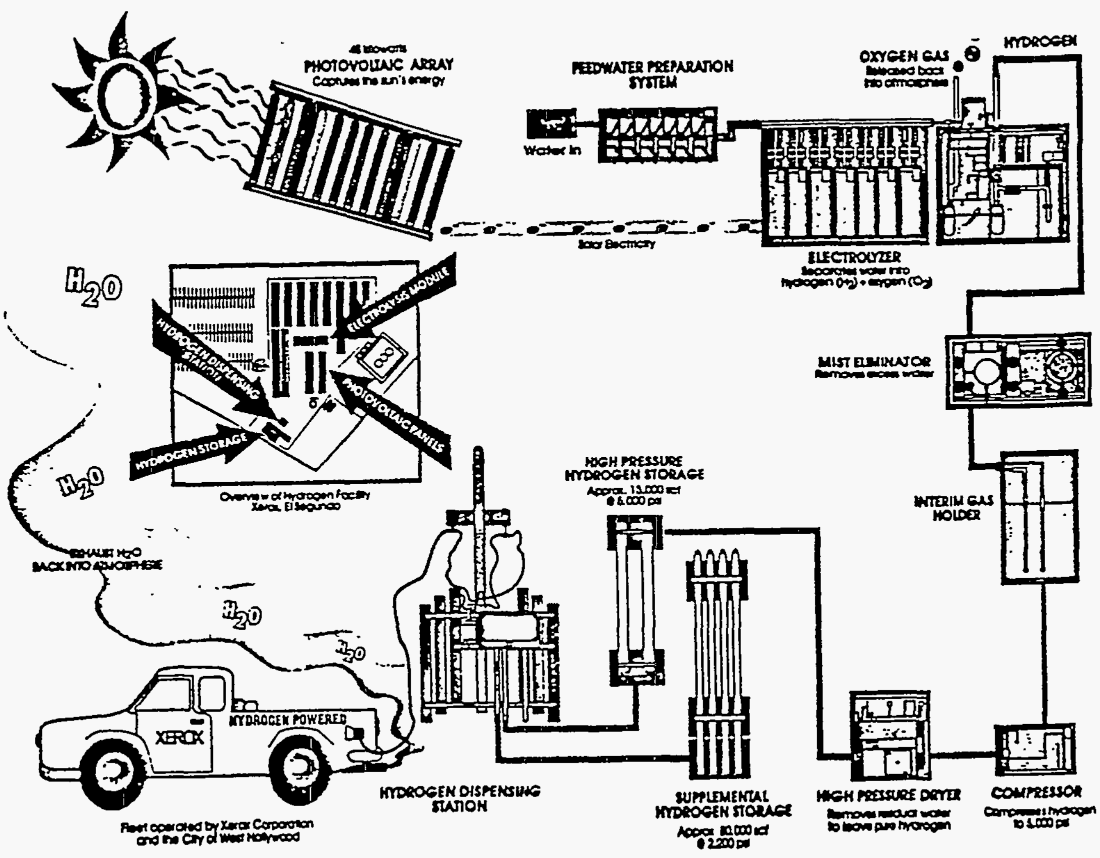

Figure 1. Solar hydrogen generator, fueling station and truck.

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[a] The project is supported, in part, by the South Coast Air Quality Management District and by DOE contract DEFC36-94GO10039. Such support does not constitute an endorsement by DOE of the views expressed herein. Substantial cost sharing investment was also made by all members of the project team.

II - THE STAND-ALONE HYDROGEN GENERATOR

Hydrogen fuel is unique in that it yields heat without carbon monoxide or dioxide, hence poisoning neither life nor earth. The CAN Solar Hydrogen Generator is designed to "stand-alone", i.e. have no connection to the commercial power grid, such that all hydrogen produced results from solar energy. The CAN trucks run on a truly renewable fuel. It is produced by using electricity from the sun's energy to split water to hydrogen, which recombines with oxygen to water by combustion in the engine of the truck.

Xerox Corporation considers social and environmental responsibility essential to a healthy long-term bottom line. This philosophy, the source of its strong Corporate Environmental Policy, paved the way for this hydrogen fuel fleet demonstration project.

Figure 1 schematically shows sunlight converted to electricity powering the electrolyzer. The system is designed for operation at 16 volts, with currents to 2700 amperes. Water purification is by ion exchange membrane. The compressor is also powered from the solar array, with a variable frequency DC to AC inverter which provides a "slow start" for the compressor. The compressor will not run at low insolation; hydrogen generated during these periods is stored in the gasholder.

Batteries, recharged only from the PV array, are used for control functions to ensure that the electrolyzer runs optimally even with nil or low insolation.

The compressor can fill only the high pressure solar hydrogen storage. The supplemental hydrogen storage was installed for commercial hydrogen, which is trucked to the site by tube trailers. Due to trucking regulations the supplemental hydrogen is limited to 2200 psi pressure. The solar hydrogen is contained in dual steel cylinders rated for pressures to 5000 psi.[b] The solar hydrogen supply has been adequate for the truck fleet. The commercial hydrogen is provided to assure that we can meet the needs of visitors (such as when CAN hosted the Ballard bus for demonstrations at LAX).

The hydrogen dispensing station is used to make the connection from the fixed storage tanks to the tankage on the trucks. Both the commercial and the solar hydrogen storage are kept separate in two (higher and lower pressure) reservoirs. Fill valves allow the operator to select from first the lower pressure, then topping off from the higher pressure storage (of either solar or commercial hydrogen).

Meticulous attention to grounding is essential to safety when using hydrogen, as a consequence of the low ignition energy. Multiple ground rods are located near the fueling

[b] Presently the system is programmed to shutdown at a maximum pressure of 4200 psi, as the tankage on the trucks is rated for a working pressure of 3600 psi.

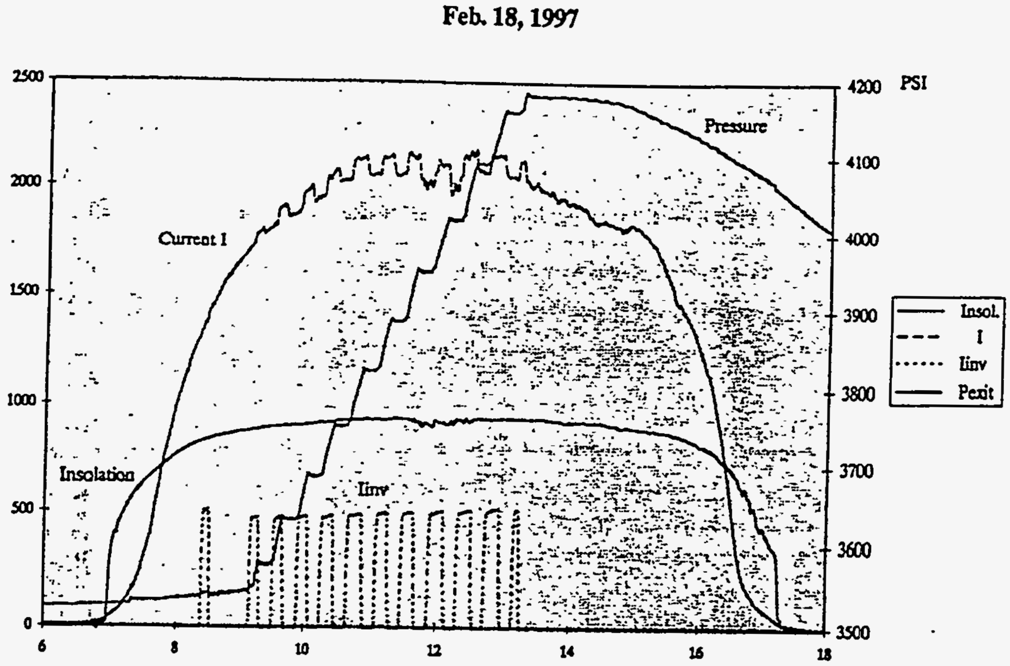

Figure 3. Illustrating insolation, total current I, inverter current Iinv, and the resulting hydrogen pressure.

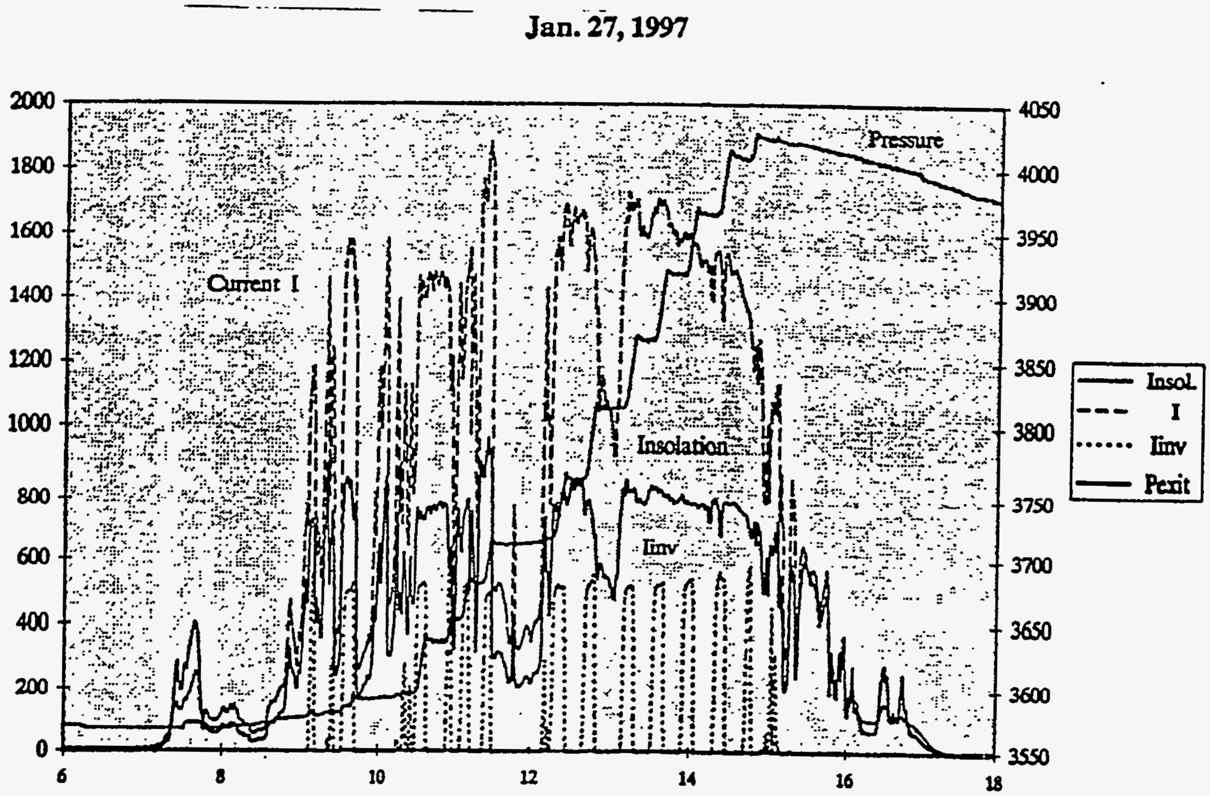

Figure 4. As in Fig. 3, but for a partly cloudy day.

CAN Solar February 21, 1997

and thus did not compress for the rest of the day. Note that there are morning and evening periods during which the voltage-current conditions will not support compressor operation. During these periods the generated hydrogen is used to fill the gasholder, following which overage is released to the atmosphere.

Note that as the compressor is on, the total current increases. Due to the lowered circuit impedance with the compressor on line, the voltage is dropped and hence the current from the PV (photovoltaic) supply is increased.

The pressure increases sharply with each compression cycle, more notably on these days because only the high pressure cylinder was connected to the system. The pressure rise of 660 psi corresponds to approximately 1340 SCF (and would have been some 2000 but for the maximum pressure cutoff). On the day with sporadic cloudiness approximately 900 SCF of hydrogen was generated.

Figure 5. The Xerox (white) and West Hollywood hydrogen fueled trucks.

III - THE HYDROGEN FUELED TRUCKS

Three Ford Ranger trucks were converted to store and use compressed gaseous hydrogen as fuel. Figure 5 shows a "family photo" of the trucks.

Vehicle safety is of paramount concern. The use of hydrogen as the fuel is itself a key safety feature, as it avoids fires following liquid fuel spills.[d] Were the flammable gas to escape, it most likely would burn harmlessly while rising above the vehicle. To prevent such escape, additional structure has been added to protect the tankage and fuel lines from a side impact collision. Dual check valves and an excess flow limiting valve protect from a regulator or line failure. Hydrogen detectors are located under the hood and near the fuel lines.

A large crankcase relief valve is provided to open in case of a pressure rise in the crankcase/valve cover space.

Transferring hydrogen to the trucks is a critical step. Grounding is an essential safety precaution. A ground cable (#4 copper) is first connected to the ground receptacle on the truck body. Mating *Tweco* welding connectors (they require insertion and then a twist) are used, with the fueling door interlocked until the grounding connector closed. The twist motion retracts a pin from the fuel port door, allowing the door to pop open yielding access to the fuel connector.

The truck bed mounts dual carbon fiber wound tanks, storing 2418 SCF hydrogen at 3600 psia. Range, using 3500 psi of fuel, is 140 highway miles.

The truck engines are converted from the stock 4 cylinder, 2.3 liter Ford engine. Bore and stroke are increased to 2.9 liters and a supercharger further increases mass airflow. The hydrogen injection system is of the Constant Volume Injection (CVI) design from Frank Lynch of Hydrogen Components, Inc. Engine compression ratio is increased to 11:1 to enhance efficiency. Air heating caused by the supercharger boost, as high as 7 psi, is removed by a large cross-flow intercooler.

The engine controller delays fuel flow for 1/2 second after cranking starts. As the key is turned off, cranking and spark continue briefly following fuel flow cutoff.

The equivalence ratio (hydrogen-air mixture ratio) is run ultralean - at less than 0.5 of stoichiometric - to reduce the flame propagation speed, promote "cool" combustion and

[d] Cannon (Ref. 1) reports that 600 lives are lost each year - in the USA alone - in automotive vehicle accident fires. One of the health benefits of conversion to gaseous fuels will be the virtual elimination of these tragic deaths.

minimize NOx production. An exhaust gas oxygen (EGO) sensor is used in the CVI control loop to continually monitor the degree of combustion and maintain a set mixture.

Misfires, and even backfires, are reported as a problem with earlier hydrogen fueled engines. These engines, when properly set up, are relatively benign. Misfires do occur sporadically but only under extreme operating conditions.

Each of the three trucks was evaluated using the chassis dynamometer and associated instrumentation at the University of California at Riverside, College of Engineering, Center for Environmental Research and Technology (CE-CERT) under contract to CAN. Proper adjustment of the CVI controller was found to be critical for proper operation. For example, CAN1 initially was subject to surging and excessive NOx, with highly irregular combustion pressures. CAN3 originally was set up to run very lean, at equivalence ratio of approximately 0.32, with the result of reduced low end performance and extremely low NOx - below 35 ppm.

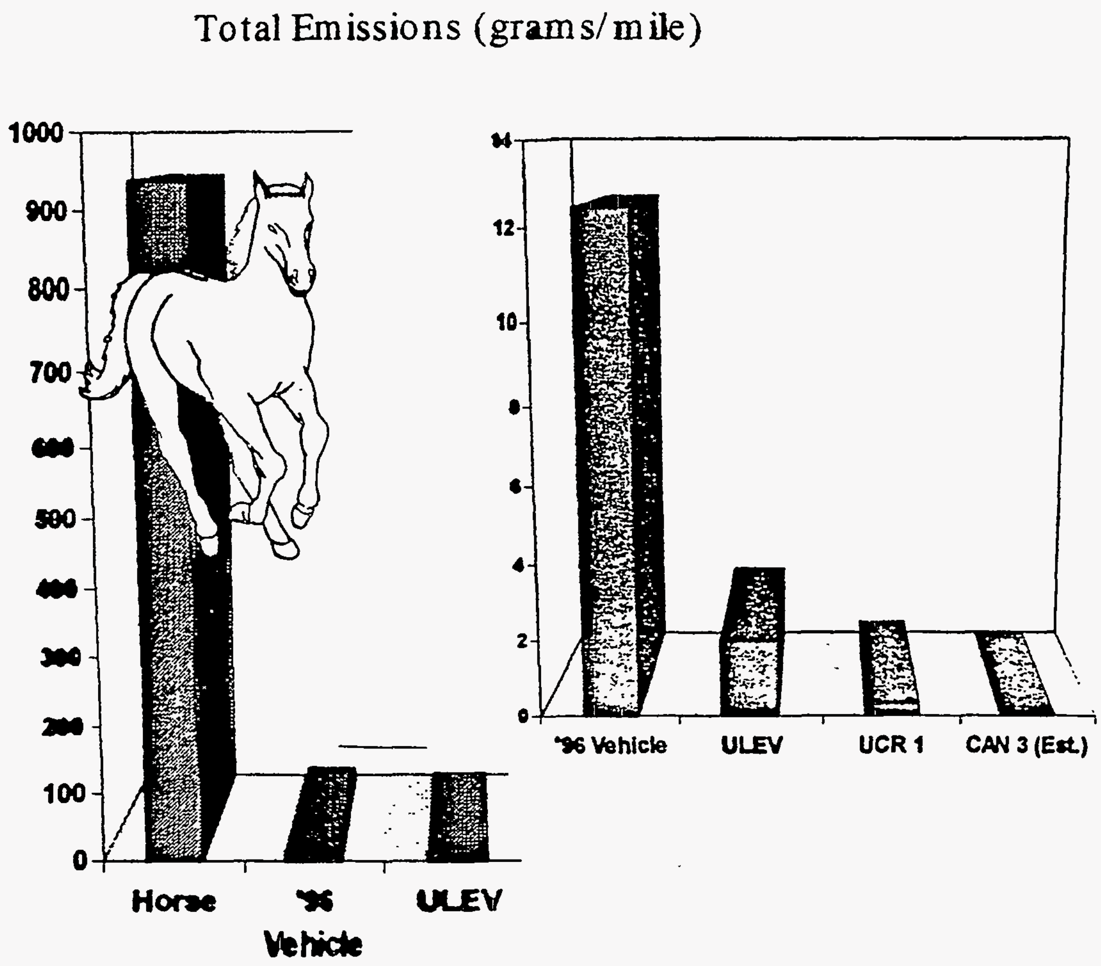

Figure 6. Showing emissions reductions over the last century.

Chassis dynamometer tests show the hydrogen fueled engine is more powerful than the stock gasoline powered engine at all but the highest engine speeds. Peak power occurs at about 4000 rpm. Even at this highest power level, measurement shows less than 100 ppm NOx.

Dramatic public health progress is shown in Figure 6. Before 1900 the horse, with some 940 grams/mi "emissions"[1], was the preferred means of personal transport. Barely a hundred years from the introduction of the horseless carriage the total emissions are down to 12.5 gm/mi (for the average car on Los Angeles freeways), or down to 2 grams/mi for a modern car meeting the ULEV standard. UCR1, the first of the Ford Ranger trucks converted to hydrogen fuel two years ago at the UCR CE-CERT facility, tested at a total emissions (CO, HC and NOx) of 0.37 grams per mile. The CAN trucks are cleaner than UCR1. By further improvement in the control system, we believe below 0.1 gm/mi is achievable. Van Blarigan et.al. have shown hydrogen, or hydrogen/natural gas mixed fuel engines can achieve the proposed EZEV (Equivalent Zero Emission Vehicle) California standards.[2] As an additional benefit, the greenhouse gas yield is also cut by factors of hundreds (using renewable hydrogen).

IV - HEALTH BENEFITS - A KEY MOTIVATION FOR USE OF HYDROGEN FUEL

The CAN Solar Hydrogen Project was motivated by the health effects of the air of Los Angeles and other metropolises. The epidemiological data showing the effects of fossil fuel combustion byproducts has been extensively documented.[3] In the last 3 years particular attention has been focused on the health effects of small particulate matter and ozone[4], resulting in proposed new EPA standards.

Of particular concern are the small (submicron to 2.5 micron size) particles, which are small enough to be inhaled deeply into the lungs where they may persist. Diesel engine exhaust is the dominant source of elemental carbon particle emissions in the Los Angeles area.[5] These products of diesel combustion include known mutagens, carcinogens, and lung irritants. The bulk of particulate emissions (by mass) are in this small size range. They are not accounted for by present PM10 standards.

Ironically, as we ask that engine manufacturers get rid of diesel smoke, the result is a substantial reduction by weight of total particulate matter, <u>and an increase</u>

by 15 to 35 times in the total number of particles due to increase in the small, primary particles.[6]

Hall et.al.[7] have presented a cost benefit assessment of the health effects of ozone and particulate matter in the Los Angeles region. They estimated **annual benefits of $10 Billion** would accrue by avoidance of these effects. Nationwide health cost estimates range to ten times this.[8]

Worldwide, air pollution is severe in many cities - particularly in evolving economies such as Mexico and China. Many would benefit from a cost effective means of using hydrogen for motive power.[e]

V - IMPLICATIONS AND CONCLUSION

Some cite the cost of renewable hydrogen as excessive, particularly as compared to USA gasoline prices. Cannon, noting that the consumer's fuel cost is composed of the sum of the wholesale cost, the distribution and the tax costs, cites the gasoline distribution costs at 25 cents per gallon.[1] He suggests that, "Refueling station costs are

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[e] Let us pause to speculate on the implications of a program which would devote 10% of the health cost of air pollution towards a long term - non-carbon - solution. This national program would grow to invest up to 3 billion dollars per year into research and development of a hydrogen economy. We now spend 70 billion per year to import oil, this would add some 4%, or about one dollar, to the cost of an imported barrel of oil. The cost to the motorist or trucker - at the peak of the program - would be about 2 cents per gallon.

Benefits of the program would include improvement in urban population health, improved national economic security - as we are weaned from imported oil - and new employment and exports as new and attractive technologies move into production.

Appropriate goals of such a program would include:

* Providing increasing support for promising investigations regarding improved hydrogen production, storage, and utilization.
* Providing tax credit incentives for conversion of van, bus and trucking fleets to EZEV vehicles, and for fueling stations open to the public.
* Development of a national capability, including NASA, aircraft manufacturers and suppliers, for building a fleet of hydrogen fueled transport aircraft.

Politically impossible? Without leadership, yes. George Bush, in a moment of watery vision in 1990, proposed a NASA mission to Mars with cost ten times this. He didn't sell it - but it is hard to argue it hurt his Presidency. A legacy of taking the world to a hydrogen economy could be even larger than that John Kennedy won with going to the moon.

CAN Solar February 21, 1997

projected to range from 30 cents per equivalent gallon[f]... to 70 cents for a liquid hydrogen refueling station."[9] Further, he claims a hydrogen manufacturing cost range from 80 cents/equivalent gallon (from natural gas) to $4/equivalent gallon.[g] Including some transportation fees, the cost at the pump - given the cost reductions available with a large, assured market - could be as low as $1.45/eq. gallon for non-renewable hydrogen (from natural gas). Hydrogen from renewable resources will be more expensive, perhaps $3 in some locales.

We emphasize that the CAN fleet of three trucks is but a quick and crude conversion of an engine designed for gasoline use. Trucks designed specifically for hydrogen fuel will be more drivable and more efficient. In fact, much more efficient if hybrid design is used[10]. Given these improvements, the range of a state of the art hydrogen truck can be over 300 miles, and the **cost of renewable hydrogen fuel becomes less than 5 cents per mile.** Considering the national economic security, job creation and export potential in combination with health benefits, a national opportunity exists.

The CAN demonstration features on-site PV generation of the hydrogen fuel. It is important at this time to implement site specific generation using different methods. An important next step will be hydrogen production at a wind generation site. Biomass and waste pyrolysis are also of interest for some sites.

Large scale implementation of hydrogen for fleet use is now appropriate in urban areas. The immediate public health benefit will be the substitution of water vapor for the present toxic carbon monoxide and hydrocarbons from car engines or the toxic particulates and fumes from diesel engines. Potentially of great importance are increased operator safety and assured fuel supply. These trucks will not be idled by turmoil in the mideast - a factor that will be of key importance to companies that need assured transportation!

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[f] The "equivalent gallon" used by Cannon, and herein, is that amount of gas which contains the energy of a gallon of gasoline. However, the "equivalent gallon" quantity of hydrogen may be <u>much</u> more effective, with the range of a 21st Century hydrogen vehicle likely approaching 80 miles per equivalent gallon. Hence when Cannon refers to hydrogen at $3 per equivalent gallon, we are speaking of $12 to $15 to fill the tank.

[g] Our analysis shows wind generated electricity driven electrolysis to be a most attractive renewable source. Using today's cost (5 cents per kilowatt hour) for wind electricity, the hydrogen cost at generation site would be $2.60/equivalent gallon. This would likely be halved in the next decade.

Solar Hydrogen Project Mission Statement

The Solar Hydrogen Project promotes the development and awareness of clean renewable technologies and the use of hydrogen as a means of energy storage, making available domestically produced and environmentally benign technologies essential to our national security and public health.

It is the intent of the Solar Hydrogen Project to develop clean technologies using solar fuel, and to demonstrate these technologies to the community. We invite innovative projects for collaboration. The site is open to visitors including - in particular - school children from surrounding communities. Hundreds of children have made Solar Hydrogen the subject of a field trip and class projects in recent months, providing for them a glimpse of the possibility of a pollution free energy economy.

CAN Solar February 21, 1997

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10. Our analysis shows wind generated electricity driven electrolysis to be a most attractive renewable source. Using **today's cost** (5 cents per kilowatt hour) for wind electricity, the hydrogen cost at generation site would be $2.60/equivalent gallon. This would likely be halved in the next decade.

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CAN Solar February 21, 1997

HYDROGEN: KEY TO AEROSPACE MOTIVE POWER TODAY AND TOMORROW

William J.D. Escher
Kaiser Marquardt

ABSTRACT

Hydrogen, noted by the Russian pioneering theorist of astronautics, Konstantin Tsiolkovsky, to be the rocket fuel of choice in the late nineteenth century, was a long time in arriving at its status today as the leading "high energy" fuel candidate for our advanced aerospace propulsion system applications. Liquid hydrogen, a non-dense deep cryogen at 20 K, up to the mid-1950s, remained pretty much as "laboratory curiosity," with an occasional small non-flight-type research rocket being tested from time to time on hydrogen/oxygen propellants. But its promise of high performance and outstanding cooling propertise was escalating within the aerospace community.

The practicable development of liquid hydrogen as a propulsive fuel for, not just rockets, but also by certain advanced airbreathing engine types got underway toward the end of World War II. It was a high-flying supersonic airplane development taken on by the renowned Lockheed Skunk Works, one never completed however, that finally began the engineering process of actually embracing its numerous technical challenges, and finally gaining its striking benefits. The General Dynamics Centaur rocket upper stage was the first flight vehicle predicated on the hydrogen/ oxygen propellant combination. Its Pratt & Whitney RL-10 engines, deriving obliquely from that canceled aircraft program in the mid 1950s, are still in production today.

Then followed the Apollo moon program with its outsized Saturn 1 and 5 vehicles with very large hydrogen oxygen upper stages powered by Rocketdyne's J-2 engines. Going from kerosene to hydrogen roughly halved the vehicle takeoff mass for sending the astronauts to the Moon and bringing them safely home. This paper recounts this progression to hydrogen's staple fuel status today, and its prospect for continuing in this leadership role in the decades ahead. For instance, hydrogen is unexcelled as an airbreathing scramjet mode fuel.

HYDROGEN FUEL CELLS FOR AEROSPACE AND COMMERCIAL APPLICATIONS

To
National Hydrogen Association

March 12, 1997

P. J. Farris (860) 727-2305

- 227 -

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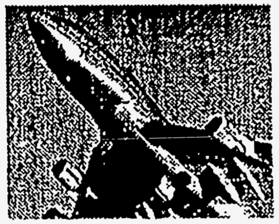

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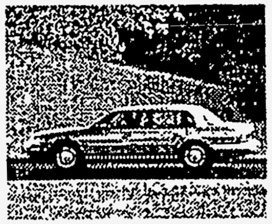


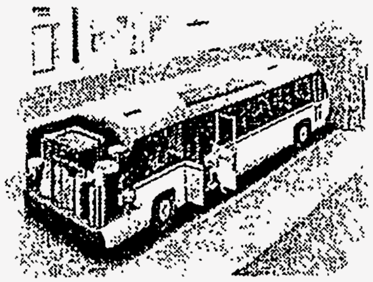
Carrier

Otis

Hamilton Standard

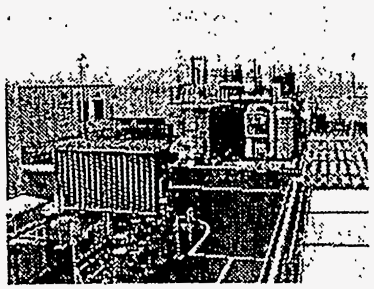
STATIONARY

Transportation



Space & Defense

Multi-Megawatt



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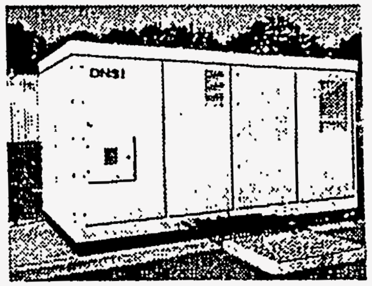
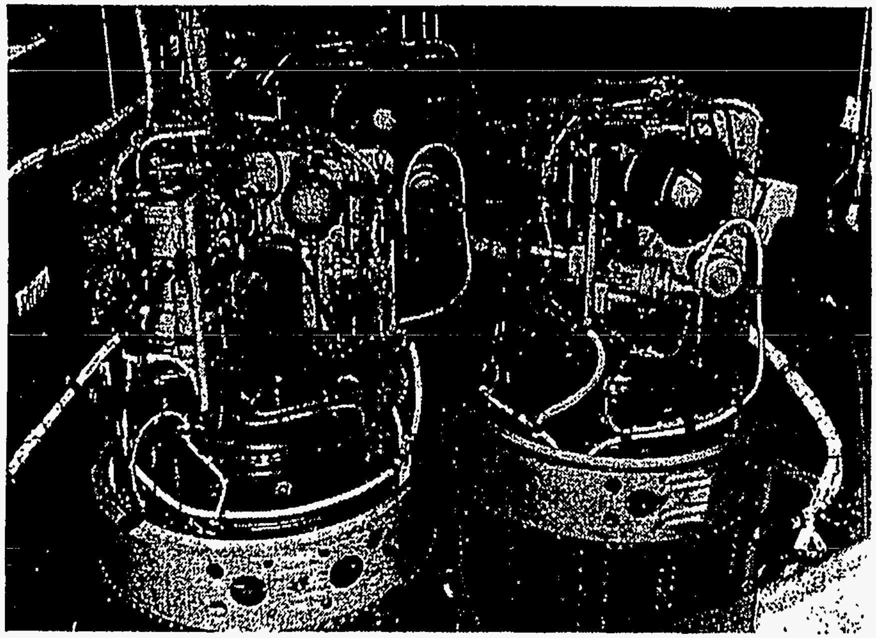


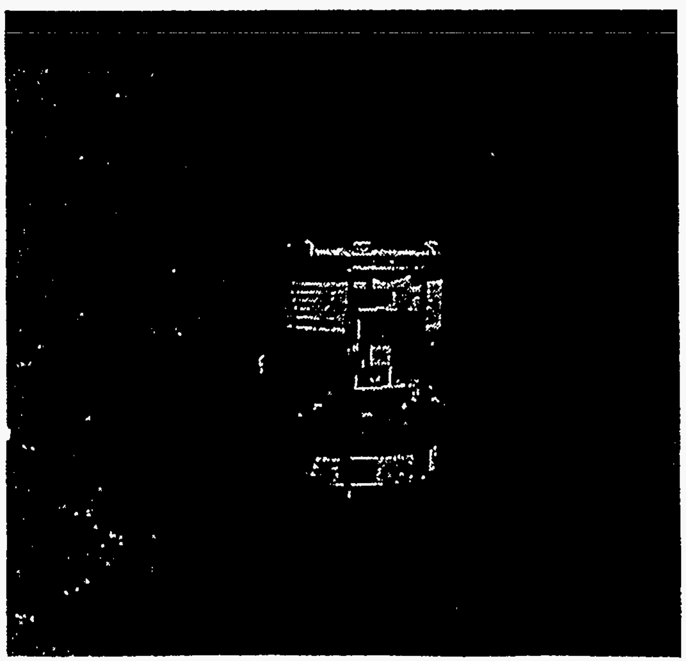
INTERNATIONAL FUEL CELLS

FC37600
R961804

AEROSPACE and DEFENSE APPLICATIONS

Fuel Cell Installation



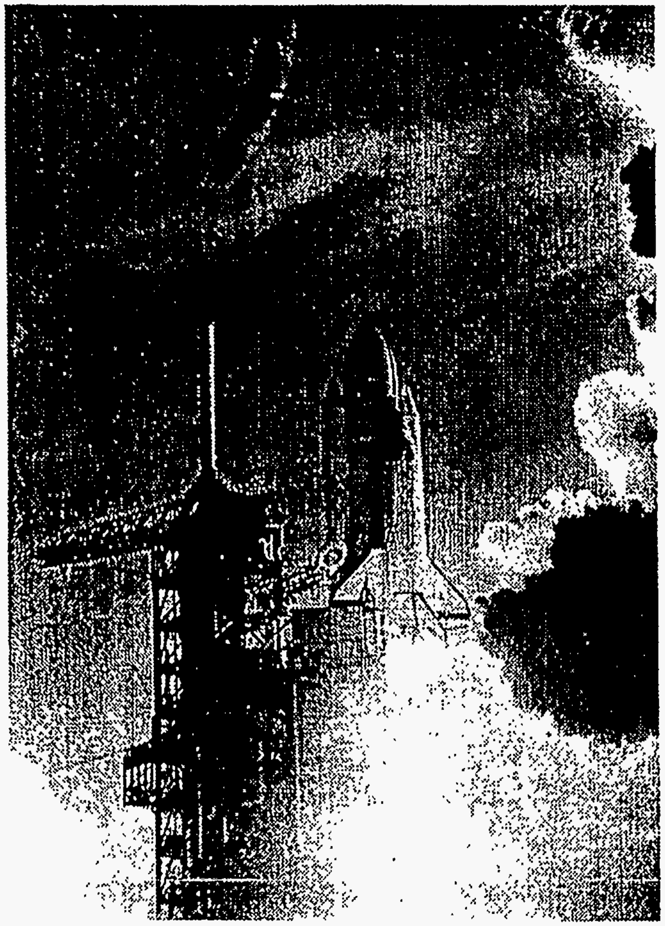


APOLLO FUEL CELL OPERATION

- Prime power for command and service modules
- 18 flights
  - Apollo
  - Skylab
  - Apollo-Soyuz
- 10,750 hours

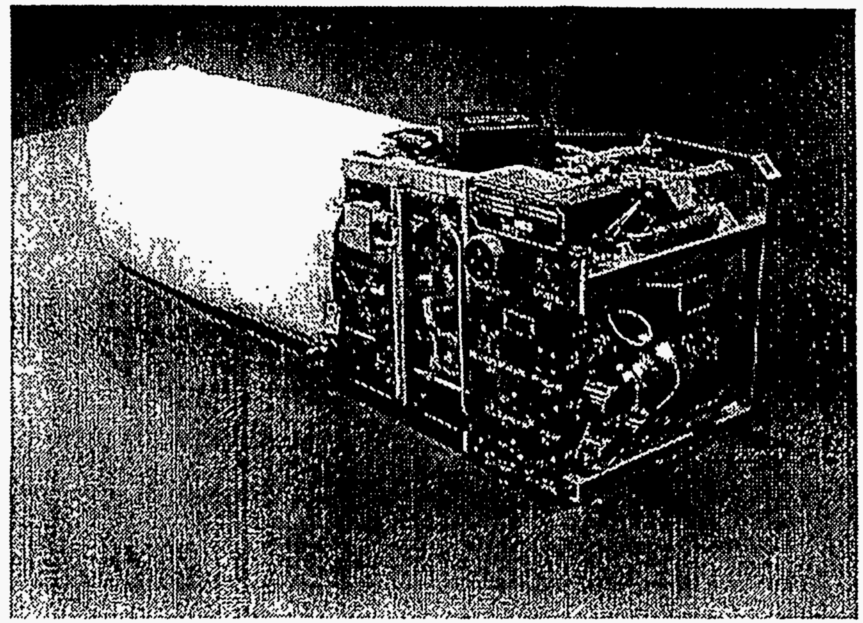
FC29730
900904

SPACE SHUTTLE ORBITER FUEL CELL



WCN 8986

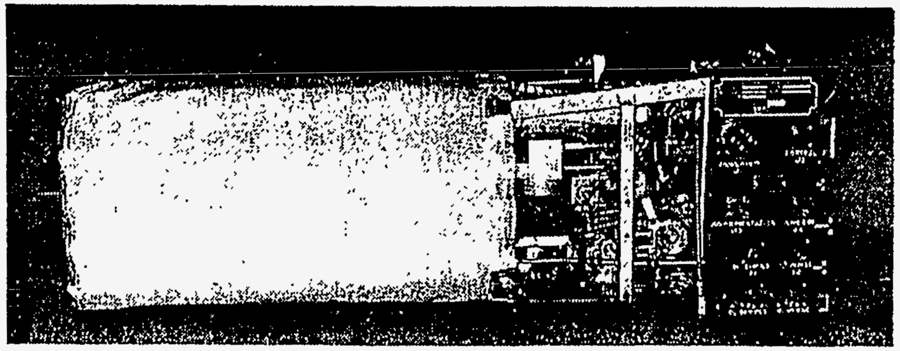
- 82 Missions
- 60,839 Hours



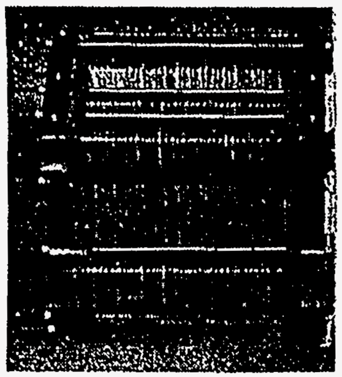
WCN -10462

FC34161S
R970303

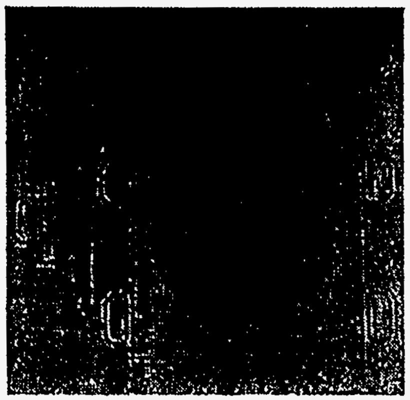
ELEMENTS OF SPACE SHUTTLE ORBITER FUEL CELL POWERPLANT



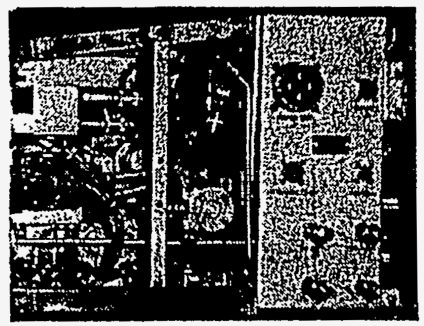
Power section



Cell assembly

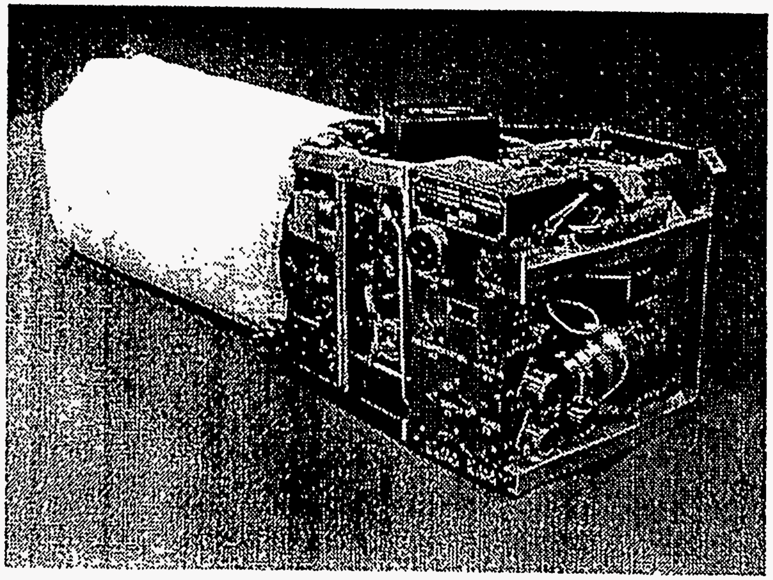


Accessory section

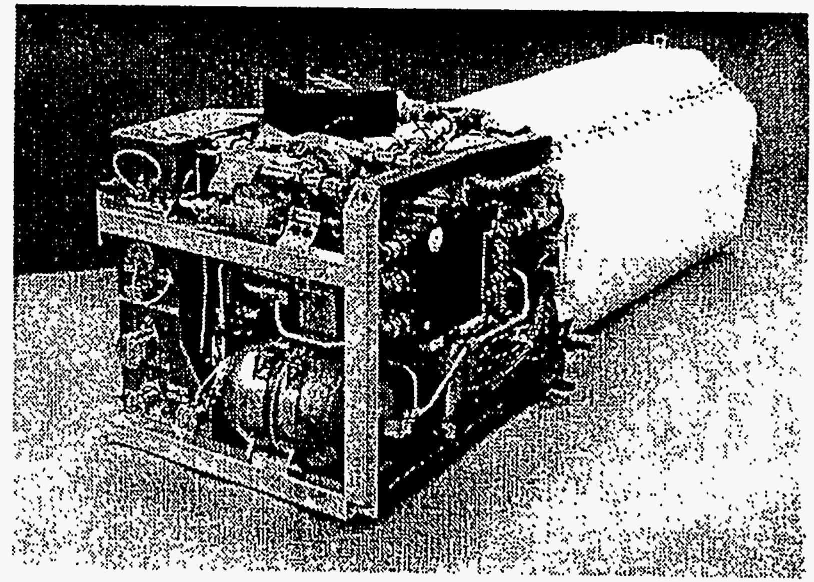


FC24609
871009

ORBITER FUEL CELL POWERPLANT



WCN10462



WCN10464

Characteristics

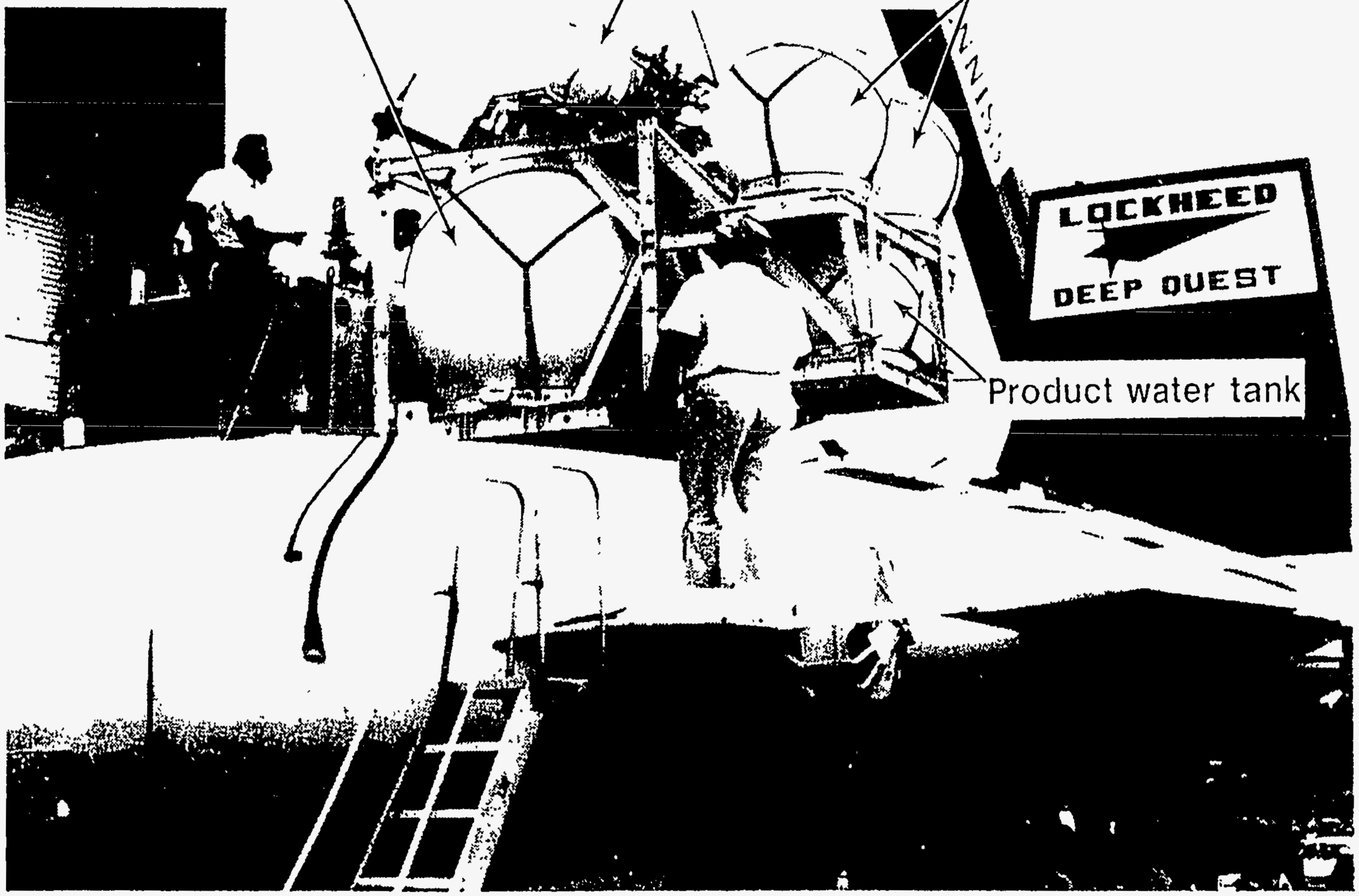
- 12 kW nominal
- 16 kW maximum
- 260 pounds

Installation

- 3 per Orbiter
- All on-board power
- H_2O for crew drinking and vehicle cooling

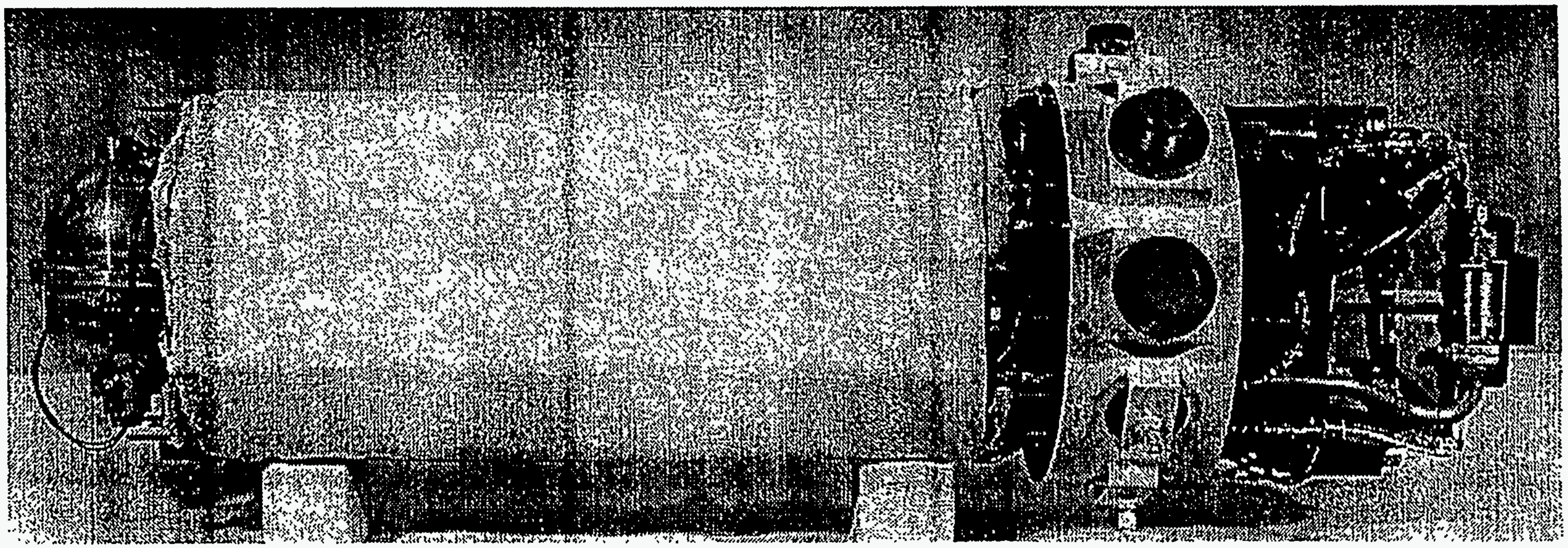
FC29732S
r971501

FUEL CELL POWER SYSTEM
DEEP QUEST



FC24983
R882209

PC15 FUEL CELL POWERPLANT

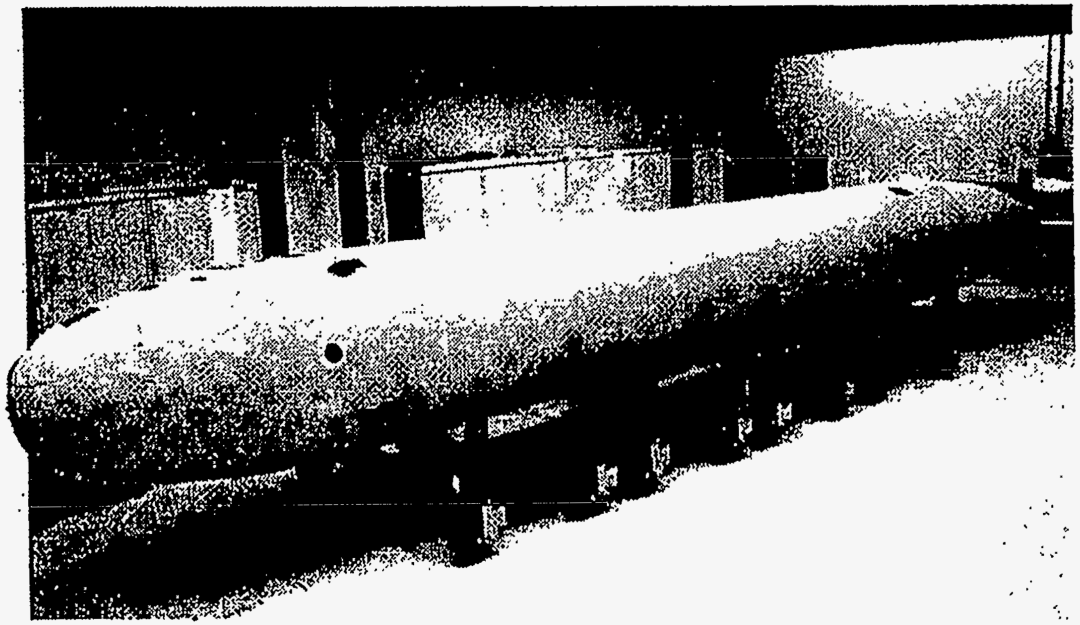


WCN-2957

- 120 Volt system – 30kW
- Power source for Deep Quest Vehicle
- Five powerplants built
- More than 7000 hours of operation
- Weight – 391 lbs
- Envelope – 14” diameter x 72” long – 6.4 ft^3

FC38321
962210

DARPA UUV FUEL CELL PROGRAM

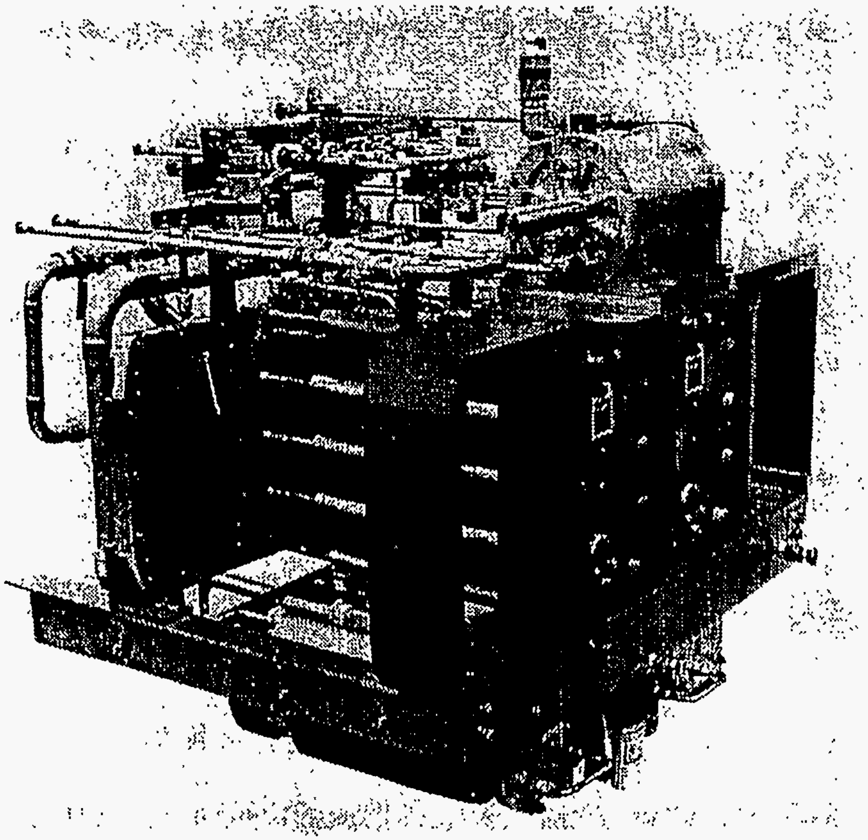


CA-0005

- **Demonstrate 3–8x AgZn energy density**
- **Establish fuel cell operating credibility**

FC34867
920312

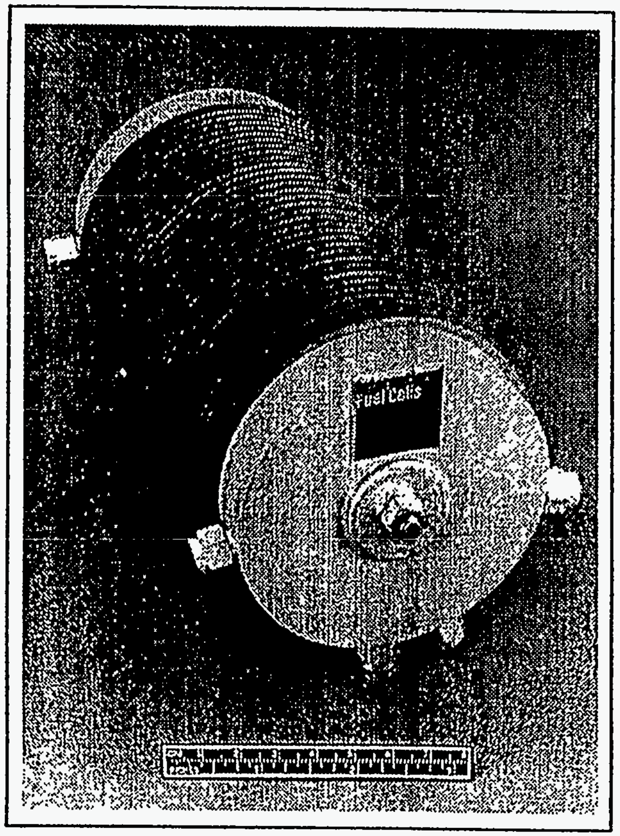
PC27 PROTOTYPE FUEL CELL POWER PLANT



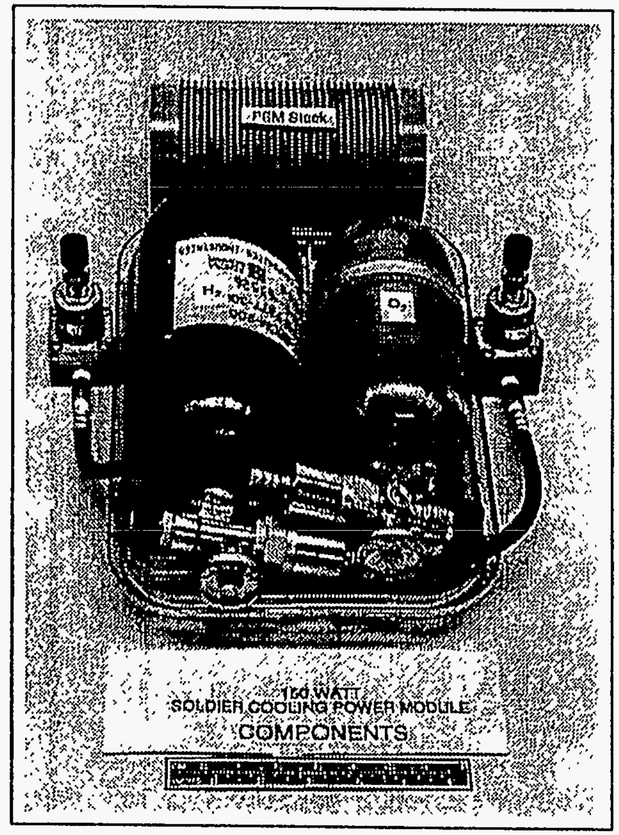
- 10 kW
- Upgradable to 20 kW
- H_2/O_2 reactants
- 130 Vdc

FC36690S
942408

150-WATT SOLDIER COOLING MODULE



WCN 15126

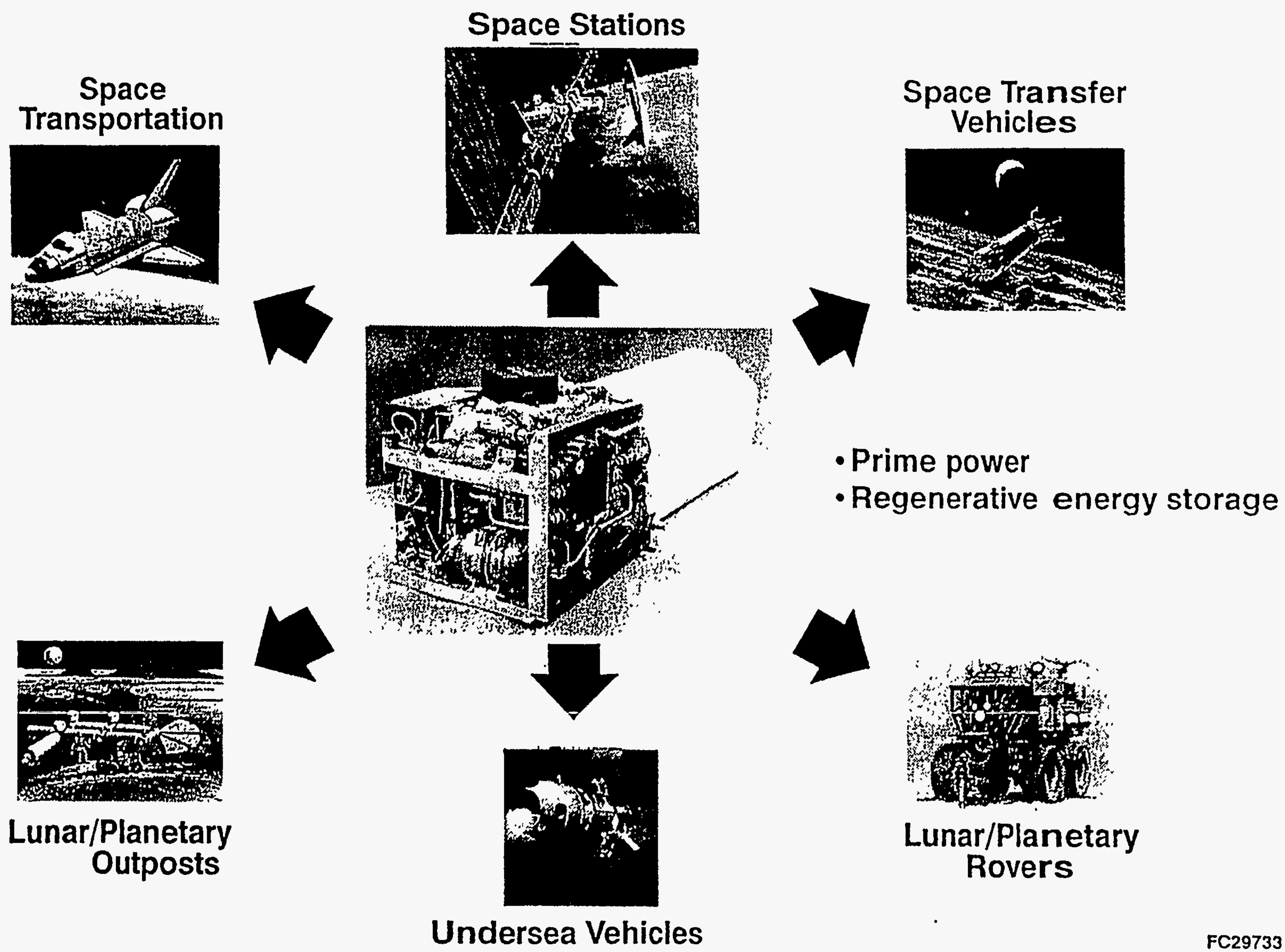


WCN 15276

- H_2 – O_2 Unit tested 12/96
- H_2 – Air contract awarded – 1/97 start

FC38519
970303

POTENTIAL APPLICATIONS



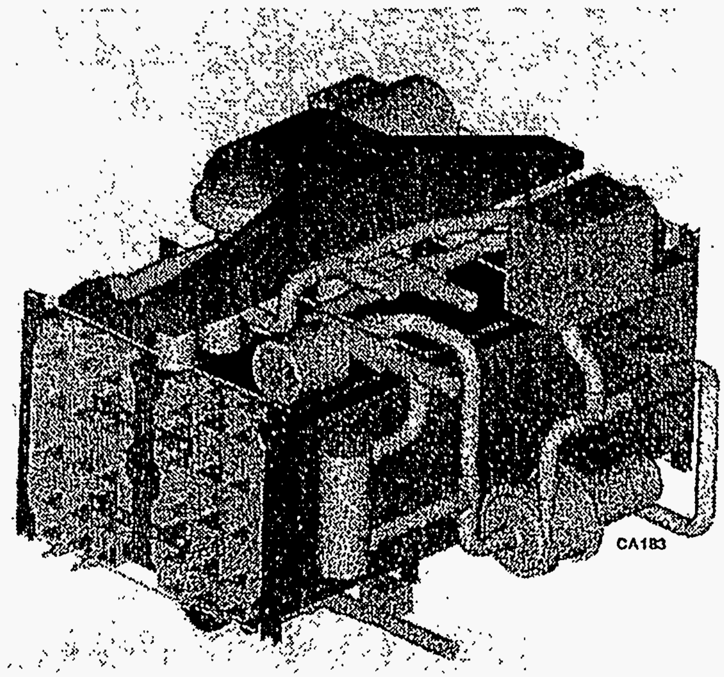
FC29733
R901104

HYDROGEN FUEL CELLS FOR COMMERCIAL APPLICATIONS

- TRANSPORTATION
- STATIONARY

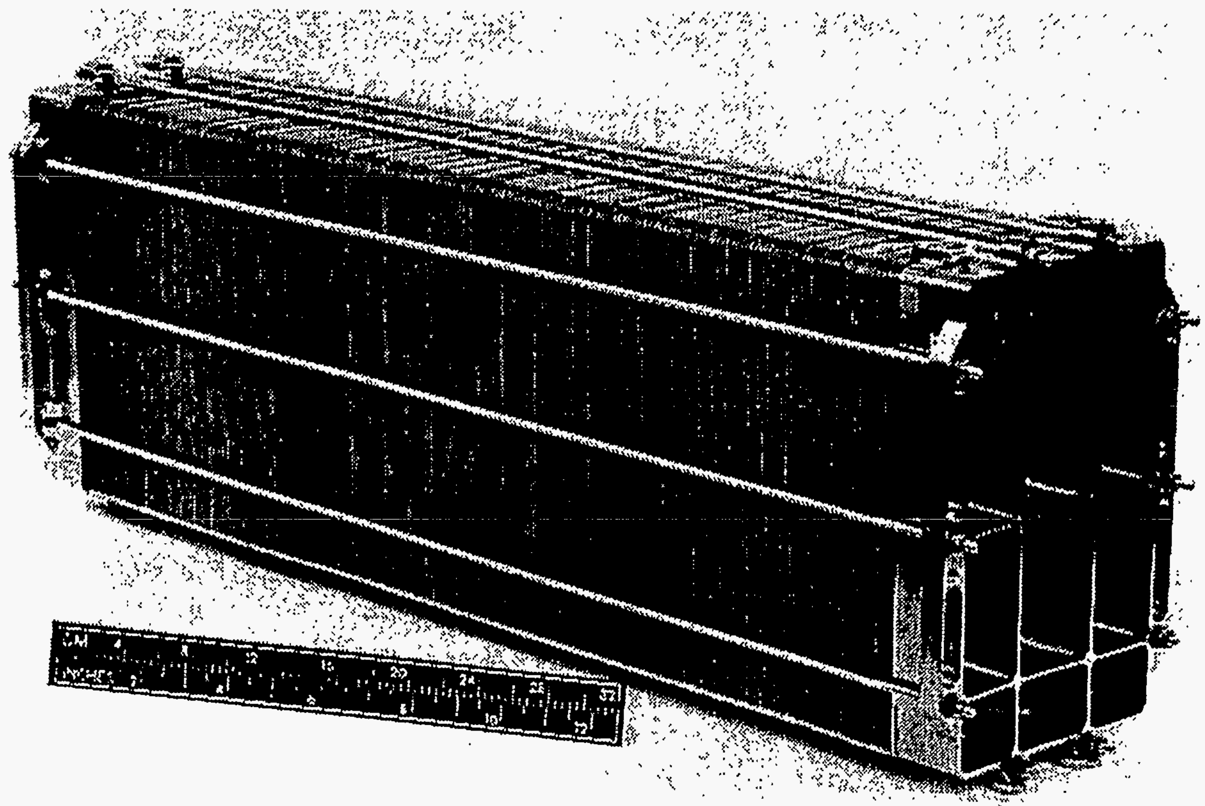
50kW NET PEM FUEL CELL POWER SYSTEM FOR VEHICLE APPLICATIONS

Weight = 142kg (313 lb.)
Volume = 234.6 liters (8.29 cu. ft.)
Efficiency at 50kW = 43%
Pt Loading = 1.20g/net kW



FC38521
970303

PHASE II STACK MOCKUP



WCN15381

FC38171
962607

STATIONARY HYDROGEN FUELED POWER PLANTS

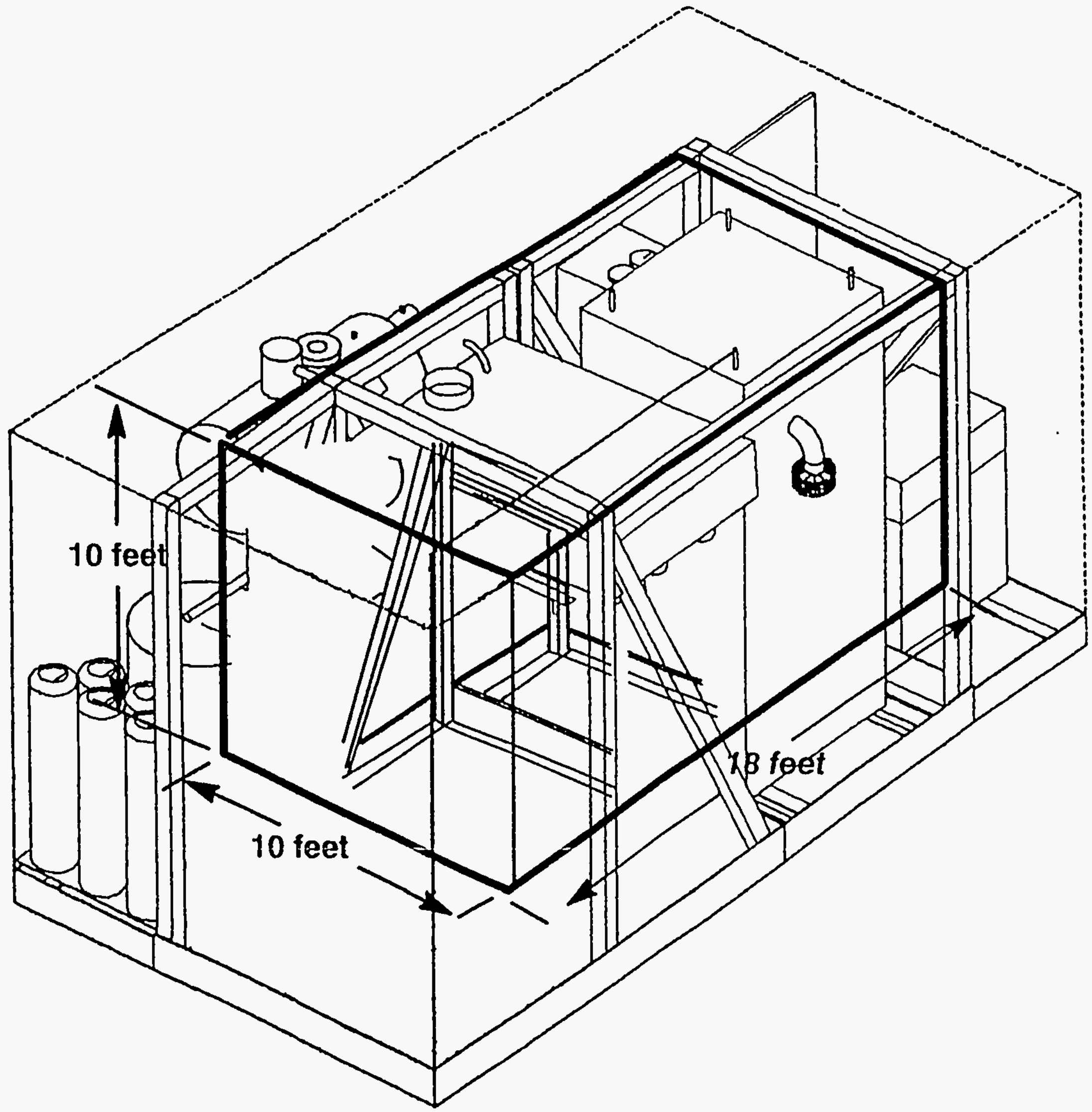
- 200kW Power Plants
- Scale to Multi–megawatt

200kW HYDROGEN FUELED POWER PLANT

- **Power plant builds on existing PC25 technology and design base**
- **Modifications for hydrogen fuel**
  - Simplify fuel processing section
  - Modify heat and water management system
  - Redesign power plant control system
- **Assembly and manufacturing procedures modified for production of hydrogen power plants**
- **Scale to multi-megawatt capability**
  - Multiple units
  - Repackage cell stacks and scale-up BOP equipment

FC38517
970303

HYDROGEN VERSION OF THE PC25 C



FC38518
970303

REUSABLE LAUNCH VEHICLE TECHNOLOGY PROGRAM

Partnerships for Space Launch Leadership

Program Overview

Mr. David Stone
Manager
Space Transportation Vehicle Systems Technology
National Aeronautics & Space Administration (NASA)
600 Independence Avenue, SW
Wasington, DC 20546

X-33 Program Background

- U.S. Share of Launch Market has Fallen Steadilly Since Early '80's
- Space Shuttle Becoming Obsolete (25 Year Old Technology)

- NASA Access to Space Study in 1993

  Options:

  (1) Upgrade Shuttle, (2) New Expendable Fleet, (3) New Fully Reusable Fleet

  Result:

  - Fully Reusable Single Stage to Orbit (SSTO) Rocket is Feasible
  - Pursue a Program to Mature Technologies to Prove Feasibility of SSTO
  - Combination of Ground and Flight (X Vehicle) Demonstrations

- NASA Reusable Launch Vehicle (RLV) Technology Program in 1994
  - Cryogenic Tank, Composite Structures, Durable TPS, Reliable Propulsion Demonstrations Initiated
  - DC-XA Used to Integrate Several Technologies

- Presidential Space Launch Policy (1994)

  Pursue Technologies and and X Prototype to Allow Decision at End of Decade on a *COMMERCIALLY DEVELOPED AND OPERATED NEXT GENERATION SYSTEM*

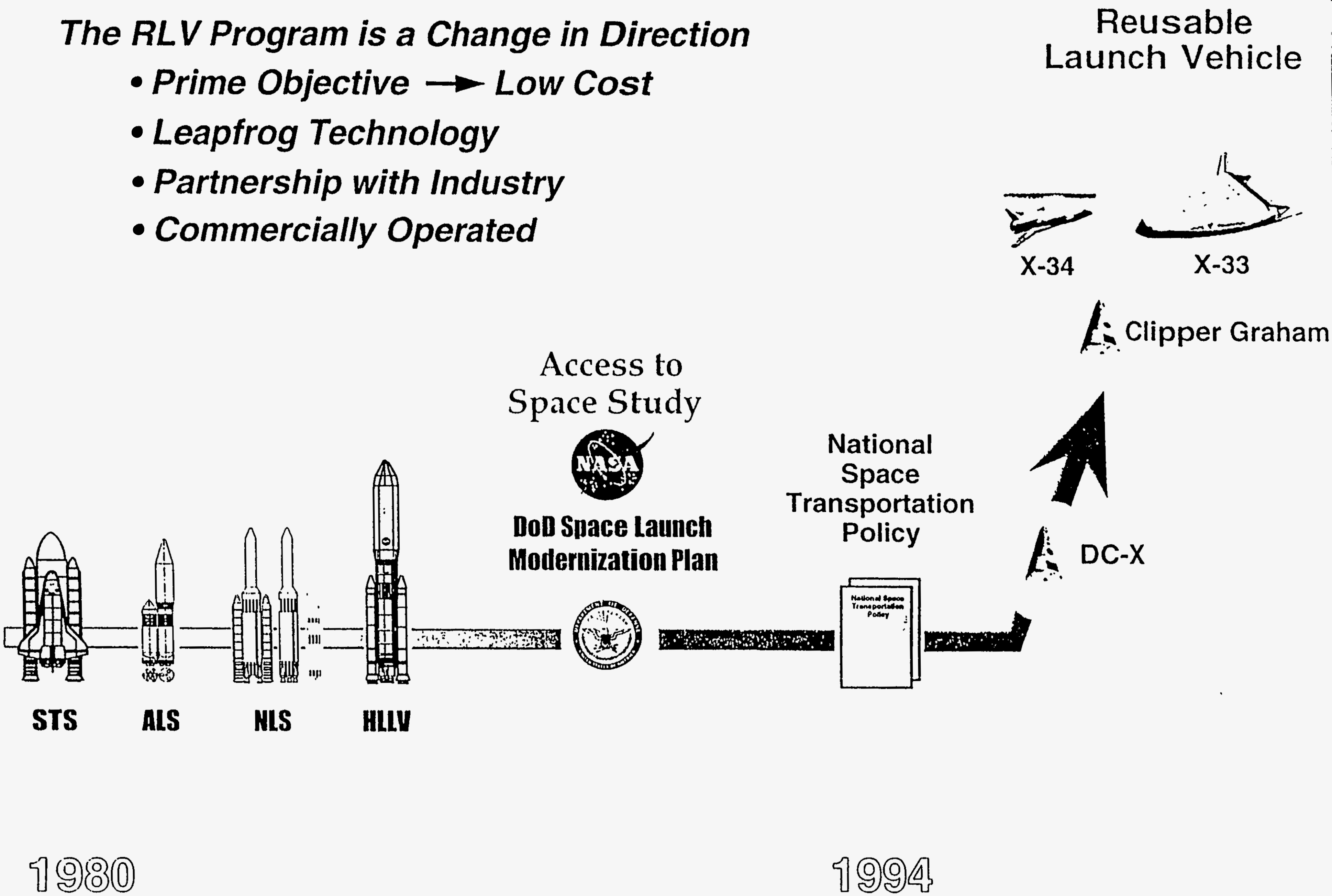
X-33 Advanced Technology Demonstrator Program (1995)

- 15 month Competitive Preliminary Design and Tech Demo Phase (Phase I)
- Build and Fly a 50% Scale Prototype of Operational RLV in Key Environments
- $ 1 Billion Cooperative Partnership with Industry thru 1999

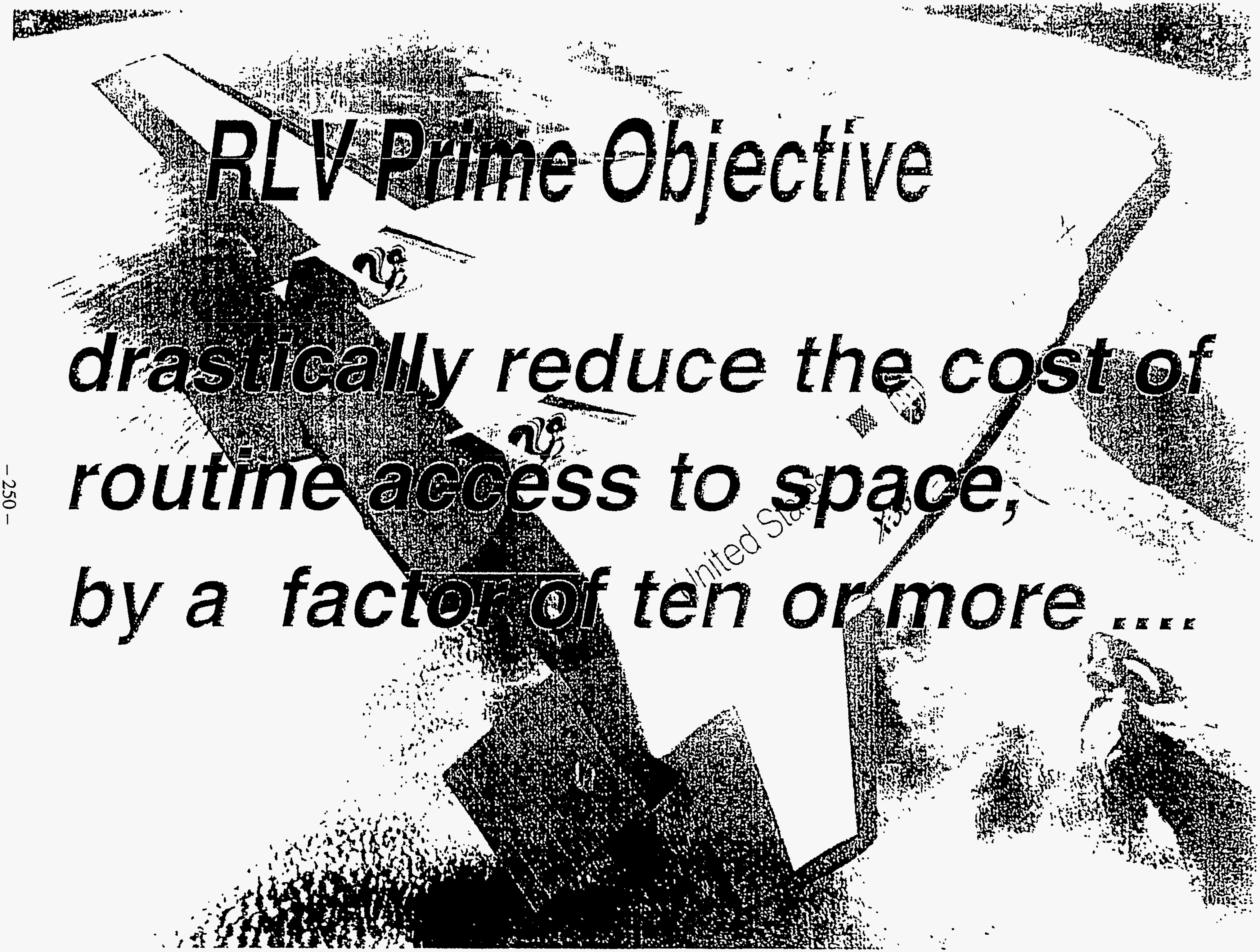
RLV Program Heritage

The RLV Program is a Change in Direction

- ***Prime Objective → Low Cost***
- ***Leapfrog Technology***
- ***Partnership with Industry***
- ***Commercially Operated***

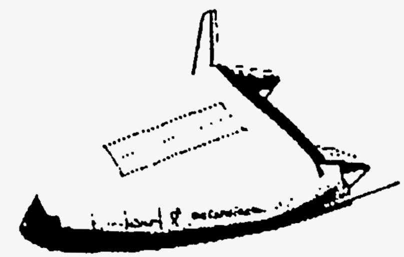


rl/ 8 23 96


RLV Prime Objective
drastically reduce the cost of
routine access to space,
by a factor of ten or more ....

GOVERNMENT - INDUSTRY PARTICIPATION

1994 | 2000 | 2010



Base
Technology
Program

Government Funded
Partnership with
Industry Cost Sharing

Technology
Demonstrator
Development
& Test

RLV
Full Scale
Development

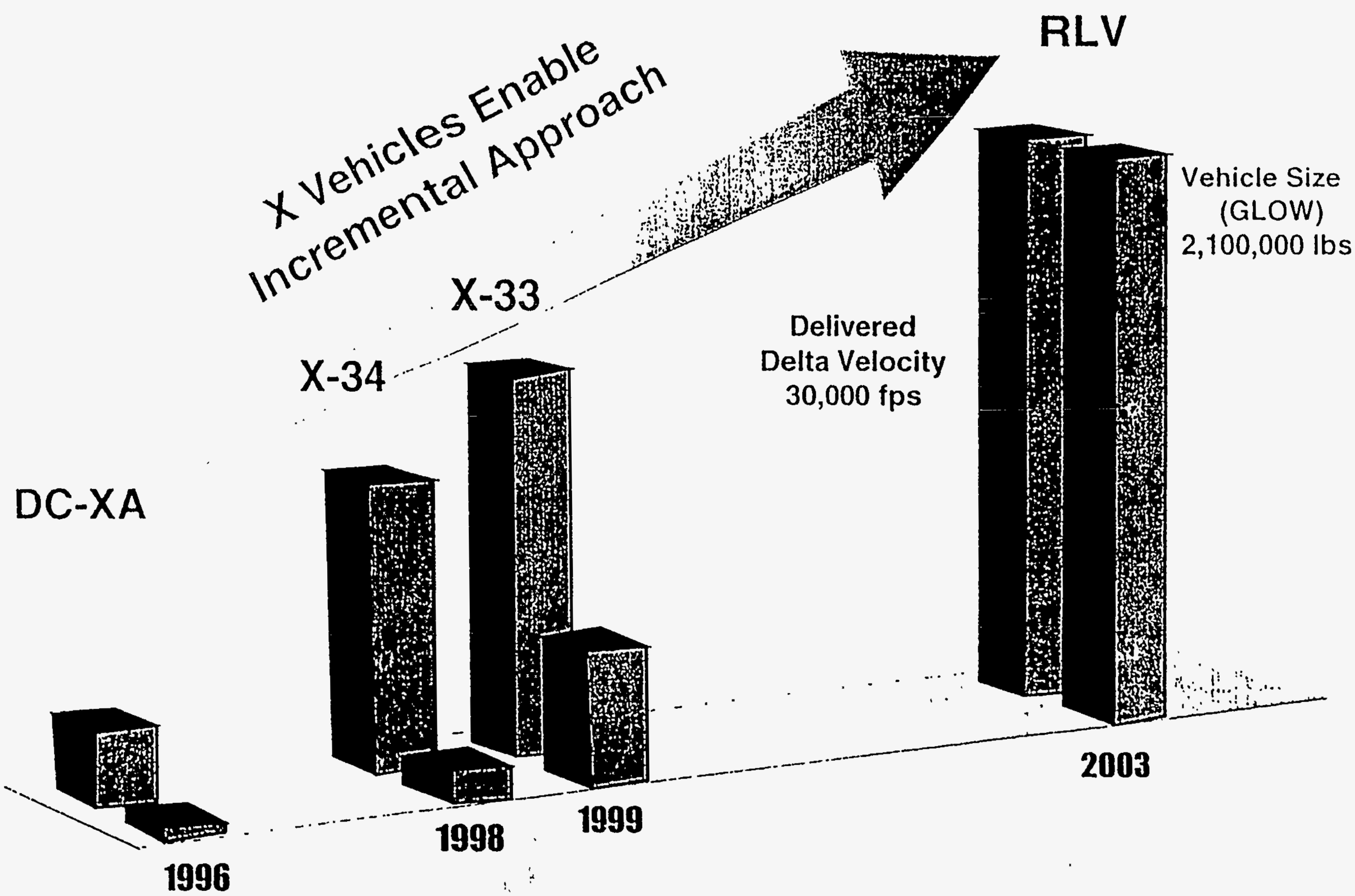
Industry Funded
with TBD
Gov Participation

Commercial
RLV
Operations

Industry Operated
with Government
& Commercial
Customers

INCREMENTAL X-VEHICLE APPROACH

Individual Test Vehicles Contribute Unique Technical and Programmatic Information to the Overall RLV program



Reusable Launch Vehicle Programs

Core Technology Program

Reusable Cryogenic Tanks

Graphite Composite Primary Structures

Advanced Thermal Protection

Advanced Propulsion

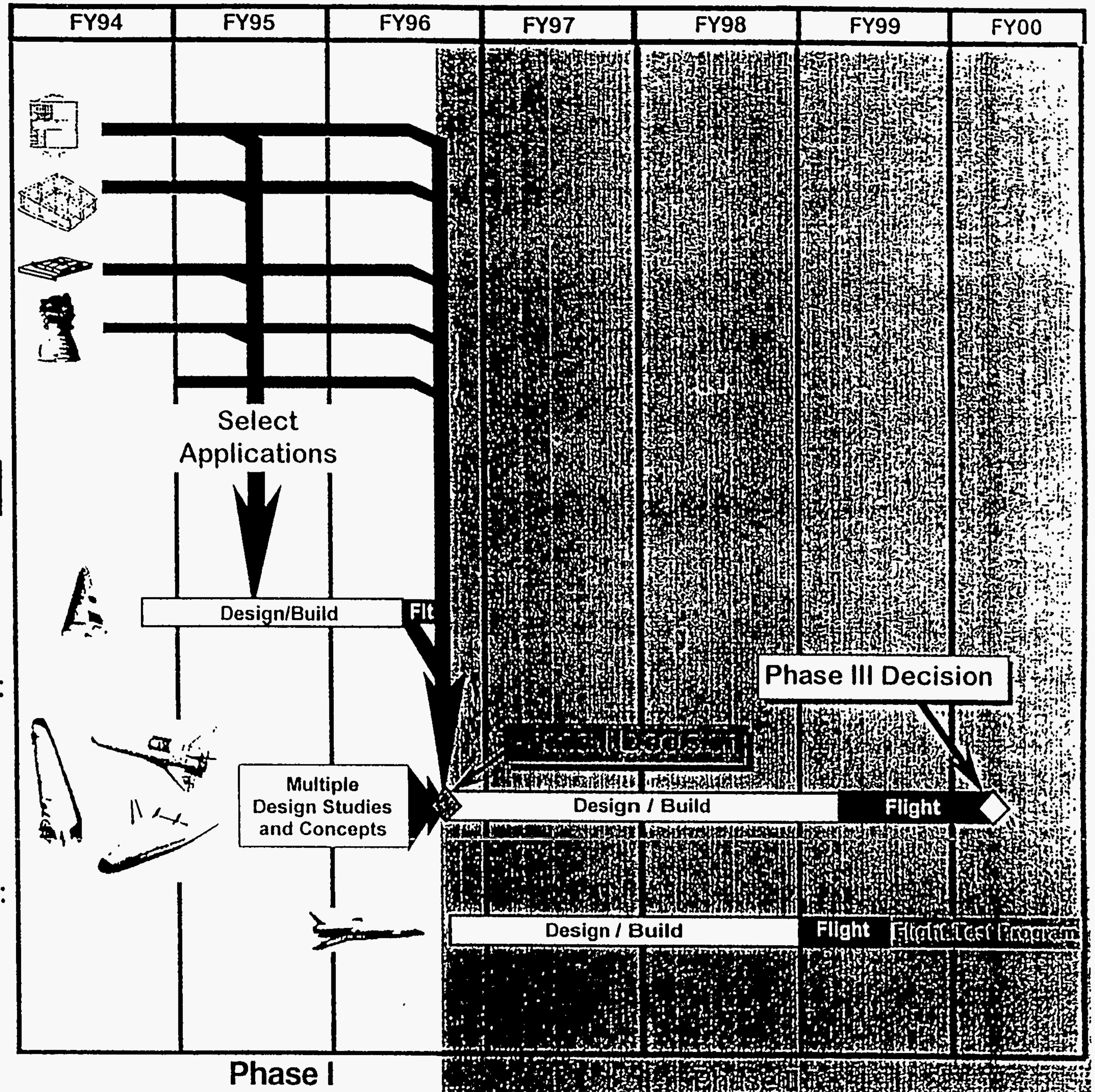
Avionics / Operable Systems

Next Generation X Vehicles

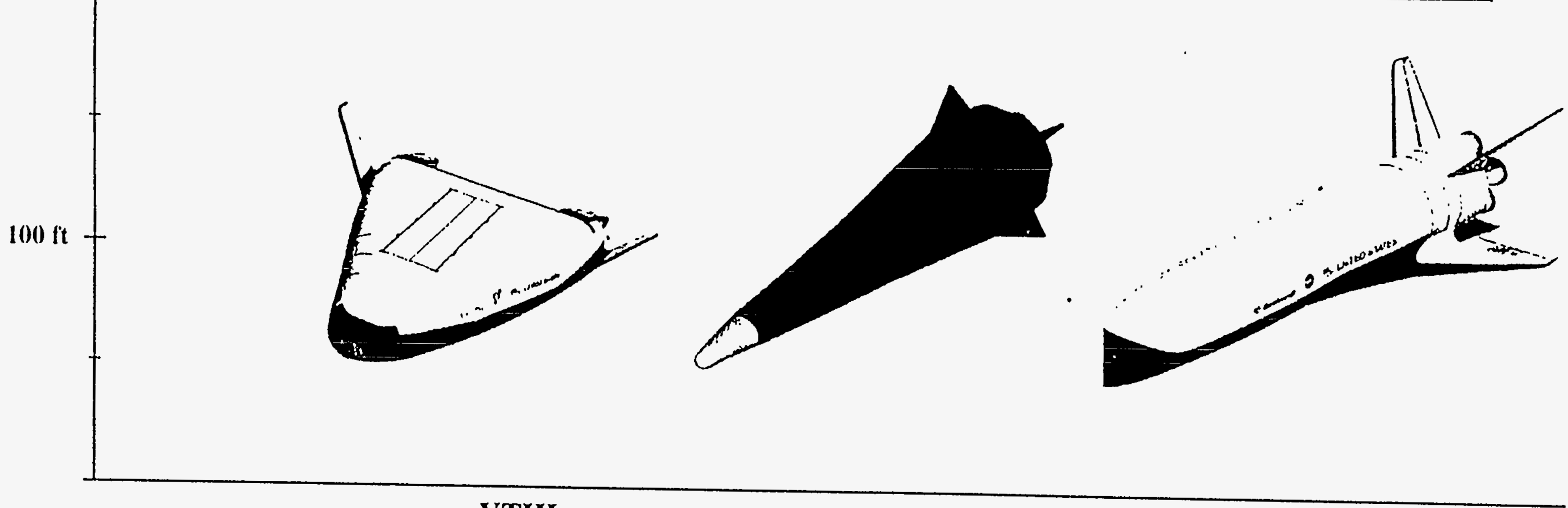
DC-XA
- Operations
- Advanced Technology

X-33 Technology Demonstrator:
- Flight Operations (Mach 15)
- Advanced Systems
- Demonstrate SSTO
- Ground and Flight Demo's

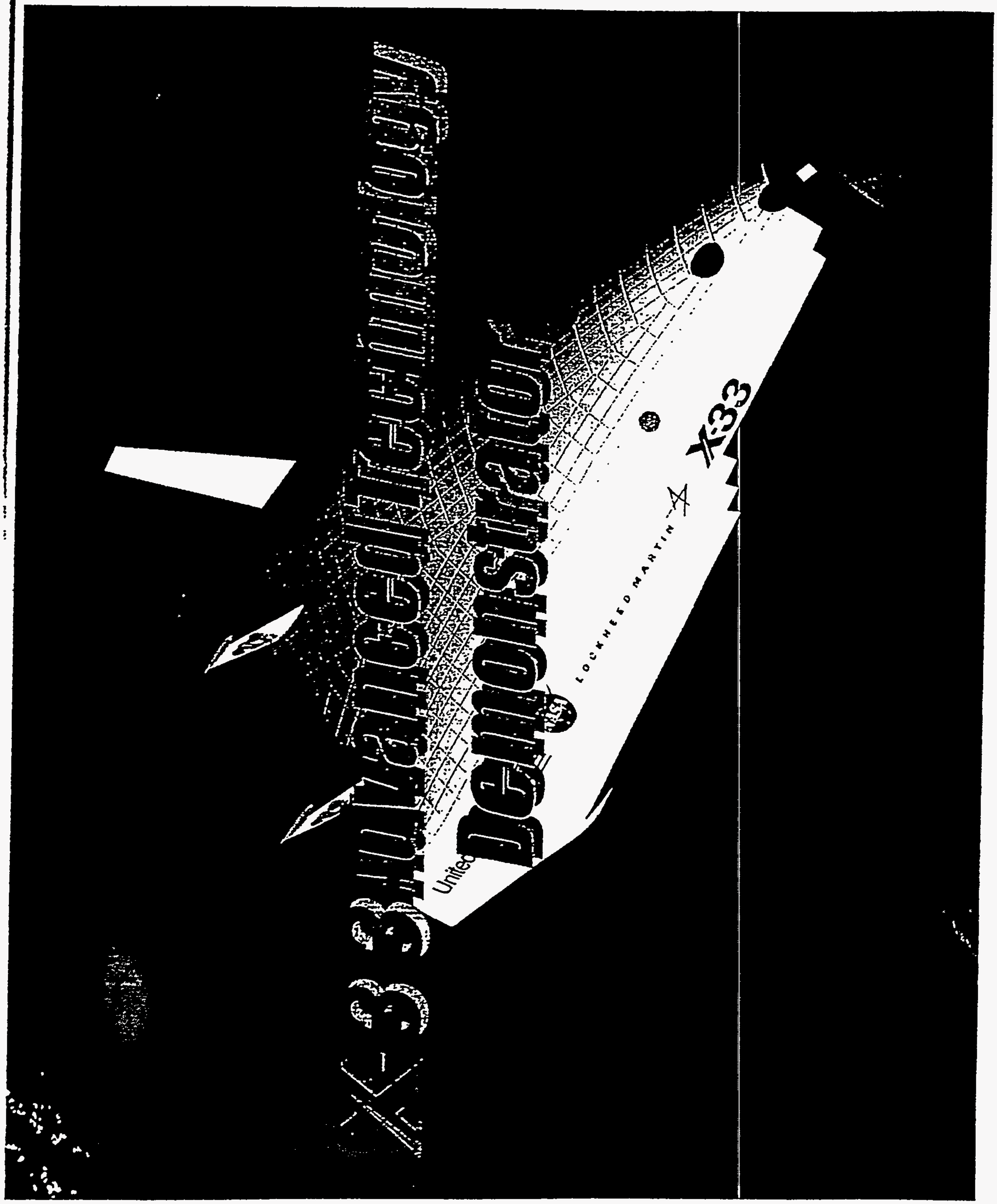
X-34 Technology Demonstrator:
- Flight Operations (Mach 8)
- Advanced Systems



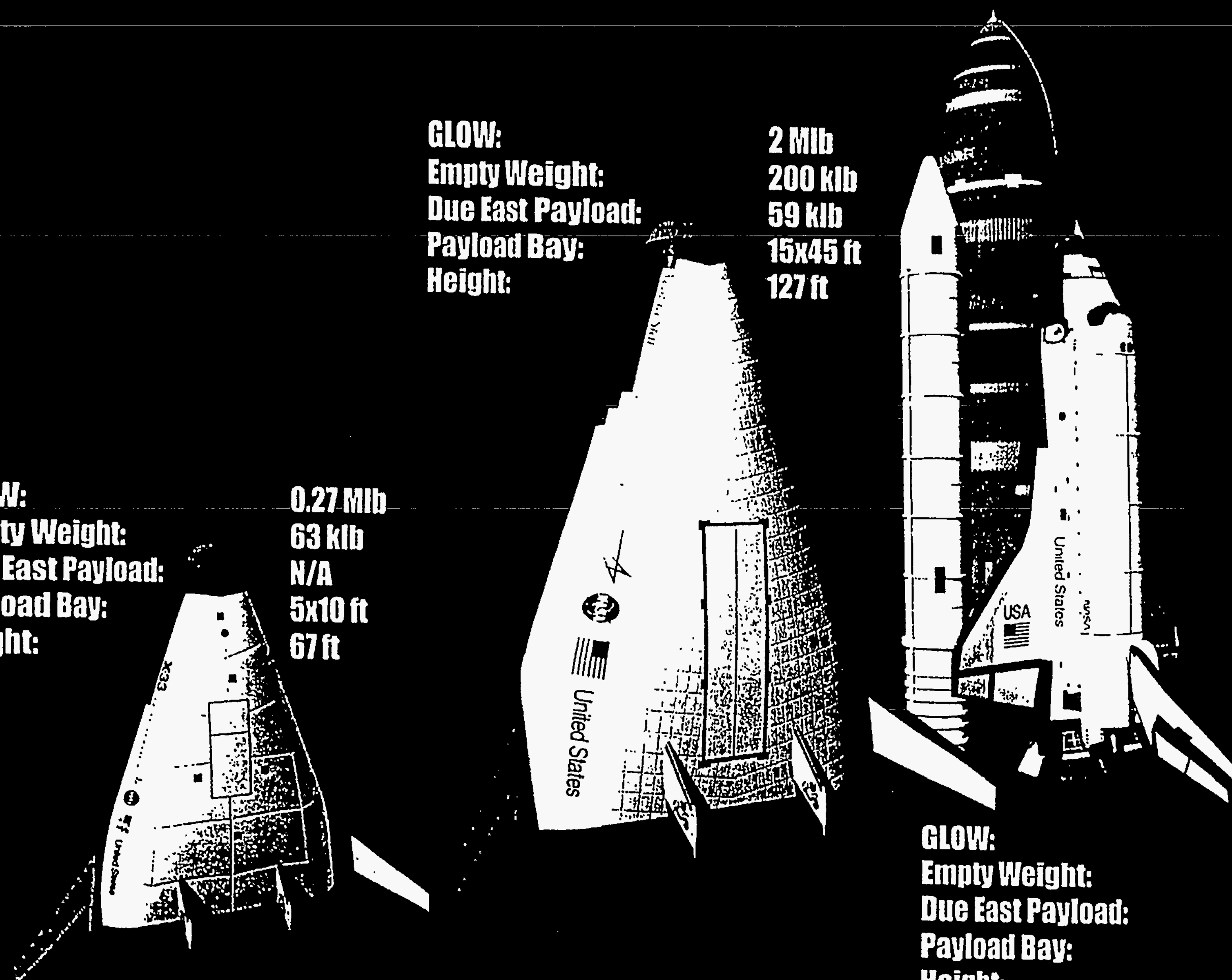
Reusable Launch Vehicle Comparison



	Lockheed Martin Skunkworks	McDonnell Douglas Phantom Works	Rockwell
	VTHL	VTVL	VTHL
GLOW	2,150,000 lb	2,410,000 lb	2,190,000 lb
Dry Weight	197,000 lb	219,000 lb	206,000 lb
Propellant Mass Fraction	0.91	0.905	0.906
Payload Due East	59,000 lb	45,000 lb	42,000 lb
LO_2 Cryo Tank	Composite	Composite	Al-Li 2195
LH_2 Cryo Tank	Composite: IM7/977	Composite: IM7/8552	Composite: IM7/977
Acreage TPS (Windward)	Inconel Standoff Aeroshell	C/SiC Panels	AETB Tiles & TABI Blankets
Airframe	Gr-BMI Frame	Gr-BMI	Gr-BMI
Ascent Engines (LO2/LH2)	7 - RS2200 GG Aerospike	8 - DCME Full Flow, Bell	6 - RS2100 Full Flow, Bell
Descent Engines (LO2/LH2)	N/A	4 - DCME (Dual Bell)	N/A


X-33 Advanced Technology
Demonstrator
X-33
LOCKHEED MARTIN

Shuttle / RLV / X-33 Comparison

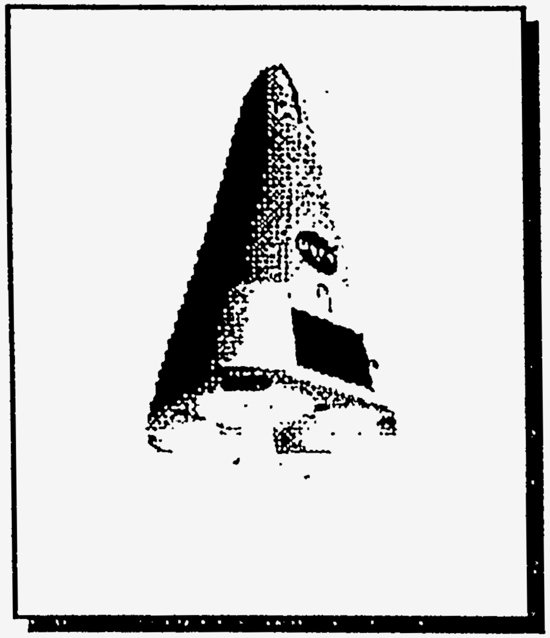


GLOW:	0.27 Mlb
Empty Weight:	63 klb
Due East Payload:	N/A
Payload Bay:	5x10 ft
Height:	67 ft

GLOW:	2 Mlb
Empty Weight:	200 klb
Due East Payload:	59 klb
Payload Bay:	15x45 ft
Height:	127 ft

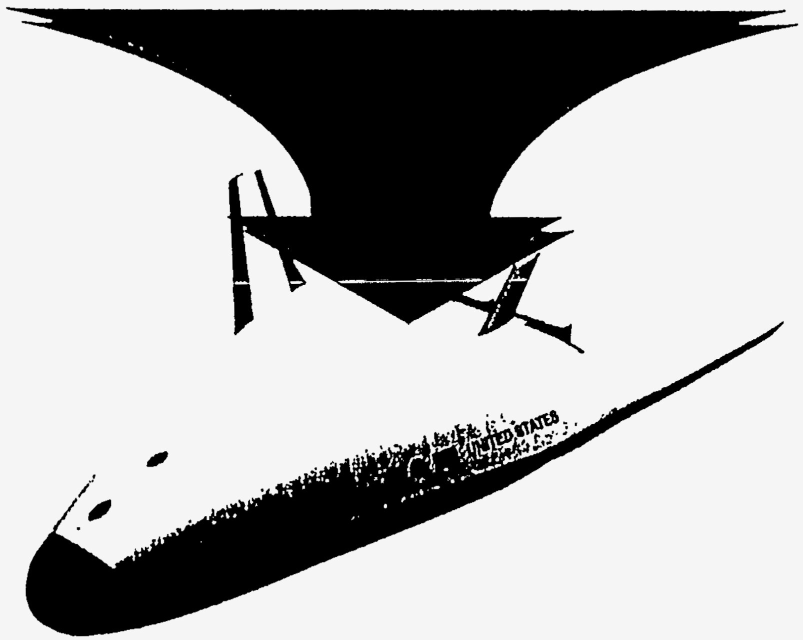
GLOW:	4.5 Mlb
Empty Weight:	600 klb
Due East Payload:	51 klb
Payload Bay:	15x60 ft
Height:	184 ft

X-33 Will Build on DC-XA Operational Experience

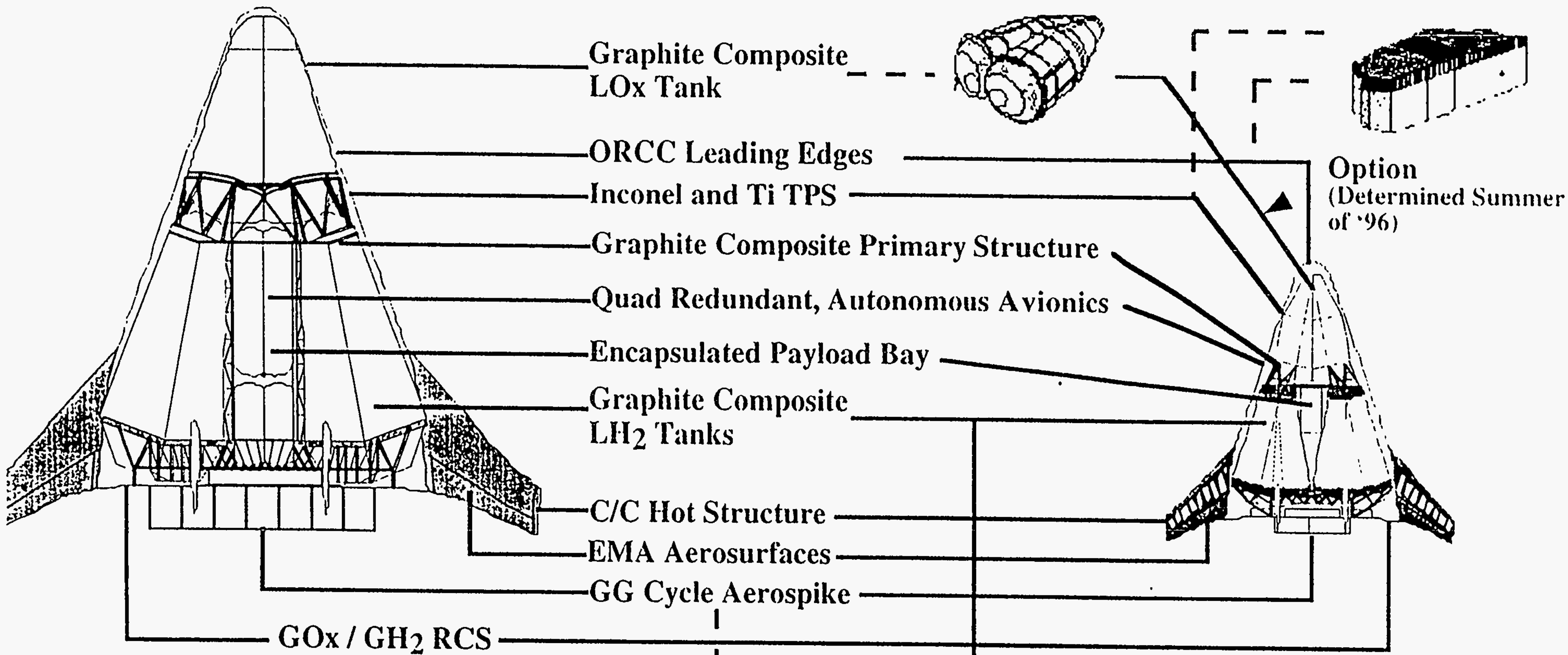


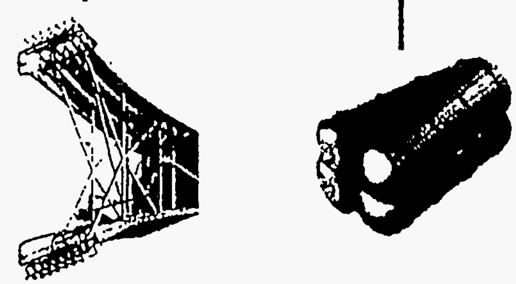
- Overland Flights

- Small Ground Crew
- Minimal Support Infrastructure



RLV / X-33 Key Features Comparison



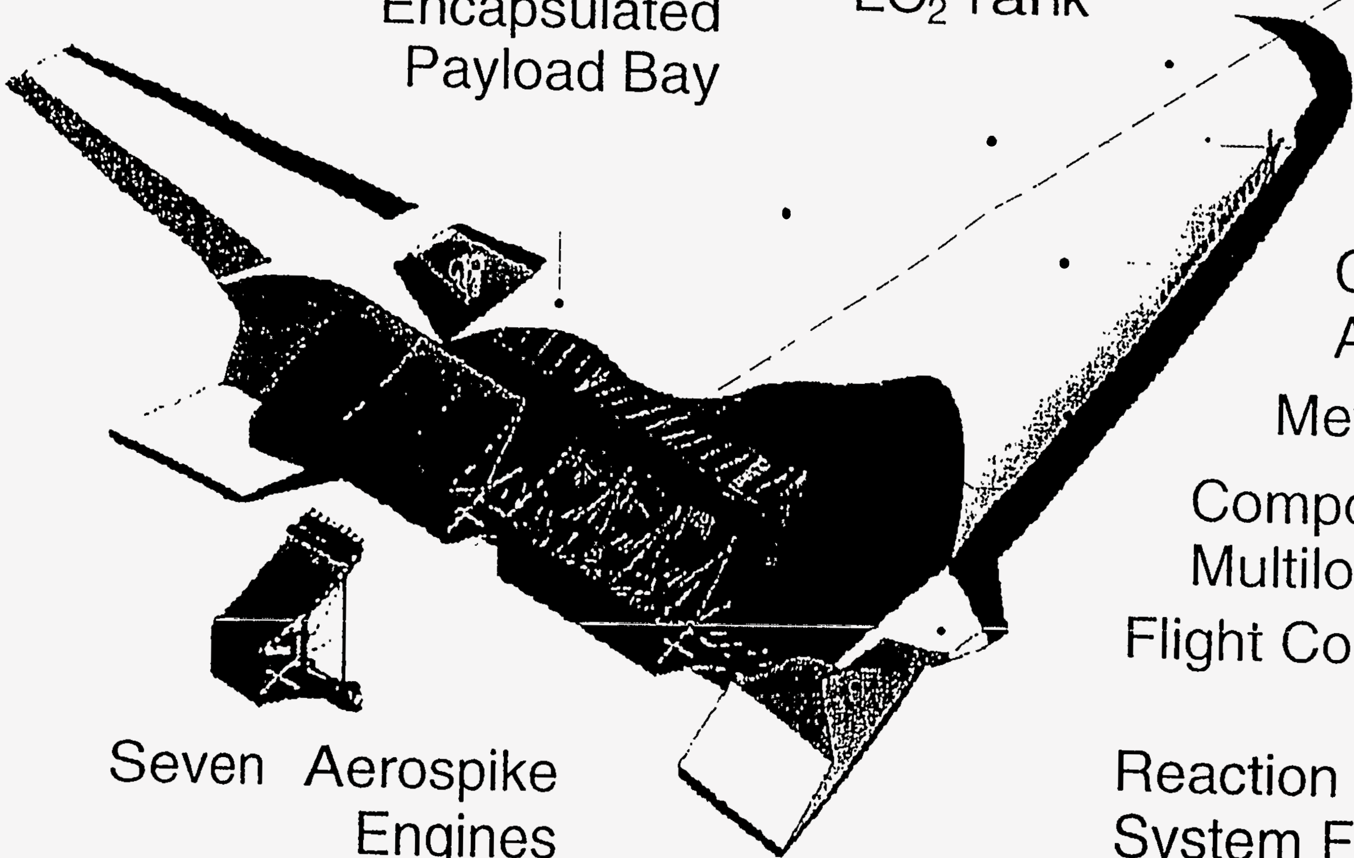


GLOW (Mlb)	2.15
Dry Weight (Klb)	197
Mass Fraction	0.91
Length (ft)	127
Velocity	Orbital

53% Scale

GLOW (Mlb)	0.28
Dry Weight (Klb)	63
Mass Fraction	0.77
Length (ft)	63
Velocity	Ma 15

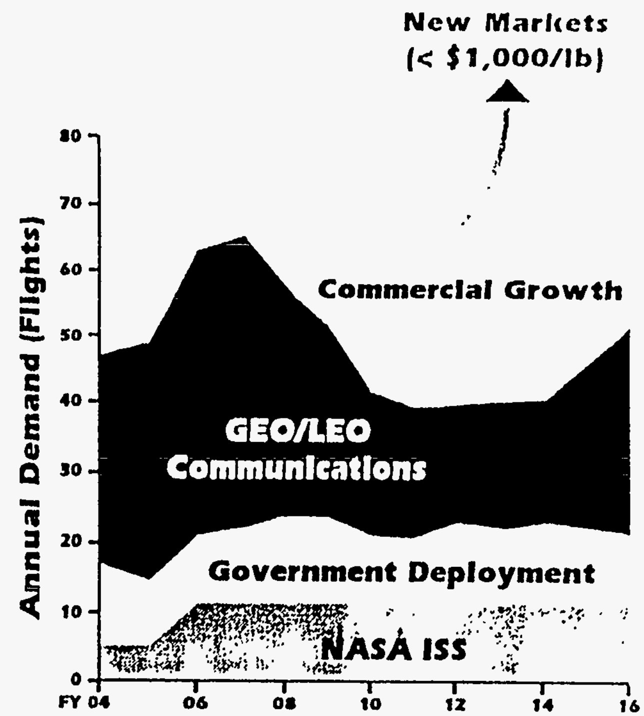
Venture Star™ Reusable Launch Vehicle

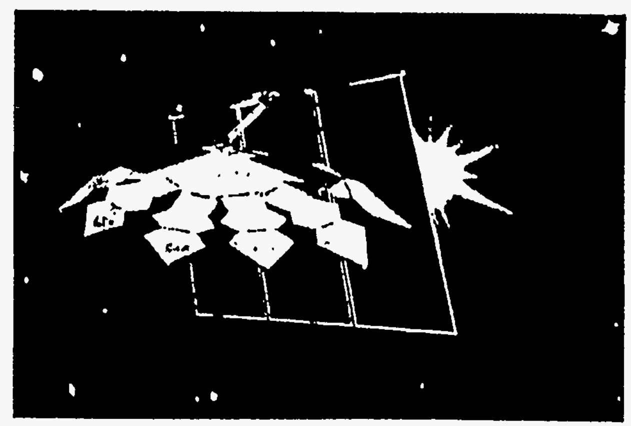


Commercial Launch Trends

- **Since 1990, U.S. and Europe have launched 21 to 27 GEO communication satellites per year**
  - Russians, Chinese getting into the market
- **GEO satellite weight growth** (~10,000 lb to GTO today)
  - Driven by need for more transponders coupled with limited orbital slots
- **Emergence of Big LEO communication Systems**
  - Large constellations: 66 (Iridium) to 840 (Teledesic) in various orbital planes
  - Systems require regular replacement/upgrades (up to 100 per year)
  - Investors require full-up constellations in as short as one year
  - Systems desire multiple launch sources
  - Other mega LEO (e.g. Teledesic-like) concepts require less than $1,000 lb
- **Launch rates (medium to heavy)**
  - Conservative: 16 to 25 per year
  - Less conservative (Big LEO): 60 per year

Global Launch Demand

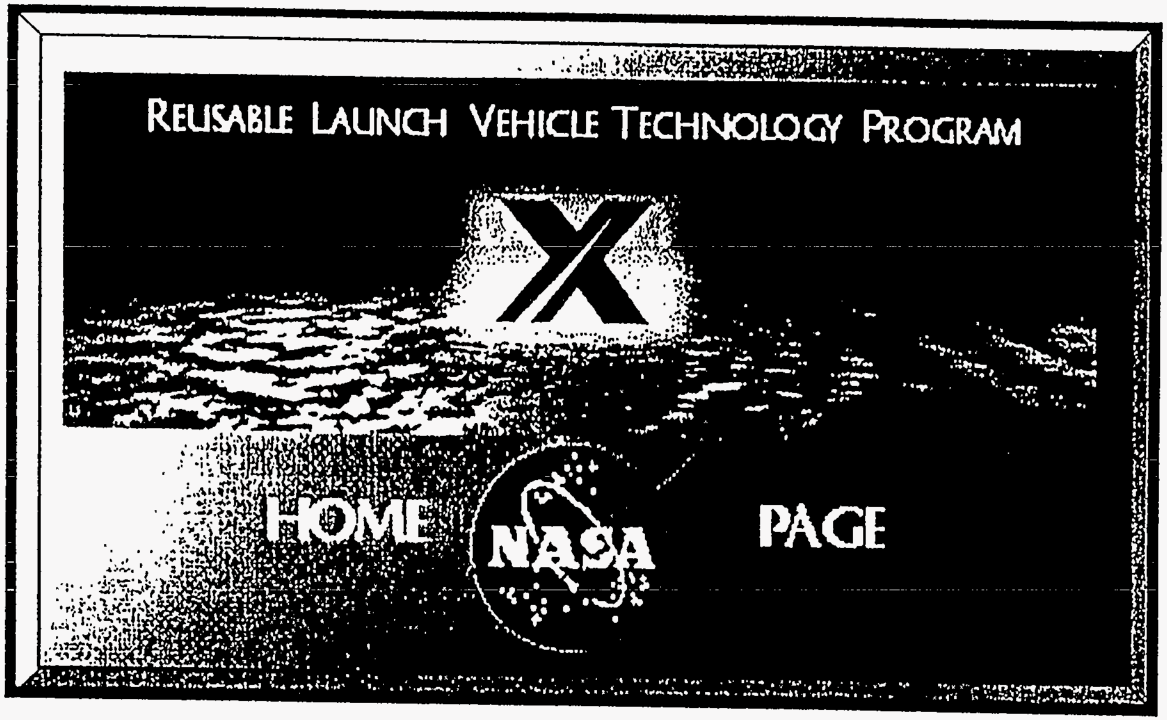




Venture Star™ Reusable Launch Vehicle Missions

Payload Capabilities:

- 25,000 lb to Space Station
- 45,000 lb to Easterly LEO
- 15 ft Dia x 45 ft Long Bay
- Initial Operation in 2004



http://rlv.msfc.nasa.gov/

GEOTHERMAL RESOURCE REQUIREMENTS FOR AN ENERGY SELF-SUFFICIENT SPACEPORT

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Abstract

Geothermal resources in the southwestern United States provide an opportunity for development of isolated spaceports with local energy self-sufficiency. Geothermal resources can provide both thermal energy and electrical energy for the spaceport facility infrastucture and production of hydrogen fuel for the space vehicles. In contrast to hydrothermal resources by which electric power is generated for sale to utilities, hot dry rock (HDR) geothermal resources are more wide-spread and can be more readily developed at desired spaceport locations. This paper reviews a dynamic model used to quantify the HDR resources requirements for a generic spaceport and estimate the necessary reservoir size and heat extraction rate. The paper reviews the distribution of HDR resources in southern California and southern New Mexico, two regions where a first developmental spaceport is likely to be located. Finally, the paper discusses the design of a HDR facility for the generic spaceport and estimates the cost of the locally produced power.

INTRODUCTION

The future of hydrogen as a transportation fuel for automobiles, trucks, and buses is bright in large metropolitan cities when the potential for essentially zero-emission exhaust is taken into account. Hydrogen is currently utilized as a fuel in the national space program. Stimulation of hydrogen production as a general transportation fuel could be accelerated by development of commercial space travel. In 1988, a White House space policy statement directed federal agencies to assist the private sector in developing commercial facilities for launching space vehicles. A number of studies were undertaken to examine the potential for commercial spaceports near existing military installations. One study, initiated by the Army, Air Force, and NASA, involved design of a commercial spaceport facility in southern New Mexico near the White Sands Missile Range.

Studies at New Mexico State University resulted in a technical report (NMSU, 1995) which included a strategic development plan for a Southwest Regional Spaceport. The power requirement for operating the facility were considered modest: an initial load of 5-20 MWe with growth over the development period to about 100 MWe at full operation. It was expected that the local electrical utility could supply the power from existing lines. It was also suggested (Gomez, Spain, and McCune, 1995) that local production of LH2 and LO2 would be required during the growth phases of the spaceport.

The long-term potential for space-vehicle launchings and commercial space travel provides a corresponding long-term potential for large-scale utilization of hydrogen as a transportation fuel. However, safety requirements, analogous to commercial airports, will dictate that commercial spaceports be located in isolated areas away from population centers. As a result, electric power for isolated spaceports will have to be transported over long distances or produced locally. For year-round launching of space flights under favorable weather conditions, the southwest states provide attractive candidates as spaceport locations. The availability of geothermal resources in the southwest provides a great opportunity for development of isolated spaceports with local energy self-sufficiency. Geothermal resources are able to provide both thermal energy and electrical energy, the latter for meeting the electricity demand of the spaceport facility and the electrolytic production and liquefaction of hydrogen fuel for the space-vehicle launches.

The first challenge in identifying potential geothermal energy resources adequate to provide energy self-sufficiency is the determination of spaceport power requirement over the development period from initiation of spaceport construction to mature launching operations. For this purpose, the power requirement estimated for a proposed (NMEDD-OSC, 1995) spaceport development in southern New Mexico was adapted for a generic spaceport to be located in a southwestern state. An analysis was made of the geothermal power requirement for energy self-sufficiency based on the schedule of total electric power requirement to run the spaceport facility and to produce the necessary hydrogen fuel and oxidizer to meet the expected space-vehicle flight schedule for each stage of the spaceport development.

The second challenge is to locate geothermal energy resources that can meet the reserves and deliverability necessary to supply the spaceport power requirement. For development of new commercial spaceports, geothermal resources can be the sole source of power. For mature spaceports with large total power requirement, it might be desirable to combine geothermal resources with other alternate energy resources, such as solar and wind. Currently, commercially utilized geothermal resources are those from which naturally occurring steam or hot water can be extracted. Electricity is produced from such hydrothermal resources at a number of locations in the western United States, but geothermal resources without natural water in place, termed Hot Dry Rock (HDR) geothermal resources, are more common. The technology to access and extract energy from HDR reservoirs has been developed and demonstrated, first at Fenton Hill, NM in the United States (Duchane, 1995) and later in other countries (e.g., Matsunaga, 1995; Garnish, et al., 1994). HDR geothermal resources provide a very large resource base for supplying the energy needs of a spaceport in either southern California or southern New Mexico.

Evaluation of a potentially commercial geothermal resource relies on exploration data to estimate the volumetric size, temperature distribution, and hydraulic characteristics of the thermal reservoir needed to calculate the estimated reservoir heat content (reserves), the possible range of thermal energy delivery rate (deliverability) and the useful lifetime (longevity) of the resource. Estimates of electric power production depend on the conversion efficiency of the turbine-generator system, which is a function of the type of generator system and the incoming fluid temperature. The exploitable heat content of a HDR geothermal resource (Kruger, 1993) is given by

$$HC = (\rho V_r)\, C_p (T_r - T_a) \tag{1}$$

where HC = heat content of reservoir, (J)
ρ = rock density, (kg/m^3)
V_r = reservoir volume, (m^3)
C_p = rock specific heat, (J/kg-C)
T_r = initial reservoir temperature, (°C)
T_a = application abandonment temperature, (°C)

The thermal extraction rate depends on two reservoir characteristics: (1) the heat transfer properties of the reservoir and (2) the flow regime for heat transfer. The heat transfer properties are determined by the rock-type and fracture network which control the rate of conductive heat transfer to the rock-block surfaces. The flow regime is determined by the connected fracture porosity and permeability distributions. The circulation flowrate can be varied within some range by pressure control. An optimum energy production schedule balances the need for maximum power output (larger flowrate) with maximum thermal extraction efficiency (smaller flowrate). The commercial quality of the resource can be evaluated by the potential for achieving an adequate sustainable thermal extraction rate over a given amortization period until the abandonment temperature is reached.

The total thermal energy extracted is given by

$$HE = \int_{t_o}^{t_a} Q(t)\, \Delta h(T_i, T_o, t)\, dt \tag{2}$$

where HE = thermal energy extracted, (J)
Q = production flowrate, (kg/s)
h = fluid enthalpy, (kJ/kg)
T_i = injection fluid temperature, (°C)
T_o = produced fluid temperature, (°C)
Δh is the increase in enthalpy of the produced fluid above that of the injected fluid.

For a spaceport application, where the total electricity demand is specified, the process for evaluating suitable geothermal resources is reversed. The needed reserves and longevity are fixed, while the minimum reservoir size over a range of reservoir temperatures and flowrates adequate to provide the necessary thermal extraction rate must be calculated. A graphical algorithm was designed to estimate HDR reservoir size and circulation conditions necessary to provide sufficient electric power for the generic commercial spaceport. The results were used to identify potential sites in southern California and southern New Mexico where a first commercial spaceport might be located. The resource analysis was based on published reconnaissance studies of geothermal regions close to existing space launching facilities. From the calculated reservoir size and production requirement, a conceptual design of a HDR facility to supply on-site power to the spaceport was prepared and the cost of the power was estimated for each of the development periods.

GEOTHERMAL RESOURCE REQUIREMENT MODEL

The model to specify the size of a geothermal resource needed to meet the power requirement of a development spaceport was prepared with the commercially available Stella II dynamic modeling program (Hannon and Ruth, 1994). The geothermal and hydrogen production aspects of the model were adopted from the Geothermal Hydrogen Model prepared by Fioravanti (1996) for estimating hydrogen production capacity from geothermal resources. Input to the model is the total power demand as a function of time from initiation to maturation of spaceport launching operation. A schematic drawing of the geothermal resource model is shown in Figure 1. The components of the model demonstrate how the HDR reservoir size and fluid flowrate are influenced by geothermal and hydrogen system parameters such as resource temperature, electricity conversion efficiency, and electrolyser type and operating temperature, and liquefier efficiency.

A. Input Parameters

The power requirements for an on-site geothermal resource adequate for development of a new spaceport over a 15-year development period are given in Table 1. The dynamic model generated an input function for the 5-year stepped growth period as shown in Figure 2. The power capacity requirement increases in the fifth year of each phase. The power requirement for hydrogen production is calculated by the model.

Table 1
Input Power Requirements for a Model
Energy Self-Sufficient Spaceport*

	Scheduled Year		
	2000	2005	2010
Number of flights per year	3	12	36
LH2 demand per year (kt)	0.6	2.4	7.2
Facility power demand (MW)	5	20	100

*adapted from NMEDD-OSC (1995) for a project lifetime of 15 years.

The study focused on HDR geothermal resources which could be developed in hot rock directly beneath a spaceport site. Development of a HDR power system begins by drilling an injection wellbore into impervious hot rock, applying hydraulic fracturing techniques to create an engineered geothermal reservoir in the formation, and drilling one or more production wells in an appropriate geometry. Important characteristics of HDR systems, such as rock temperature and reservoir volume, are determined by the design of the drilling and fracturing operations. The HDR system is operated by pumping water through the reservoir in a closed loop to extract the thermal energy from the hot rock. At the surface, the high-pressure hot water can be used directly for its thermal content or converted to electricity with a turbine-generator system using either flashed steam or a closed-loop binary heat exchanger. In closed-loop operation, the water is recirculated and only a make-up water supply is needed for long-term operation.

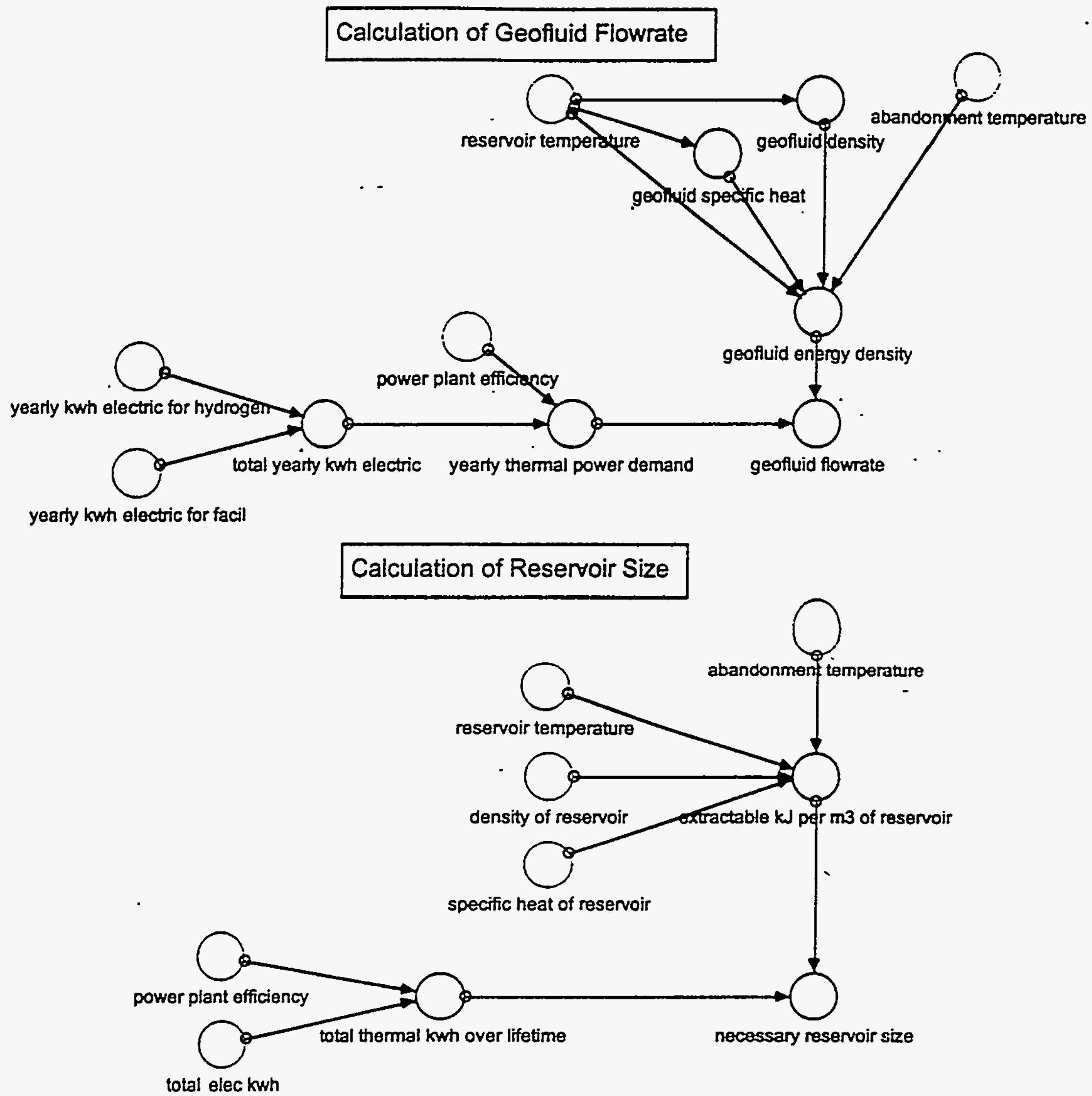

Fig.1. Schematic of the geothermal hydrogen system model. (from Fioravanti (1996)).

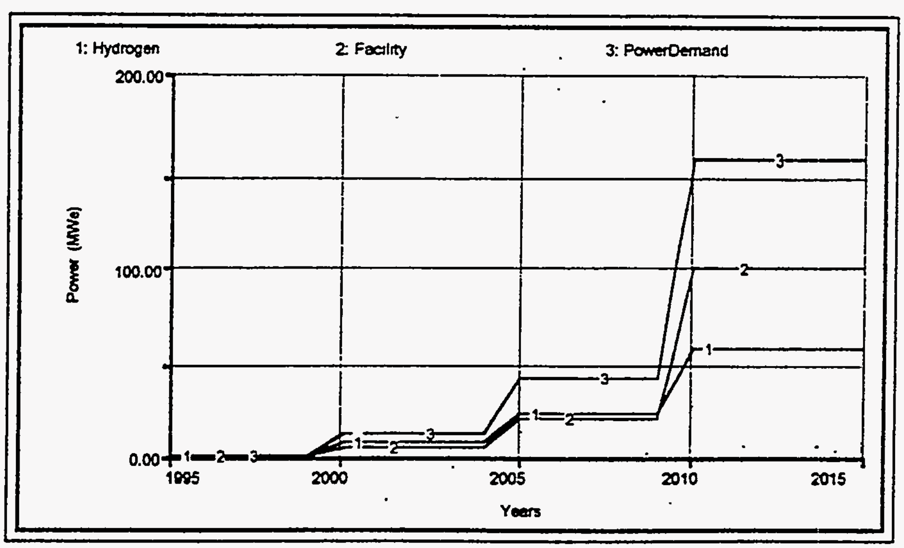

Fig.2 Model generated input function for the 5-year power capacity requirements, increased during the fifth year of each period.

The practical range of HDR geothermal resource temperatures at potential spaceport sites in southern California and southern New Mexico was used to select the parameters for calculating the heat content needed for the sites by Eq.(1) and the flowrates needed to provide the phased 5-year power capacity increases by Eq.(2). The set of model parameters selected for the spaceport application is listed in Table 2.

Table 2
Selected HDR Geothermal Resource Parameters

Parameter	Range of Values			Units
Resource temperature	180	250	300	°C
Abandonment temperature		140		°C
Rock density		2500		kg/m^3
Rock specific heat		1000		kJ/kg-C
Conversion efficiency*	14	22	26	%

* based on use of binary power plant technology in which the geothermal fluid is reinjected in the closed-loop circulation system.

Parameters for the liquid hydrogen production system include electrolyser type and efficiency, liquefier efficiency, and liquid hydrogen losses due to transfer and boiloff. Integration of liquid hydrogen production at a geothermal site offers several opportunities to minimize conversion losses and inefficiencies. One advantage of producing liquid hydrogen on site is that a cold gas recovery loop can be installed between the liquefaction unit and the fueling system. Delivery from off site precludes a recovery loop and transfer losses can be as high as 50% (Taylor, et al., 1986). Another advantage of producing hydrogen at a geothermal site is an increase in electrolyser efficiency due to use of geothermal pre-heat for medium and high-temperature electrolysis. Although these more efficient electrolysers are not considered in this analysis, their use would improve the economics of hydrogen production at a HDR site. The range of values selected for on-site production of hydrogen, adapted from the study by Fioravanti (1996) for geothermal resources, is listed in Table 3. The values are conservative numbers based on industry figures, with an allowance for modest increases in efficiency over the 15-year analysis period.

Table 3
Selected Input Parameters for the Electrolyser System*

Parameter	Range of Values	Units
Electrolyser efficiency	44-48	kWh/kg
Liquefier efficiency	15-25	kWh/kg
LH2 system losses	17-27	%

* from Fioravanti (1996); efficiencies are based on lower heating value of hydrogen.

B. Model Setup

The Geothermal Resource Requirement Model is designed to take the time-varying inputs and calculate the power demand of the spaceport through time. From the power demand function (Fig.2), the model calculates the minimum HDR reservoir size and circulation flowrate based on the selected geothermal and hydrogen system parameters. For the hydrogen fuel requirement, the model uses electrolyser and liquefier efficiencies and storage and transport losses to calculate a specific electricity requirement (in kWh/kg) for each kilogram of liquid hydrogen delivered to the spaceport. The total annual energy demand (in kWh/yr) for hydrogen fuel is obtained from the specific energy demand and is expressed as an annual average power requirement (in MWe). For operation of the spaceport, the input data (in MWe) is used to calculate the annual energy demand (in kWh/yr) for the facility. The total annual power demand is the sum of the two requirements The Stella-based model uses the time-varying inputs to run a 15-year simulation of spaceport operation yielding annual and cumulative values for energy demand.

The electric energy demand (in kWh) is converted into a thermal energy demand (in kJ) based on the resource-dependent power-plant efficiency. The reservoir parameters given in Table 2 are used to calculate a minimum extractable heat content (in kJ/m^3) of the reservoir. The thermal energy demand is converted to a minimum reservoir size at each given reservoir temperature using the volumetric heat parameters in Table 2. The circulating fluid flowrate (in kg/s) is obtained from the thermal power demand (in kJ/s) and the fluid enthalpy (in kJ/kg).

C. Model Results

The model calculations made for each of the three reservoir temperatures listed in Table 2 are summarized in Table 4.

Table 4
Model Results for the Study Spaceport

Phase		Power Requirement (MWe)			Reservoir Temperature (°C)		
		Facility	Hydrogen	Total	180	250	300
1		5	7	12			
	Reservoir size (10^6 m^3)				170	40	23
	Fluid flowrate (kg/s)				480	100	50
2		20	23	43			
	Reservoir size (10^6 m^3)				790	180	107
	Fluid flowrate (kg/s)				1730	365	180
3		100	59	159			
	Reservoir size (10^6 m^3)				2700	600	350
	Fluid flowrate (kg/s)				6450	1360	670

The results show that the total power requirement for the three phases of spaceport development range from 12 MWe in phase 1 to 159 MWe in phase 3. The results indicate that the initial reservoir temperature has a strong impact on the minimum reservoir size and circulation flowrate. For a specific engineered HDR geothermal reservoir, calculation of the minimum required reservoir volume and flowrate for a given power output would require detailed exploration of candidate sites to determine their mean initial resource temperature.

GEOTHERMAL RESOURCES SURVEY

Potential geothermal resources in southern California and southern New Mexico were evaluated using published geothermal data. Figures 3 and 4 are maps showing geothermal gradients derived from the data, with map centers located at Edwards Air Force Base in California and White Sands Missile Range in New Mexico, respectively, on the premise that future spaceport development is likely to take place somewhere in the general vicinity of one of these established space facilities.

The gradients shown on the two maps were calculated from temperature readings obtained at various depth in wellbores throughout the mapped regions, with the additional assumption in all cases that the surface temperature was 20°C. Data indicating gradients of less than 30°C/km were discarded, because such low-quality resources do not have the potential to meet spaceport energy needs at any reasonable cost. Data obtained from surface manifestations such as springs and some very shallow wells were also discarded because these surface data were not considered a reliable indicator of the average geothermal gradient at depth.

For localities where multiple temperature readings were available from a number of wells, only the highest calculated gradients were mapped to broaden the base of potential sites for the existence of high-quality hydrothermal and HDR resources in southern California and southern New Mexico. For a more specific evaluation, any additional measurements available would be used to help define the limits of the high-quality resources shown on the maps. Finally, for some areas, only a range of geothermal gradients can be calculated. In these cases, the potential for the existence of high-grade geothermal resources at depth can only be broadly defined.

The information presented in Figures 3 and 4 provides significant evidence that HDR resources could be accessed at a variety of locations in southern California and southern New Mexico. In addition, the existence of hydrothermal resources is indicated by the designation of some localities as Known Geothermal Resource Areas (KGRAs).

Figure 3 shows that there is a wide variation in the quality of geothermal resources in southern California. There is also significant variability in the geology of the region. Several physiographic regions are noted that contain potentially useful geothermal resources. For example, Coso Hot Springs is an established KGRA on the western edge of the Basin and Range physiographic province in a tectonically active area. The China Lake Naval Weapons Center occupies much of the Coso KGRA, thus offering an already-established military facility that might ameliorate land use, security, and other issues related to the establishment of a commercial spaceport. Heat flow values ranging from 86 to 116 mW/m^2 (compared to the average worldwide heat flow value of about 60 mW/m^2),

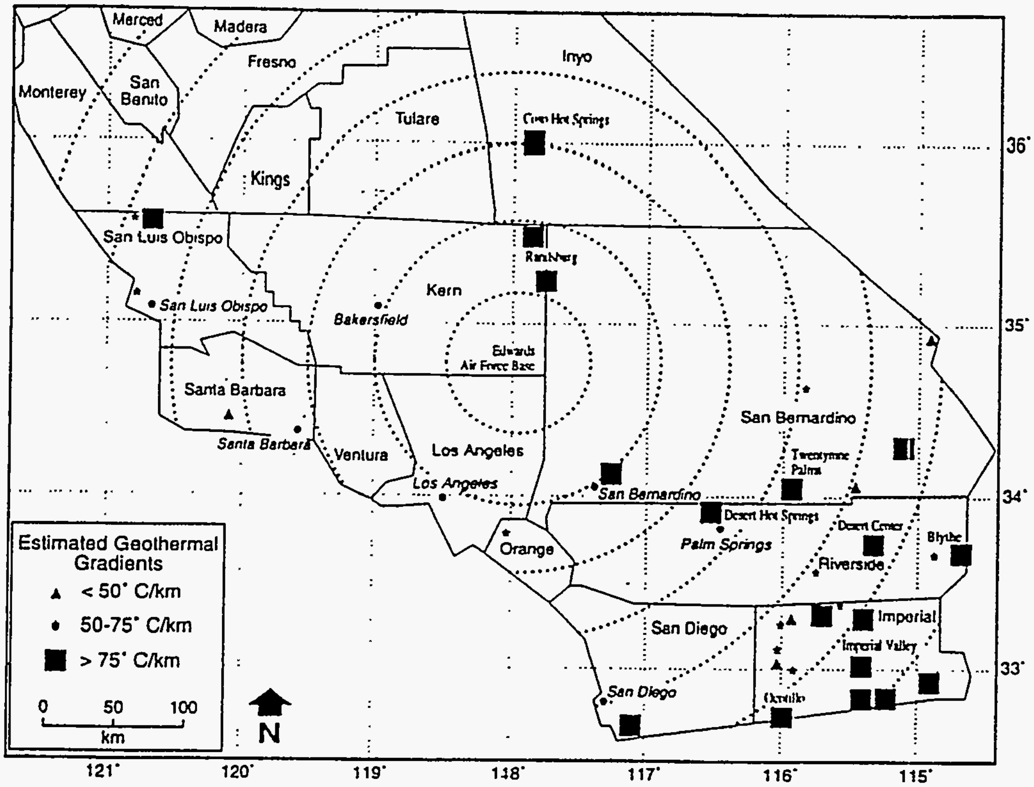

Fig.3. Locations in southern California where estimated geothermal gradients indicate the potential for high-quality HDR geothermal resources. [adapted from data of Lachenbruch et al., 1985; Lienau and Ross, 1996; Sass et al., 1994; Combs, 1980; Signorotti and Hunter, 1992].

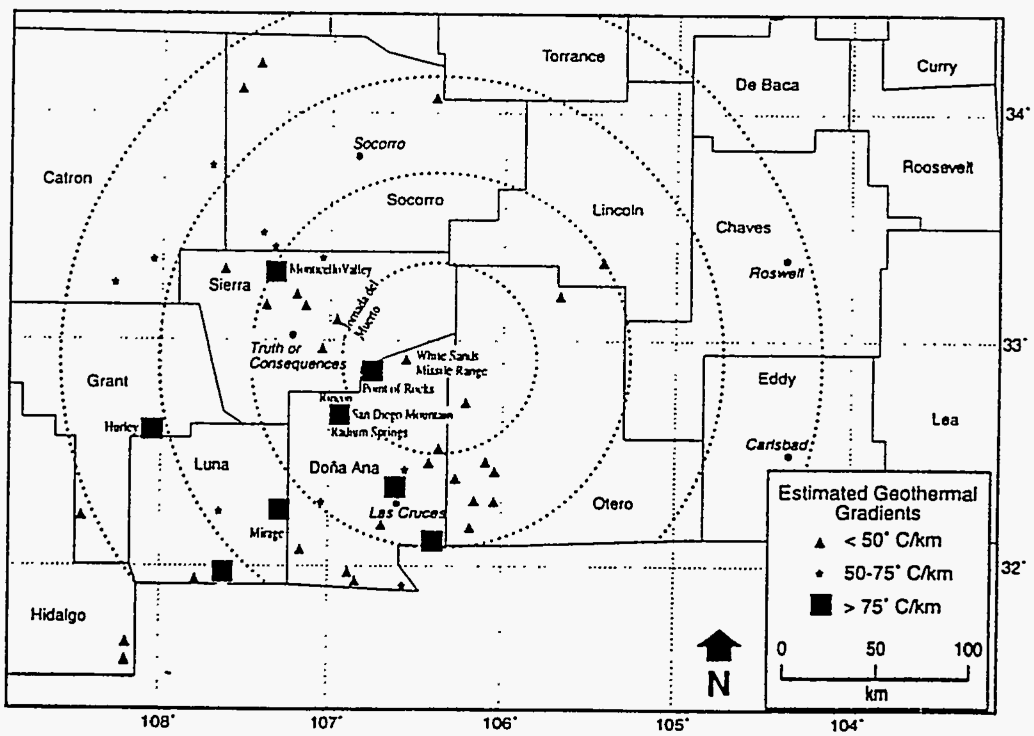

Fig.4. Locations in southern New Mexico where estimated geothermal gradients indicate the potential for high-quality HDR geothermal resources. [adapted from data of Witcher, 1995; Reiter et al., 1975; Reiter et al.,1978; Reiter et al.,1986; Decker and Smithson, 1975].

and a large range of geothermal gradients, some in excess of 300°C/km have been measured at Coso Hot Springs. While the true nature of HDR resources at depth is still uncertain, these data indicate a high probability of finding rock at temperatures in excess of 250°C at depths of 3 km or less. Combs (1980) describes a convective rhyolitic dome at Coso surrounded by a region of conductive heat flow. To avoid the hydrologic influence of the convective geothermal region containing the large hydrothermal resource currently being exploited at Coso, it would seem prudent to locate HDR reservoirs in the conductive heat flow region.

Another potential geothermal resource region is the Imperial Valley KGRA, which includes several active geothermal fields, including Salton Sea, Brawley, Westmorland, Mesquite, Niland, Heber, Calipatria, Calexico, El Centro, Holtville, Glamis, and East Mesa. This region is located in the Salton Trough, a sedimentary basin with strong magmatic and hydrothermal manifestations (Sass et. al., 1994). The region exhibits very high heat flow values (~ 150 mW/m^2) in some areas. The geothermal gradients also display a wide range, many exceeding 75°C/km.

Other candidate areas include the Randsburg KGRA with some geothermal gradients greater than 300°C/km at shallow (<250 m) depths with potential for higher temperatures at greater depth (Lienau and Ross, 1996). Another is the San Bernardino region which has shown indications of high geothermal gradients (>200°C/km) at shallow depths. This latter region is within the greater Los Angeles Metropolitan Area which could make this location environmentally impractical for a spaceport. Additional areas of possible HDR or hydrothermal resources in southern California include Desert Hot Springs, Twentynine Palms, Desert Center, and Blythe. The survey of resources in southern California indicates that a spaceport can be located near a suitable geothermal deposit, but determination of the specific resource characteristics at candidate sites will require in-depth exploration projects.

In southern New Mexico, many of the potential geothermal resources noted in Figure 4 are located along the Rio Grande rift. Evidence of magma bodies and recent intrusions along the rift at depths of about 15 to 30 km has been reported (Reiter et al., 1986). Although high heat flow values (in the range of 90 to 135 mW/m^2) exist along the rift, it has been difficult to determine whether these are the result of shallow magmatic sources interacting with groundwater or the result of groundwater circulation at greater depths with higher regional gradients. Further hydrological studies and deep borehole tests are needed. The individual sites of high heat flow values include Jornada del Muerto, which could be a candidate site for a HDR reservoir, and the area located around the Rincon - Las Cruces vicinity, including Rincon, San Diego Mountain, Radium Springs, and Point of Rocks. Several sites in this region have high heat flow (> 90 mW/m^2) as well as geothermal gradients greater than 75°C/km. Although Rincon exhibits few surface manifestations, Witcher (1995) suggests that the setting is favorable as a hydrothermal resource. Available data for Radium Springs and the San Diego Mountain region suggest (Witcher, 1995) deep thermal deposits in granite at depth, possibly suitable for a HDR resource at temperatures in the range of 100 to 150°C. The Las Cruces area, with high temperature gradients, may contain hydrothermal resources, but its urban character may preclude the development of a spaceport facility. Other sites identified as future candidates for HDR or hydrothermal development include Monticello Valley, Socorro Peak, Hurley, and Mirage, all with geothermal gradients in excess of 75 °C/km.

CONCEPTUAL DESIGN OF A HDR GEOTHERMAL ENERGY SYSTEM

The calculated data from Table 4 is the basis for designing a HDR geothermal energy system that can provide the required energy to the spaceport. The conceptual design envisions a modular approach to increasing geothermal power production as the needs of the spaceport grow over a 15-year period. It draws primarily on actual field experience at the Fenton Hill, NM HDR Facility (Duchane, 1995) and on data from a DOE economic study by McClarty and Entingh (1996). In the conceptual design, each HDR reservoir/wellbore module would provide sufficient thermal energy to generate 12 MW of electricity (MWe) over a 15-year lifetime. Although no commercial HDR facility has yet been constructed, a 12-MWe size appears to be within the practical range of extrapolation from the system operated at Fenton Hill, which routinely produced about 4-5 MW of thermal energy (MWt) from a single injection/production wellbore pair. Brown (1994) calculated an increase in production to about 20 MWt with connection of a second production wellbore to the reservoir. Electricity was not generated at Fenton Hill, but for a thermal-to-electric conversion rate of about 17% for the 180°C fluid produced, a 3-well system could generate electric power of about 3.4 MWe. In their economic study, McLarty and Entingh (1996) postulated a HDR system based on a 3-well, enlarged, Fenton Hill type reservoir with the capacity to produce 5.8 MWe over a 30-year lifetime.

A. Spatial Design of a HDR Geothermal Power System

When a HDR reservoir is formed by hydraulic fracturing, rock joints open in response to the applied pressure. Joints oriented along the direction of least principle natural stress in the rock, which are more easily opened, determine the principle axis of the reservoir. The fluid circulating through the reservoir during operation will preferentially flow along the direction of least principle stress. For this reason, the production wellbores are located at each end of the longest axis of the reservoir. Seismic analyses and other data indicated that the Fenton Hill HDR reservoir was ellipsoidal in shape with its major axis tilted 30° from the vertical and axis ratios of 3:2:1. Figure 5 shows the design of a unit 12 MWe spaceport reservoir/wellbore module based on the Fenton Hill HDR reservoir as a model.

The calculated dimensions of the model elliptical reservoir for the reservoir volumes listed in Table 4 are calculated by:

$$V = (4/3)\,\pi\,(3a)(2a)(a) = (4/3)\,\pi\,6a^3 = 8\pi a^3 \qquad (3)$$

where a is the shortest axis and 3a is the major axis.

For the model temperatures of 180°C, 250°C, and 300°C (Table 4), the shortest axes, a, would be approximately 190 m, 116 m, and 97 m for a 12 MWe power module with major axes, 3a, equal to 570 m, 348 m, and 291 m, respectively. Because the major axis of the model HDR reservoir is inclined 30° from the vertical, its length projected onto the surface of the earth is 3a(sin30°) = 1.5a. Thus, the projections of the three major axes on the surface become 436 m, 174 m, and 146 m.

The land requirement for the power facility can be estimated from the surface projections, for which the model reservoir can be considered an ellipse contained in a rectangle with dimensions of 2a (the length of the intermediate axis) by 1.5a (the projected length of the longest axis). The rectangular surface area required per unit reservoir is then $3a^2$ or 0.97, 0.36, and 0.25 km^2 for the three unit reservoir temperatures. In Figure 5, the production wellbore separation is shown as (3/2)a, which corresponds to injection well-production well separations of 218 m, 87 m, and 73 m for the HDR unit reservoir. A summary of the spatial characteristics of the unit 12 MWe HDR module reservoirs is given in Table 5.

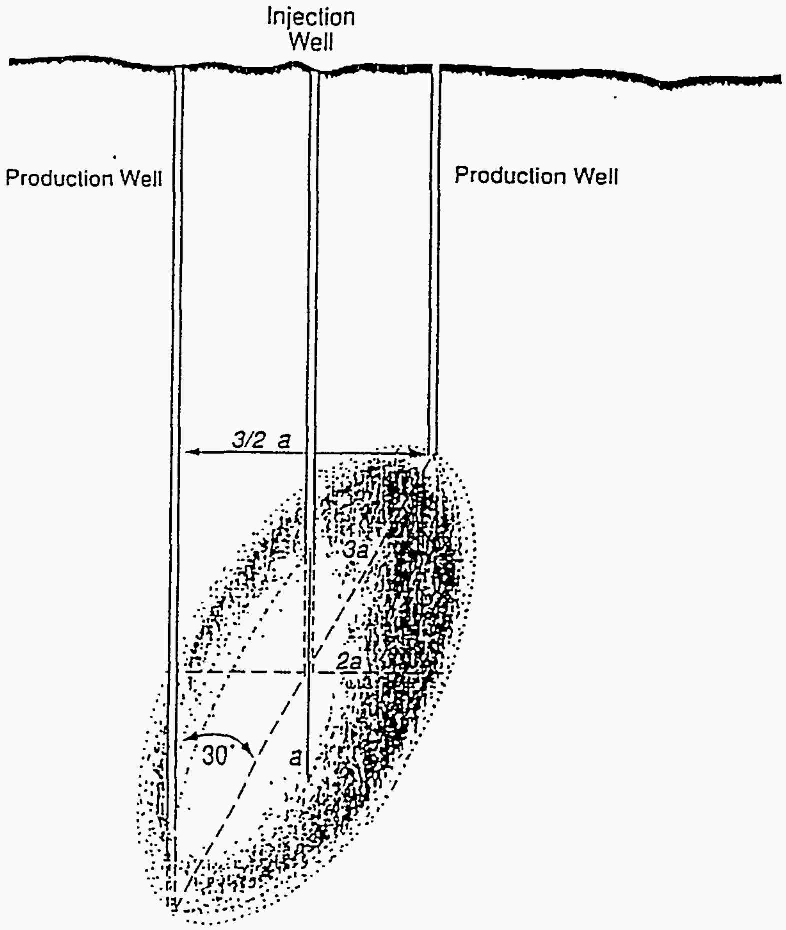

Fig. 5. A conceptual HDR reservoir/wellbore module for a spaceport application, with axis ratios of 3:2:1. The major axis (3a), along the direction of the least principle stress, is tilted 30° from the vertical. The injection wellbore is located at the center of the reservoir. Production wells are positioned at each end of the major axis. Circulating fluid flows preferentially along this axis.

Table 5
Surface Characteristics of 12 MWe Unit HDR Reservoirs

Resource Temperature (°C)	Reservoir Volume (10^6 m^3)	Rectangular Surface Area (km^2)	Wellbore Separation (m)
300	23	0.25	74
250	40	0.36	87
180	170	0.97	218

Table 5 shows that the land requirement for a HDR 12 MWe unit reservoir would be less than 1 square kilometer (0.4 square miles) even for the minimum quality HDR resource. Additional modules would be constructed as the power demand of the spaceport increases to a total of 13 reservoirs for full spaceport development. The total land requirement for the HDR energy system would be as low as 1.5 square miles for the 300°C HDR resource, and just over 5 square miles for the lowest grade (180°C) resource. These are relatively modest areas when considered in the context of the large arid regions in which a spaceport is likely to be developed.

Surface power plants could be constructed in modules ranging from 12 to about 50 MWe, common sizes for geothermal power plants. The 50 MWe plants could each be positioned at the center of a 4-unit reservoir grid to minimize piping runs and most efficiently capture the geothermal fluid. Upon full development, the surface manifestations of the HDR energy field would include wellbores, power plants, piping and ancillary utilities, but most of the land on the surface would remain unoccupied and would be available for other uses.

Another important aspect of power production in the southwestern states is the availability of water. For a HDR geothermal-powered spaceport, in particular, the water requirement includes the reservoir circulation water, make-up water to replace losses in the reservoir, power plant cooling water, spaceport water supply, and the feedwater for the hydrogen electrolyser unit. These requirements are best considered on a site-by-site basis. The total water requirement for an isolated spaceport could be reduced by recycling and fresh water recovery. The availability of water is considered in the section on power cost estimate.

C. Cost Estimates of the model HDR Power System

Fixed Costs. The estimated cost of the model HDR geothermal facility has been calculated on the basis of fixed and variable cost factors. The primary fixed costs involve drilling and reservoir development which were estimated from a review of recent costs for drilling geothermal wells to depths of 2-3 km (McLarty and Entingh, 1996), augmented with data from the Fenton Hill HDR site for deeper resources. The estimated drilling cost for each reservoir was obtained by using a standard cost of $201/ft for a 10,700 ft well. Drilling costs increase rapidly with depth, so a factor was introduced to adjust the cost per foot by $0.027 per foot for every foot the depth of the well varies from the standard depth of 10,700 ft. Fracturing costs, at $31,000 per million cubic meters, were also adapted from McLarty and Entingh.

Additional fixed costs involve surface piping and power plant installation. These costs were adapted from two recent studies (Pierce and Livesay, 1993; McLarty and Entingh, 1996) and were estimated at $1,500 per kilowatt or $18 million for each 12 MWe power station. Parasitic power consumption and plant downtime were estimated at 23% and 10%, respectively, adapted from the work of Pierce and Livesay (1993) and McLarty and Entingh (1996). The total capital costs for each 12 MWe system were estimated using a 10% discount rate with financing over a 15-year period. A summary of the relevant fixed cost data for a 12 MWe HDR system drawing from resources at each of the three temperatures considered in this study is given in Table 6.

Table 6
Estimated Fixed Costs for a HDR Reservoir Power Module

Reservoir Temperature (°C)	Wellbore Depth (km)	Cost per 3 Wells ($M)	Fracture Cost ($M)	Reservoir Dev.Cost ($M)	Capital Cost ($M)	Installed Cost ($/kW)
180	2.3	2.4	5.2	7.6	44.5	3708
250	3.3	6.3	1.2	7.5	44.7	3723
300	4.0	10.7	0.7	11.4	51.4	4284

Variable Costs. The variable costs included operation, maintenance (O&M), and water supply. The O&M costs were based on the estimates of McLarty and Entingh (1996), adjusted to a 12 MWe system with a 15-year lifetime. The resulting O&M cost was estimated as $2.4 Million per year or 2.53 ¢/kWh at an availability factor of 90%.

The cost of water for circulation through the HDR system depends on the tightness of the fracture network of the reservoir. At Fenton Hill, the demand for make-up water amounted to about 7% of the injected volume. The water requirement for hydrogen production was calculated by the geothermal resource requirement model for the three time steps. The results showed water consumption of 21.4 m^3/day to produce 2.24 tons of hydrogen per day for phase I, increasing to 226 m^3/day for the 23.8 tons/day required in phase III. These quantities are small compared to the circulating and cooling water quantities needed for the power plants and are included in the overall quantities of water needed for the spaceport facility.

The average cost of residential water in the United States was estimated at about $508 per acre-foot (Calypso, 1993). Since one acre-foot is the equivalent to 325,000 gallons of water, the cost per gallon is about 0.15 cents. Combining the several water costs, the total water costs for power production from a 12 MWe unit HDR power system is calculated to be 0.54, 0.122, and 0.056 ¢/kWh for HDR power plants drawing from 180, 250, and 300°C resources, respectively.

Total HDR Unit System Power Costs. Table 7 summarizes the data for the fixed and variable costs and the total estimated cost of power that might be provided for a spaceport from a 12 MWe HDR geothermal power system.

Table 7
Estimated Power Costs for a 12 MWe HDR Geothermal System

Resource Temperature (°C)	Fixed Costs (¢/kWh)	Variable Costs (¢kWh)	Total Costs (¢/kWh)
180	4.21	3.07	7.28
250	4.24	2.64	6.88
300	4.86	2.58	7.44

The data of Table 7 indicate that it should be possible to produce power for a spaceport from a HDR geothermal resource at costs that are within the broad competitive range of energy prices in the United States. When other factors such as the pollution-free characteristics of geothermal energy and the reliability afforded by on-site generation from a resource with 24-hour-a-day availability are considered, HDR may well be the resource of choice for spaceport power generation.

CONCLUSIONS

Geothermal energy is one of several alternative energy resources that can be utilized to produce on-site thermal and electric power for a spaceport. Energy self-sufficiency provides several logistical, environmental, and potentially economic advantages for on-site production of the electricity needed for both infrastructure support and electrolytic hydrogen production. Developmental spaceports are likely to have spaceport electric power needs that will grow from an initial level of about 15 MW to about 200 MW as the number of launches is increased. The widespread availability of HDR geothermal resources provides a promising approach to development of isolated, energy self-sufficient spaceport applications .

Geothermal resources in the southwestern states are adequate for locating energy self-sufficient spaceports at desired locations. A survey of known temperature gradients in southern California and southern New Mexico indicates that both areas possess HDR resources of sufficiently high quality to support the development of HDR plants capable of generating electricity in the quantities required for support of prospective spaceport applications. The first step in considering any of these sites for a spaceport utilizing geothermal energy would be to obtain more detailed exploration information about the geophysical characteristics of the potential reservoir. For suitable sites, test drilling to further document the potential for practical development of a HDR resource would be justified. The data produced from the exploration phase would be useful in subsequent detailed design and timed development of HDR facilities at the site.

Unit HDR geothermal reservoirs and power plants based on the electricity production needs for the model spaceport were designed as modules of 12 MWe capacity. Staged development of multiple HDR units of this size, each with its own engineered geothermal reservoir, appears to be the most appropriate approach to scaling up electricity production capacity as the power needs of the spaceport grow. This modular approach minimizes the technical risk and allows development of standardized energy extraction and conversion procedures. For maximum advantage of economy of scale and yet concentrating reservoir development in the smallest possible geographic area, spaceport conversion plants could be sized to units of 50 MWe, a common size for geothermal power installations. Each plant could be fed from 4 surrounding HDR reservoir modules. The maximum total electric power requirement for the 15-year model spaceport is 159 MW. At full development, such a facility could be supplied from a total of 13 HDR reservoirs feeding 3 conversion plants of 50 MW capacity and one smaller plant, without allowing for technology improvements during the build-up phases.

Economic analyses, derived from data developed for the U.S. Department of Energy, indicate that it should be possible to produce geothermal power for spaceport applications from a 250°C resource at busbar costs in the range of 6-7 ¢/kWh. The study shows that geothermal electricity can be used not only to provide power to a spaceport facility but also for local electrolytic generation and liquefaction of hydrogen as a fuel. While production costs for electrolytic hydrogen at 6-7 ¢/kWh are higher than off-site production from natural gas, the final delivered cost of liquid hydrogen produced with on-site geothermal power can be economic due to elimination of liquid hydrogen transport costs and smaller transfer losses. When the emissions-free and other environmental and energy advantages of geothermal technology are taken into account, the potential for geothermal powered spaceports appear attractive.

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TECHNICAL SESSION II:

Codes and Standards

A MANUAL OF RECOMMENDED PRACTICES FOR HYDROGEN ENERGY SYSTEMS

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Abstract

Technologies for the production, distribution, and use of hydrogen are rapidly maturing and the number and size of demonstration programs designed to showcase emerging hydrogen energy systems is expanding. The success of these programs is key to hydrogen commercialization. Currently there is no comprehensive set of widely-accepted codes or standards covering the installation and operation of hydrogen energy systems. This lack of codes or standards is a major obstacle to future hydrogen demonstrations in obtaining the requisite licenses, permits, insurance, and public acceptance.

In a project begun in late 1996 to address this problem, W. Hoagland & Associates has been developing a *Manual of Recommended Practices for Hydrogen Systems* intended to serve as an interim document for the design and operation of hydrogen demonstration projects. It will also serve as a starting point for some of the needed standard-setting processes. The *Manual* will include design guidelines for hydrogen systems in the U.S.A. and Canada, recommended handling and operating practices, emergency response procedures, case studies of experience at existing hydrogen demonstration projects, a bibliography of information sources, and a compilation of suppliers of hydrogen equipment and hardware. Following extensive professional review, final publication will occur later in 1997.

The primary goal is to develop a draft document in the shortest possible time frame. To accomplish this, the input and guidance of technology developers, industrial organizations, government R&D and regulatory organizations and others will be sought to define the organization and content of the draft *Manual*, gather and evaluate available information, develop a draft document, coordinate reviews and revisions, and develop recommendations for publication, distribution, and update of the final document. The workshop, *Development of a Manual of Recommended Practices for Hydrogen Energy Systems*, conducted on March 11, 1997 in Alexandria, Virginia, was a first step.

Workshop Overview

The objectives of this workshop were to begin to identify the specific need for and benefits of a *Manual of Recommended Practices*. Presentations and discussions on three current hydrogen demonstration projects highlighted important issues and the need for a *Manual*. Overviews of design guideline considerations for each of the hydrogen systems to be included in the *Manual* added clarification of its form and content, another workshop objective. A final objective was the identification of resources and participants and reviewers.

The four hour workshop began with a presentation of the proposed objectives, organization and content of the draft *Manual*. Design guidelines for vehicle systems, onboard storage systems, stationary storage systems, on-site production, hydrogen detection and safety, and dispensing stations were presented and discussed. Due to limited time, participants were asked to supplement the discussions with written comments at the close of the workshop.

Case Studies Highlight the Need for a Manual

Experiences from three current hydrogen demonstration projects that were discussed illustrated the practical aspects that should be the focus of the *Manual.*

Need for Hydrogen-Specific Codes, Standards, and Equipment

While many codes, standards, recommended practices, and guidelines have applicability to new hydrogen energy systems, those conducting demonstrations found that there is a definite need for hydrogen-specific codes and standards. Local authorities such as fire marshals or building inspectors were not always comfortable applying existing building codes and ASME, NFPA, or CFR standards to hydrogen systems.

The people conducting the demonstrations strongly recommended opening the lines of communication with local authorities early in a project to become familiar with local regulations and their concerns. The applicable codes and standards at the installation site often differ from those used by the equipment manufacturer, and learning this early in a project can help avoid expensive retrofits. Exemptions or special permits to implement new technologies can often be obtained if it can be demonstrated that they can be better or safer.

Components certified for use with hydrogen are also needed. Those conducting demonstrations reported that finding equipment designed for hydrogen applications is difficult, and modifications made to equipment designed for other fuels can be expensive. In some cases, components had to be specially designed for a project, or specifications had to be written for particular systems where none existed.

No Public Failures

In addition to gaining systems experience, an important goal of many hydrogen demonstration projects is to counteract the myths that hydrogen cannot be safe. It is important to have success stories, so it is critical that there be no public failures on any of these projects.

It was recommended that rigorous safety and hazards reviews must be performed early in these projects. The review document should be used to check the construction and implementation of the system during construction to ensure it is safe. A person who can perform the safety and hazards analysis function and also interact effectively with inspectors is important to the success of these projects.

Other Lessons

Some issues that arose during the demonstrations are not directly related to codes and standards. These include schedule flexibility, obtaining liability insurance, and winning community acceptance and approval when siting a project.

Design Guideline Considerations

Because there is limited system experience with evolving hydrogen technologies, the group believes that design guidelines should be flexible enough to allow for innovation. While a feedback mechanism is needed from the growing field experience, caution must be used in taking too much from case studies. A risk assessment may reveal that some past practices are inadequate.

While safety is an important consideration in developing guidelines, so is cost. Cost is a huge barrier for hydrogen vehicles. On the other hand, developers can't afford an accident in the early stages of introducing hydrogen technologies, because it will make it more difficult or impossible to gain public acceptance of hydrogen. Before hydrogen can become a consumer fuel like natural gas, new systems must be designed and built that are both safe and economical.

The need to define vehicle systems was brought out in discussion, and many questions were raised. Should there be a separate section for each device, such as hydrogen heat exchangers and hydrogen valves, or should there be a separate guide? Another issue is software safety. Fuel cell vehicles will have computer controls. How do you address a situation where all of the hardware works, but a software error causes a dangerous situation to evolve?

There is a natural interface between the refueling system and the vehicle at the connection point. Whose guidelines should be used? NFPA standards and building codes cover compressed gas. Standards for liquid hydrogen also need to be included. Where does the refueling connection fit? A standard has to be developed to make sure that a 5000 psi fueling hose can't be hooked into a low pressure line.

The consensus was that the near-term focus of the *Manual* should be on design guidelines for a filling station with a supply of hydrogen that can be pumped and stored. Bulk hydrogen storage practices are already laid out in a number of prescriptive codes and standards such as the NFPA 50a. These codes should be listed in the *Manual's* bibliography of related codes and standards, but resources are better spent elsewhere. The work done by the natural gas vehicle industry for standards for compressed and liquid natural gas is a good starting point that should be adopted, with exceptions made for the unique characteristics of hydrogen. (This is being done by the National Hydrogen Association in their work on developing standards for containers, connectors, and service stations.)

Safe Operating Practices

Part of the process of developing a *Manual* is to provide a mechanism for safety reviews on specific projects. A *pro forma* system safety plan that ranks hazards, risks, and severity criteria was suggested. The quality of the safety review of a proposed system design is a key safety aspect. The inclusion of information and technical assistance in the *Manual* is to provide a mechanism to help approving authorities feel confident that any design they're approving is safe and within reasonable limits, and can also help in the training of operators and other personnel.

A fundamental tenet of safety is situational awareness: real-time information on the status of a system. To reduce risks and hazards, a general guideline in a plant, appliance, vehicle, facility, or any system that uses hydrogen, is to reduce the amount of gas contained in the process. There are two underlying causes for failure modes for a hydrogen system: the formation of a flammable mixture in the process or hydrogen stream, and the potential for ignition within the area where a flammable mixture can be formed. Leakage is a major concern. Design guidelines that reduce or minimize these hazardous situations should be implemented. Some examples:

- Establish precautionary measures to reduce the risk of ignition. In a plant, these include collectible barriers, seal-offs, explosion-proof instruments and actuators, and temperature and pressure instrumentation.

- When possible, operate the system in a ventilated area to reduce the risk of formation of flammable mixtures.

- Where the separation of electrical equipment is not possible, use advanced approaches such as forced ventilation, pressurized rooms, and approved combustible gas detectors.

- Develop guidelines or special requirements for hydrogen components that are in the proximity of high voltage.

In developing guidelines for operating systems safety, each subsystem that makes up the hydrogen energy system and the safety issues between each subsystem must be considered. Subsystems should be tested before they are integrated on-site. Subsystem risk propagation must then be evaluated in the integrated system.

A systems safety program must include compliance and verification guidelines which may be based on verification tests, inspections, and analyses. In developing these guidelines, mandating or embedding unnecessary expense in any one system should be avoided.

Recommendations for the *Manual of Recommended Practices*

An area of consensus is that the benefit of the *Manual* is that it can be the focal point for current practices and experience, and is a useful vehicle for the collection of information. While being technically grounded, it is envisioned to provide guidelines for people who are not experts on hydrogen. It should be a document that will serve the functions of official codes and standards to smooth the project approval process. Hopefully, it can serve as a manual to assist developers of technology in training personnel, and can provide a template for an emergency response plan that could be tailored for a particular project or site.

It was agreed that the *Manual* should be a living document capable of accommodating the technological advances in hydrogen systems. The further down the R&D path we go, the closer we are to the establishment of formal codes and standards. Concern was expressed that if the *Manual* was overly prescriptive or improperly implemented, it could inadvertently limit innovation. It was pointed out that a recommended guideline does not have the weight of a code or standard, and does not preclude innovation or fresh approaches.

The group was reminded that an important consideration in establishing recommended practices, or codes and standards, is the removal of any appearance or actual conflict of interest. Having all of the stakeholders involved is key.

Other recommendations:

- Concentrate on the system components that have to do with hydrogen.

- Don't bury those things that are unique to hydrogen in with common issues. One example is materials compatibility.

- Guidelines are needed for both components and the overall system.

- Work from a systems point of view, than move toward the component level

- Divide guidelines by type of hydrogen (gaseous, liquid) and source of storage (compressed, cryogenic, metal hydrides, carbon). There have to be different guidelines and recommended practices for each of these systems.

- Identify inconsistencies among existing references and reconcile them for applicability to hydrogen systems.

- Provide comparative safety data and facts between hydrogen and gasoline, diesel, propane, natural gas, and methanol.

- A separate, brief manual for station operators and drivers is needed.

- Include "do's and don'ts" for hydrogen operations, and a list of references.
- Distinguish between guidelines for closed spaces versus open spaces.

- Make access to component information easy. Identify resources and present design risks and performance experience.

- Set up a web page in addition to the *Manual.*

Wrap-up and Next Steps

It was made clear at the workshop that there is a definite need for a document that can help smooth the approval process. The existence of such a document would help ease concerns over the safety of hydrogen systems because it is evidence of past experience and review. There was general agreement that the outline of the form and content of the *Manual* was acceptable as proposed. Due to budget limitations, it was recommended that the design guidelines should be developed after the other elements of the outline. Resources should be identified to supplement and interpret the *Manual* for approving authorities and designers of such systems. We hope to resolve this at the next workshop. Key resources that were identified at the March 11, 1997 workshop were people who volunteered to provide assistance; 13 as reviewers, and 10 as providers of information.

During the interim between this workshop and the next, scheduled for May 30, 1997, we will continue to collect information and to further define the contents of the *Manual.* In addition, we will seek to include representation from the insurance and auto industries.

Acknowledgments

This workshop was made possible by the support of National Resources Canada through the Hydrogen Research Institute and the U.S. Department of Energy through the National Renewable Energy Laboratory. Special thanks to Dr. Tapan Bose for his early support and encouragement, and to the workshop speakers and participants, who have given freely of their time and expertise in an effort to speed the commercialization of hydrogen energy technologies.

The speakers were William Summers, Project Manager, Technology Programs, Westinghouse Savannah River Company; Peter Lehman, Director, Schatz Energy Research Center; Paul Scott, Touchstone Technology, Inc.; Gregory Barthold, American Society of Mechanical Engineers; Brian James, Staff Engineer, Directed Technologies, Inc.; Dr. Jose Garcia, Centre for Hydrogen & Electrochemical Studies; Matthew Fairlie, Electrolyser Corporation, Ltd.; David Haberman, Vice President, Directed Technologies, Inc.; Jim Hansel, Senior Engineer Assoc., Engineering Safety, Air Product & Chemicals; and Robert Hay, Tektrend International.

I would also like to acknowledge James Cannon, President of Energy Futures, and Russell G. Derickson, Assistant Professor, South Dakota School of Mines and Technology, Institute of Atmospheric Sciences, for their contribution in developing the early concept of the manual.

Manual of Recommended Practice for Hydrogen Energy Systems

OUTLINE

1.0 General Information about Hydrogen

- 1.1 General characteristics of hydrogen gases and liquids
- 1.2 Use in industry, historical and current
- 1.3 General Properties of hydrogen relative to other fuels
- 1.4 Benefits of widespread hydrogen usage
- 1.5 Components of typical hydrogen systems

2.0 Design Guidelines for Hydrogen Systems

- 2.1 General design considerations
- 2.2 Hydrogen transportation systems
  - 2.2.1 Hydrogen vehicles
    - 2.2.1.1 On-board hydrogen storage
    - 2.2.1.2 Hydrogen fuel cell electric vehicles
    - 2.2.1.3 Hydrogen hybrid electric vehicles
    - 2.2.1.4 Hydrogen containing fuels for internal combustion engines
  - 2.2.2 Hydrogen storage and dispensing stations
    - 2.2.2.1 Bulk storage systems
    - 2.2.2.2 Dispensing stations (connectors, valving, materials, etc.)
- 2.3 On-site hydrogen production
  - 2.3.1 Electrolysis systems
  - 2.3.2 Methane reformers
- 2.4 Hydrogen safety systems
  - 2.4.1 Hydrogen detection
  - 2.4.2 Fire protection

3.0 Safe Operating Practices

- 3.1 Discussion of risks and hazards
- 3.2 General practices
- 3.3 Personnel/operator training
- 3.4 Loss prevention
- 3.5 Emergency response

4.0 Case Studies

- 4.1 Description of current and past hydrogen projects
- 4.5 Lessons learned

Appendices

- A Sources of information and technical assistance
- B Equipment Vendors and Suppliers
- C Bibliography of Related Information
- D Descriptive Bibliography of Related codes and standards

Manual of Recommended Practices

First Workshop

March 11, 1997

Radisson Mark Plaza Hotel

Alexandria, VA

Sponsors

- U.S. Department of Energy
  - National Renewable Energy Laboratory
- Natural Resources Canada
  - Hydrogen Research Institute

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Introduction

- There is a lack of published codes or standards that directly apply to early hydrogen systems and demonstration.
- Many pioneering demonstrations to show the efficacy of hydrogen fuels have been completed or are contemplated.
- Each new demonstration should take advantage of previous experience.

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The Need

- Permitting officials and insuring organizations want reassurance that their decision to approve or insure a project is **reasonable and defensible**.
- Developers of hydrogen systems should not have to "reinvent the wheel" with each project.

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Workshop Objectives

The purposes of this workshop are to:

- identify the need and benefits,
- discuss appropriate form and content,
- begin identification/collection of needed information,
- identify resources, participants and reviewers, and
- discuss publication and distribution.

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Desired Result

- Consensus document will:
  - serve many of the functions of official codes and standards;
  - become focal point for current practices and experience; and
  - facilitate dialogue for development of more formal codes and standards.

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Purpose of a Manual

To assist early developers of hydrogen systems and technologies by:

• providing a compendium of information useful in conducting large-scale experiments, field tests, technology validations, demonstrations, and commercial applications;
• producing a product that will raise the comfort level of permitting authorities, fire marshals, and insuring organizations regarding early hydrogen systems.

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Approach

- Manual should be published by NHA or other national organization
- Coordinated by one entity, but compiled by many. It should become a consensus document
- Updated regularly to incorporate new data and operating experience

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Project Participants

- Hydrogen Research Institute
- TekTrend International
- W. Hoagland & Associates, Inc.
- South Dakota School of Mines & Technology
- Energy Futures, Inc.
- Others

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Recommended Contents (1)

- General Information
  - General Properties
  - Historical and Current Uses
  - Unique Characteristics
  - Typical H_2 Systems and Components

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Recommended Contents (2)

- Design Guidelines
  - Hydrogen Vehicles
  - Dispensing Stations
  - Storage Systems
  - On-site Production Systems
  - Hydrogen Detection/Fire Prevention

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Recommended Contents (3)

- Safe Operating Practices
  - Discussion of Risks/Hazards
  - General Do's & Don'ts
  - Personnel/Operator Training
- Emergency Response Plan
  - Sample to be tailored to needs
  - Coordination with local authorities

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Recommended Contents (4)

- Sourcebook - what has been used in industrial practice or other demonstration projects
  - Equipment (tanks, compressors, etc..)
  - Hardware (valves, sensors, etc..)
  - Technical assistance

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Recommended Contents (5)

- Bibliography of reference material
  - NGV-1, NGV-2, MSDS, NASA, NFPA, etc.
- Case Studies of Relevant Projects
- Model Code for municipalities

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Schedule

1st Workshop	March 11, 1997
Preliminary Draft	May 15, 1997
2nd Workshop	May 28, 1997
Revised Draft	???
Peer Review	???
Publication	January 1998

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Report from WG 1: Connectors

Matthew Fairlie, WG 1 Chairman

Purpose/Scope:

Connectors are key to safe vehicle refuelling

Construction

Performance

Membership:

Matthew Fairlie (Chair)	Electrolyser Corporation
Jim Adams	Ford Motor Company
Bob Mauro	National Hydrogen Association
Chris Blazek	Institute of Gas Technology
Tom Halvorson	Praxair Inc.
John Heenan	Sherex/OPW

Future Activities:

(i) Recruit more members

(ii) NFPA/ASME - recognition/process to qualify

(iii) Connector specification (?):

- Fuel Purity - Dew point/oil
- Service Pressure - 5000 psig (+)
- Flow rate

(iv) Observe NGV - ISO/TC22/SC25/WG1 process

(v) Investigate component certification; process, cost (IGT?)

(vi) Prepare 1st draft before next meeting

(vii) Compile results from field tests & materials analysis

Next Meeting Toronto June 1997

Status:

Newly-formed working group. Met in October, 1996 to discuss work plan and future activities.

Proposal for Process

Base standard on NGV-1 standard and testing of prototypes now in field

"Build it (right) and they will come"

Report from WG2: Containers

Dr. James Hansel, WG2 Chairman

Purpose/Scope:

The National Hydrogen Association recognized the need for an appropriate standard covering the design and operation of gaseous hydrogen fuel containers for gaseous hydrogen vehicle (GHV) use.

Future Activities:

Listed below are some of the changes required to convert from the CNG document to the GHV document:

•Hydride Containers

•Hydrogen Gas Composition

•Hydride Container Temperature [Exotherms/Endotherms]

•Hydrogen Embrittlement

•Weld Materials

•Nonmetallic Liner - Hydrogen Reaction

•Odorants

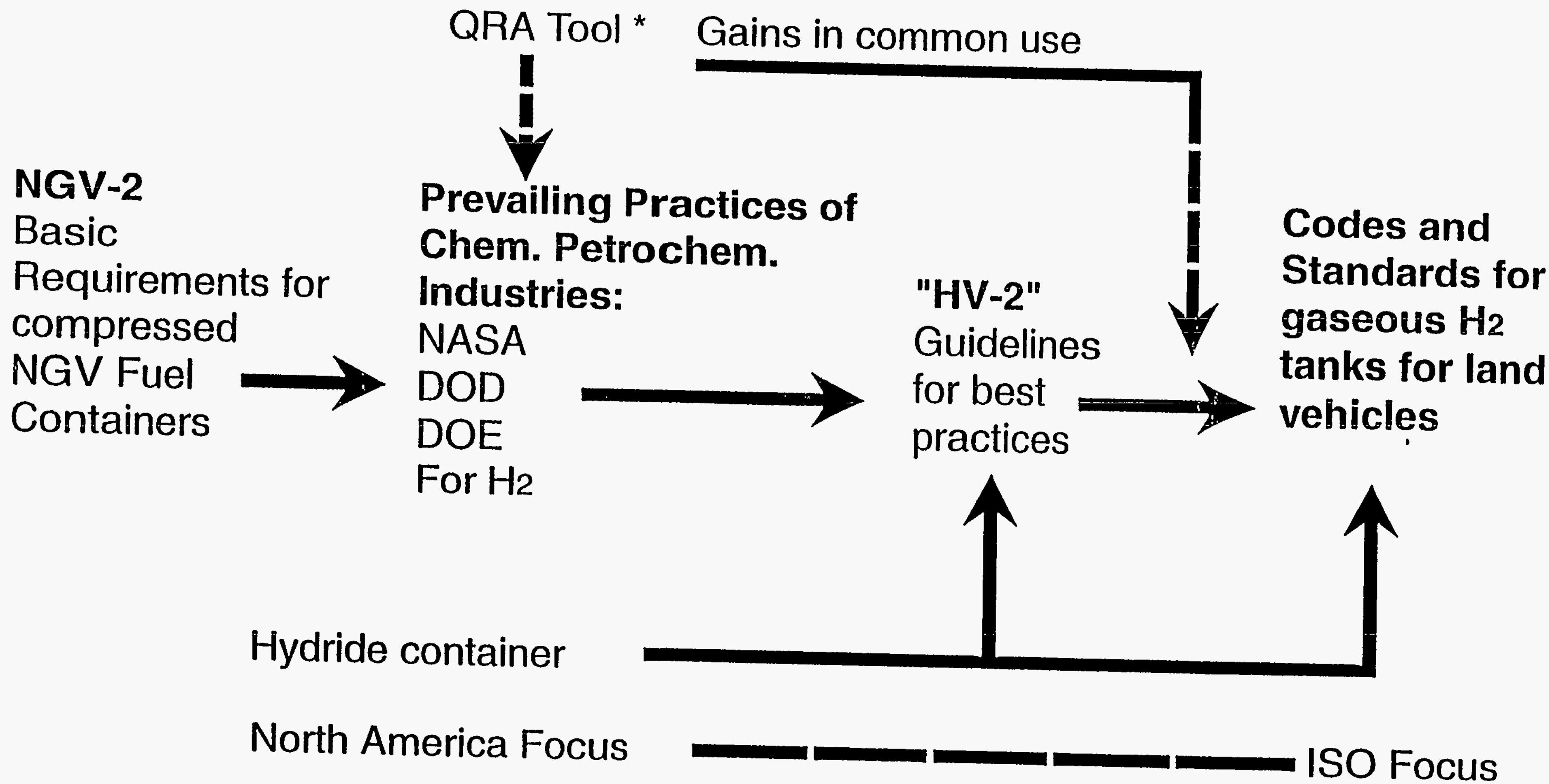
•Tank Location Within Confined Spaces

In addition, the Working Group intends to develop the guideline into a standard after aligning with an appropriate organization such as ASME, ANSI, etc. Beginning efforts are already underway to align with ANSI and ISO/TC 197 (Hydrogen Technologies).

Status:

The task group met twice in 1996 and a first draft was issued in August 1996. The 55 page second draft was issued in February 1997. The drafts closely follow the comprehensive May 1996 draft ANSI standard for fuel containers for CNG vehicles. During the August 1996 meeting the decision was made to provide a guideline initially rather than a standard because a guideline could be developed mush more quickly, and thus provide the needed information.

GASEOUS H_2 VEHICLE TANKS



*Quantified Risk Assessment

Report from WG3: Service Stations

Dr. Allan Coutts, WG3 Chairman

Service Station Requirements for Safe Use of Hydrogen Based Fuels

NHA Work Group Update

D. A. Coutts
Westinghouse Savannah River Co.
Aiken, SC
March 12, 1997

Results of October Meeting

- **Deliverable**
  - Stand alone standard based on NFPA 52, or
  - Revision to NFPA 52, CNG Vehicular Fuel Systems
- **Scope**
  - Same as NFPA 52
- **Draft text released**

Oderant/Detection Wording

A method shall be provided to indicate the presence of a fuel leak from any system covered by this standard. The method shall be sensitive enough to be detected down to a concentration in air of not over 25% of of the lower limit of flammability (LFL) if automatic or 20% of the LFL if manual.

Path Forward -- October '96

1. Obtain NHA board input on detection
2. Review strawman based on NFPA 52
3. Collect comments
   - Review engineering numbers
   - Check references
4. Update strawman (3/97)
5. Submit proposal to NFPA (3/97)
6. Submit strawman to NHA membership
7. Review and address comments
8. Submit proposed standard to NFPA (7/97)

Recent Activities

- **National Fire Protection Association (NFPA)**
  - Submitted draft standard to NFPA for consideration (1/97)
  - NFPA Vehicle Alternative Fuel Systems Committee to meet on March 20-21, 1997
- **International Standard Organization (ISO)**
  - Submitted new work item proposal (3/97)

**The Value of Odorants in Detecting
Hydrogen Diffusion in a Garage**

Dr. Michael Swain
University of Miami, Department of Engineering

ABSTRACT

The theoretical, computational, and experimental results of an ongoing investigation into the behavior of odorants in fuel gases will be presented and discussed. The purpose of this investigation is to determine whether mercaptans can be used for gas leak detection with hydrogen in the same manner they have been used with other gaseous fuels.

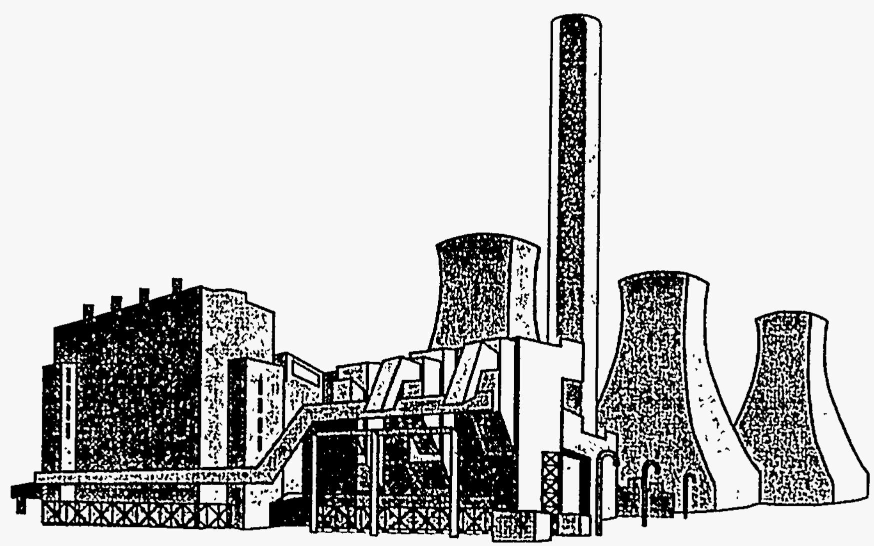
An Interdisciplinary Analysis of Odorants for Hydrogen Safety

Presented by: David Haberman,
Vice President, DCH Technology
Co-Authored by: Karen Miller,
Hydrogen Program Coordinator,
National Hydrogen Association

Introduction

Interdisciplinary Analysis

- Analytical Model
- Safety Engineering
- Community Survey & Dialog



Hydrogen Safety Background

Hydrogen Leak Categories

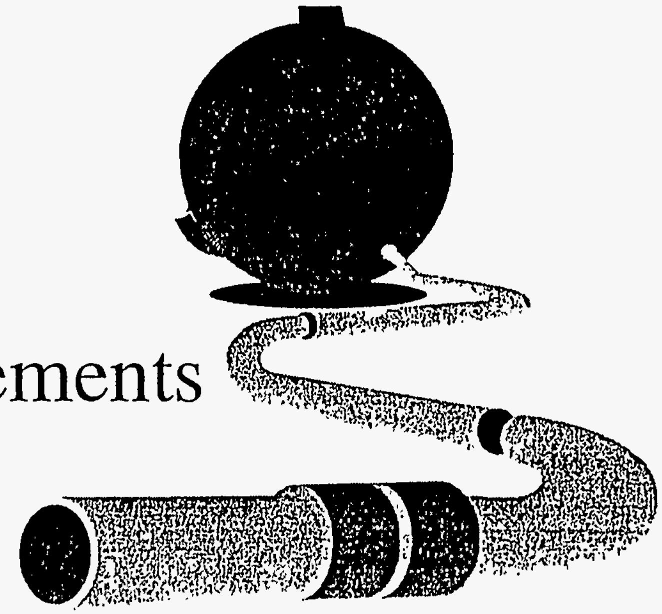
- Small, hazard is primarily accumulation,
  risk to equipment and process
- Medium, hazards include personnel safety,
  risk to operational capability and interruption
- Large, hazards focused on personnel safety,
  risk to life, capital investment and certification

Definition of Odorants

- Chemical Additive
- Natural Gas Mandate
- Hydrogen - Not Proved

History of Odorant Use

- Pipeline Safety Act
- Federal Regulations



Performance Driven Requirements

CFR 192.625

Odorization of Natural Gas

Current Use of Odorants

Natural Gas

• End User General Leak Signal
concentration in air 20% of LEL

• Pipeline Integrity Test
Life, Property and Public Safety

Conceived future use of Odorants

- LNG?
- LPG?
- Hydrogen?
- Metal Hydrides?

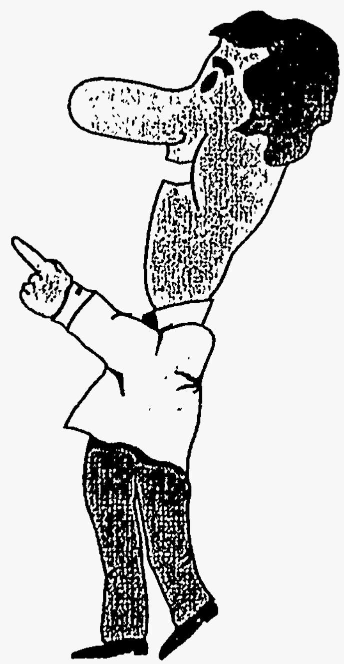
Driving forces are perceptions of simplicity in implementation and public confidence in function

Gas Detection Safety Requirements

Modern Requirements for Hydrogen

- Proximity Warning Signal
- Leak Location Cue
- Leak Trend (measurement)
- Ability To Trigger Automatic Countermeasures

How do Odorants Match these Requirements?



Only A Warning Signal If A Trained, Functional Nose Is In Proximity To A Neutrally Buoyant, Non-Fading Odorant

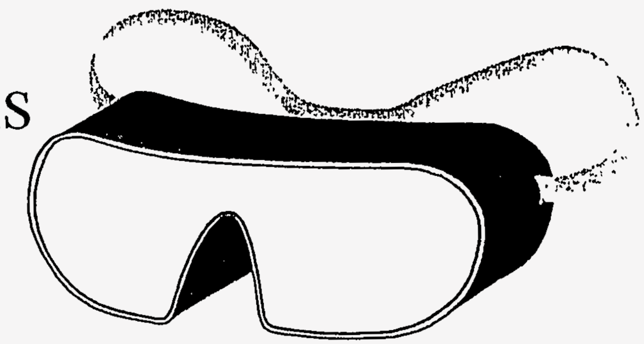
Counterpoints To Perceived Key Advantages to Odorants

- Low Maintenance - actually high maintenance
- Uniform Transmission - nonuniform distribution of odorants and a nonuniform receptors
- Easily Understood - population is not easily trained

Given the odorant does not poison or interfere with the actual use of hydrogen

Key Disadvantages of Odorants

Hazardous Materials



- Handling Precautions
- First Aid Measures
- Protective Gear

Potential Litigation

- Performance Faults
- False Positives
- Misapplication

How Odorants Fit the NHA Codes &Stds Planning

- Safety of Hydrogen Vs. Natural Gas Precedence
- Open Forum Review
- Adapting The NG Baseline

Active Sensor Roles in Hydrogen Safety

- Quantitative Measurement
- Timely Situational Awareness
- Support Automated Countermeasures
- Remote Monitoring - Man Out Of Loop
- Odorant Implementation Verification

Sensor Technologies Fit Roles

- Modern Sensors Overcome Past Limitations
- Broader Test and Evaluation Opportunities
- Liability Controls Prefer Man Out Of Loop

Advantage of Using Sensors

The ability to safely, objectively and with a high degree of confidence describe, verify and initiate appropriate action based upon a specified level of situational awareness with minimum impact to processes or equipment. Redundancy and recalibration can be implemented to obtain high confidence.

Disadvantages of Using Sensors

- Require Investment
- Planning
- Implementation
- Maintenance

Small Leak Model

Series of 45 degree bends

Tank Pressure	1000 psi
Leak Diam	.0000004 m
Gas Velocity	23 m/s
Reynold	.81
Friction Factor	14.13
Driving Force	8,000,000 Pa
Vol. Flow Rate	1.5 cucm/h

Hydrogen losses momentum at air, becomes well mixed

Summary of Findings

The duality of hydrogen as a chemical and an energy carrier contrasts the natural gas paradigm for safety.

Odorants do not, at present, offer an implementable safety device for Hydrogen.

Odorants will continue to be part of the discussion in the NHA codes and standards process

Recommendations

- Provide input to the NHA Codes & Standards Group
- Provide input to the Manual of Recommended Practices WG
- Consider Active Sensors as the preferred safety mechanism

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TECHNICAL SESSION III:

Advanced Technologies

A PORTABLE POWER SYSTEM USING PEM FUEL CELLS

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Introduction

Ball has developed a proof-of-concept, small, lightweight, portable power system. The power system uses a proton exchange membrane (PEM) fuel cell stack, stored hydrogen, and atmospheric oxygen as the oxidant to generate electrical power. Electronics monitor the system performance to control cooling air and oxidant flow, and automatically do corrective measures to maintain performance. With the controller monitoring the system health, the system can operate in an ambient environment from 0 °C to +50 °C. → cont'd on file stem with a high-pressure hydrogen storage tank attached. **Table 1** gives the meters when using different hydrogen storage methods.

Table 1 Power System Characteristics

System	Size (in.)	Weight (lb)	Power (W)	Energy (kWh)
Power subsystem and metal hydride hydrogen storage	9 x 8 x 18 (3/4 ft^3)	28	100 W continuous at either 12 or 24 V	1.3
Power subsystem and high-pressure hydrogen storage	12 x 8 x 18 (1 ft^3)	27	100 W continuous at either 12 or 24 V	5
Power subsystem and chemical hydride hydrogen storage (under development)	12 x 8 x 18 (1 ft^3)	30	100 W continuous at either 12 or 24 V	15

System Testing

After Ball assembled and checked the system operation at ambient conditions, the system was subjected to environmental and safety testing. The system tests included:

- Load testing from 0 W to 125 W
- Thermal testing from 0 °C to 50 °C ambient environment
- Humidity testing from 0% rH to 95% rH
- Vibration testing
- Shock testing
- Field testing
- Destructive testing of high-pressure gas tanks

Load Testing

We performed the power system load testing at ambient laboratory conditions under continuous loads from 0 W to 125 W. The results of this testing showed the fuel cell can supply power instantaneously to a changing load as long as reactants are available to the fuel cell. Load testing also proved the power system can supply continuous power of 100 W and a peak power of 125 W for less than 1 minute and maintain all system specifications.

Thermal and Humidity Testing

Ball completed the environmental testing in a thermal and humidity test chamber using both the metal hydride and high-pressure gas sources. We combined the temperature and humidity tests into a "four corner" test as shown in **Figure 2**. At each of the four points we varied the load in steps; minimum power of 2 W, nominal power of 10 W, high power of 100 W, and a 125 W peak load for 30 seconds. The power system performance was as expected with dehydration in the fuel cell membrane occurring at high temperature and low humidity. The fuel cell also has a slow response at 0 °C with an instantaneous load change from 2 W to 100 W. The system did not perform as well with the metal hydride storage system at cold temperatures. The high-pressure gas system did not cause hydrogen supply problems at any temperature or humidity.

Operation at 0 °C with the metal hydride source is possible only if the fuel cell stack temperature is above 10 °C. The system uses the heat from the 10 °C fuel cell stack to desorb the hydrogen in the metal hydride source. If this heat is not available, the metal hydride storage temperature falls below -8 °C and the hydrogen source pressure decays below atmospheric pressure. When the metal hydride temperature falls below 0 °C, the hydrogen source will not supply enough hydrogen to the fuel cell to sustain a 100 W load. The metal hydride source presents no problem at higher temperatures.

Vibration and Shock Testing

The customer had another contractor perform vibration testing. Testing verified the prototype power system would survive ground and air transportation vibration. The total vibration time in all axes was 12 hours at low frequency and high amplitude. The system survived the vibration test and we used the same system later in the field tests as one of two field demonstration units.

As a final packaging test, the same testing contractor dropped the power system from 3 ft onto a cement floor to show an accidental drop would not harm it. The power system operated properly after the drop test. After the system was returned to Ball, we found a cracked bracket holding the water reservoir. We made a mounting design change and repaired the unit. No further shock testing was performed.

Field Testing

The special operations forces at Ft. Bragg deployed the power system on a simulated field mission. The power system powered transceivers and scanners for the entire 3-day mission. During these tests the special operations forces used the high-pressure hydrogen source. After the special forces completed the field test, a calculation showed that the power system could supply power for a 23-day mission without refilling the hydrogen source.

To further prove the power system reliability, the special operations forces made a parachute jump with the power system in a backpack. The system survived the jump and was used by the field operations simulation team.

Destructive Testing of High-Pressure Gas Tanks

The high-pressure hydrogen tank stores one-half pound of hydrogen gas at 8,500 psi. With this much hydrogen at high-pressure there was a safety concern. Six tanks were destroyed during testing by crushing, rifle fire (both regular and tracer rounds), and a flame test. In no case did the 8,500 psi hydrogen-filled container fail catastrophically or produce any shrapnel.

Test Results

The testing showed that a PEM fuel cell power system with its associated hydrogen storage can be built to survive in a military environment. The power system's water management, thermal control, and simple user interfaces make it "user friendly."

The testing also showed that system design is critical when operating over the broad environmental and load ranges. The following sections give a test summary for each subsystem.

Fuel Cell Power System

As with all small fuel cell power systems, the biggest hurdle is the water management problem. Careful system design will allow the stack to shed liquid water during low-temperature, high-humidity operation but keep the membrane moist at high-temperature, low-humidity conditions.

Just as important is the management of the cooling air and oxidant air to the stack. A stack that is too hot or too cold will cause the system to malfunction. When the oxidant flow gets too low, the stack does not perform up to expectations. When the oxidant flow is too high, the membranes will dehydrate and cause the stack to temporarily fail.

Metal Hydride Hydrogen Storage

Storing hydrogen in a metal hydride is a well-known technique. The metal hydride we used in this power system stored 4% hydrogen by weight of the metal hydride. The biggest advantage of storing hydrogen in a metal hydride is that the storage pressures are low. This eases refilling the storage container and allows the container to be simple and safe. The biggest disadvantage is that the storage system is heavy. **Table 2** shows the major advantages and disadvantages of metal hydride hydrogen storage.

Table 2 Advantages and Disadvantages of Metal Hydride Hydrogen Storage

Advantages	Disadvantages
Safety--low-pressure hydrogen storage	Heavy
Fill hydrogen at low-pressure	Requires heat to release hydrogen
More hydrogen storage per volume than low-pressure gas storage	Operation at cold temperatures is difficult
Refillable up to 50 times	Difficult to tell the amount of H_2 remaining

High-Pressure Hydrogen Gas Storage

The high-pressure hydrogen gas storage system uses a carbon filament wound tank with an aluminum liner to store hydrogen at 8,500 psi. The lightweight, high-pressure storage container has been developed by the aerospace industry for space applications. The storage container holds 0.5 lb of hydrogen at 8,500 psi. Tank testing showed a burst pressure of 23,000 psi, giving a worst case safety margin of more than 2 to 1. During the environmental tests the high-pressure gas system proved to be the most reliable gas source for the power system. **Table 3** shows the major advantages and disadvantages of high-pressure hydrogen gas storage.

Table 3 Advantages and Disadvantages of High-Pressure Hydrogen Gas Storage

Advantages	Disadvantages
Lightweight	Safety--high-pressure hydrogen gas
Works at all temperatures	Difficult to fill at 8,500 psi
Easy to ascertain the amount of H_2 remaining	Lightweight reliable high-pressure components are expensive
Refillable up to 100 times	
Moderate amount of stored hydrogen	
Inexpensive if amortized over life of container	

Chemical Hydride Hydrogen Storage

The chemical hydride hydrogen storage system is a development unit tested with the power subsystem. We did not perform any thermal or humidity testing. The chemical hydride provides up to 1.5 lb of hydrogen, or about 15 kWh of energy. The amount of hydrogen available in the chemical hydride is greater than that available in the same volume of liquid cryogenic hydrogen. The chemical hydride is the highest energy storage device of any we developed. Although development is not complete, there have been no major problems with this method of storing hydrogen for use in a fuel cell power system. **Table 4** shows the major advantages and disadvantages of chemical hydride hydrogen storage.

Table 4 Advantages and Disadvantages of Chemical Hydride Hydrogen Storage

Advantages	Disadvantages
Low-pressure containment	Nonrefillable system
	Difficult to restart after shutdown
High hydrogen and energy content	Difficult to extract hydrogen
Uses water generated by the fuel cell	Processing solvents in the chemical hydride fuel affects purity of hydrogen
Long shelf life	Needs additional development
	Expensive

Ball's proof-of-concept power system has shown that a fuel cell–based electrical generation system is possible. The concept of using stored hydrogen and oxygen from the air has been proven. We believe the system can be made lighter and smaller if components are developed specifically for the portable system. The next generation will benefit from the experience gained with this system and will be more robust and have fewer constraints than the present power system.

Figure 1 Portable Power System Using PEM Fuel Cells

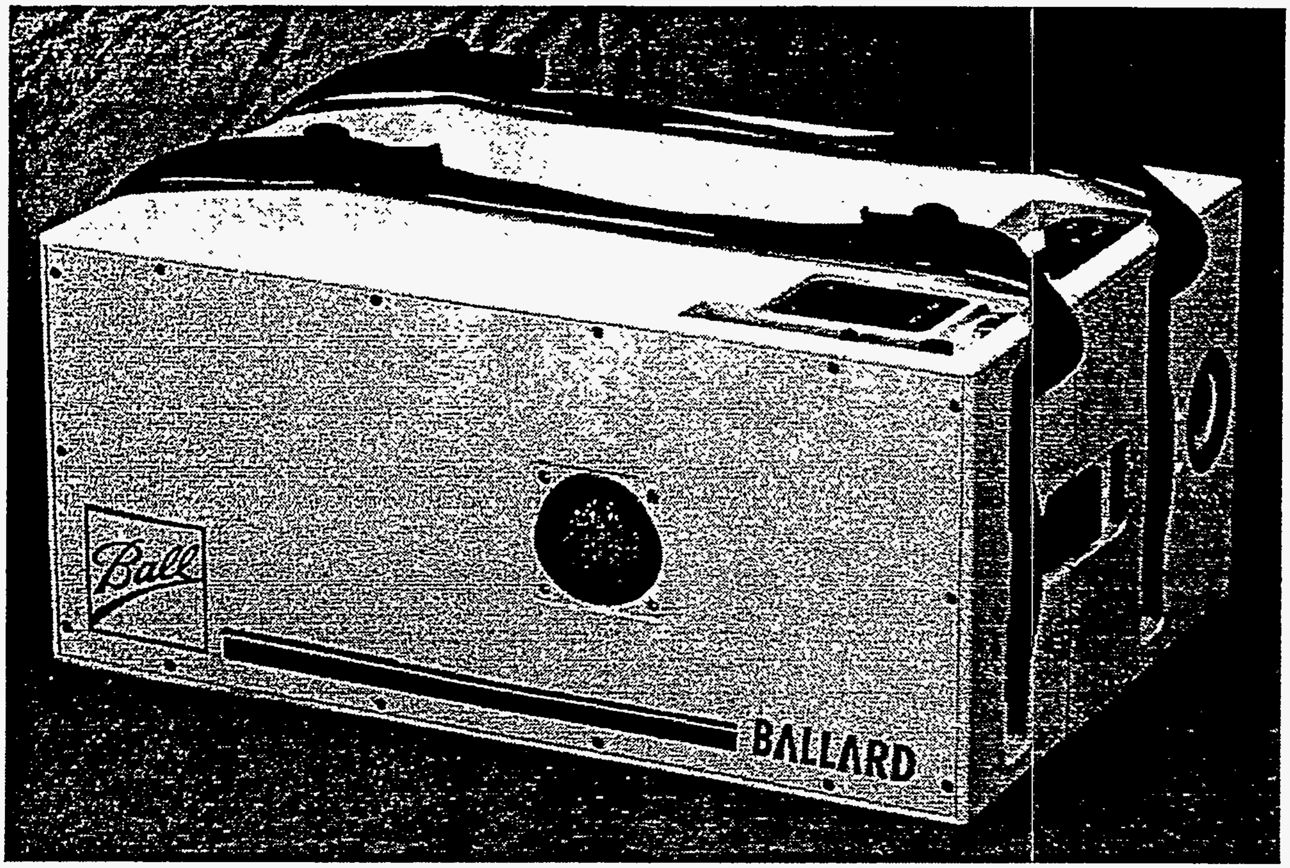
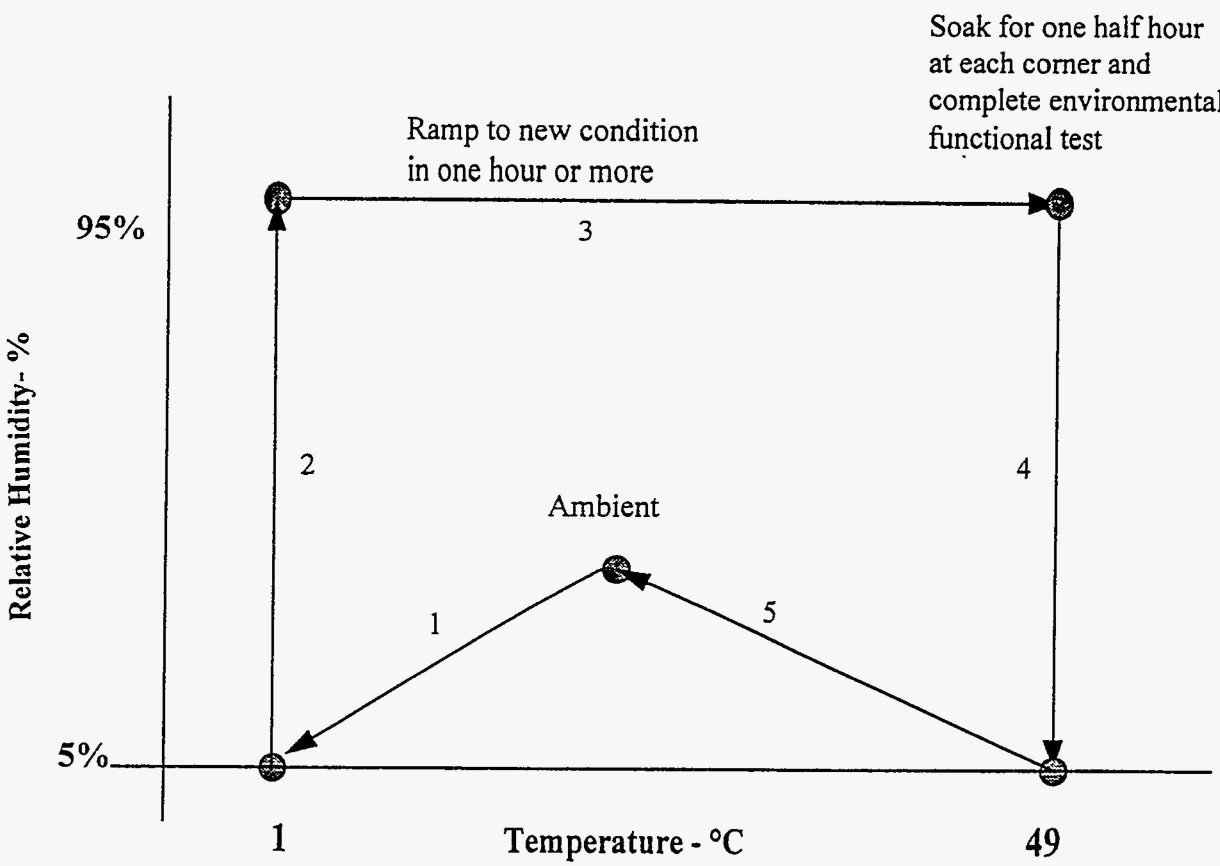


Figure 2 Environmental Corner Testing



MAGNIC HYDROGEN PRODUCTION: CURRENT STATUS OF RTI FEASIBILITY STUDY AND DEMONSTRATION

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Introduction

The MAGNIC hydrogen production process study being performed at Research Triangle Institute is based on a thermochemical, water-splitting reaction using a magnesium/nickel alloy originally developed in Russia by scientists working at St. Petersburg Technological Institute. The primary MAGNIC reaction is an electrochemical reaction between the magnesium and water with salt acting as the electrolyte. This reaction is governed by the following equation.

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 + 84\ kcal\ heat \quad (1)$$

The nickel (and other alloy metals) are involved in side reactions with chloride ions to control the buildup of a hydroxide layer which would otherwise impede the reaction.

The primary objectives of the study were: (1) demonstrate the MAGNIC reaction to be safe and controllable, and show that large amounts of excess water are not required; (2) investigate the possibility of regenerating the primary reaction byproduct, magnesium hydroxide, to magnesium; and (3) demonstrate the feasibility of a portable energy production system used in conjunction with a reverse osmosis desalination unit. The first two tasks have been completed and task three is near completion. Results expected include controllable hydrogen generation and utilization of waste heat. The demonstration unit provides an energy source which is scaled to provide 3 kWh (assuming the use of a fuel cell with 50% efficiency) for operating reverse osmosis pumps and produce 25 gal/hr potable water from 2 kg of MAGNIC in a saltwater solution.

Reverse Osmosis Desalination

Reverse Osmosis (RO) membrane throughput increases with water temperature over a range of temperatures which are achievable in the field. Literature (Sea Recovery Corp. 1994) and consultations yielded the empirical correlation that, for every 1°C increase in the feed temperature, RO efficiency increases 3% using the membrane for the current RO system. Figure 1 shows this effect. Although the amount of heat is limited by the maximum operating temperature of the membrane (50°C), significant improvements in system energy density can be achieved with just a few degrees increase in feed water temperature.

The present design is being compared with various systems for desalination on the basis of a mass efficiency (ME). ME relates potable water production in gallon per hour (gph) to system weight:

$$ME = \frac{Potable\ H_2O\ gph}{System\ Weight} \qquad (2)$$

ME best characterizes the Army's needs. Figure 2 compares mass efficiencies of MAGNIC systems, with and without waste heat utilization, and a diesel system based on current Army units. A comparison is also included for an optimized MAGNIC system (one that utilizes waste heat and specialty, lightweight materials). Conservatively assessed, MAGNIC reaction systems compete with a diesel system. In addition, MAGNIC desalination is quieter, has a lower heat signature, has no exhaust other than water, and produces only benign byproducts. The fuel cell is the heaviest piece of equipment in the MAGNIC system.

Test System

Figure 3 is a flow diagram of the prototype MAGNIC system. The current RTI MAGNIC reactor was designed and constructed to provide safe, flexible reactions that allow varied experimentation utilizing automated data acquisition. It utilizes an oversized bubble condenser for experimentation, a reactor designed to operate safely at several atmospheres, extensive data monitoring, and feedwater equipment (pumps, reactor, bubble condenser) capable of flow rates well over 300 gph. The experimental tests typically take place over the course of an hour, with startup times minimized through the use of high surface area flakes to warm the reactor. Heat exchange is performed with passive equipment and designed to take advantage of every stage of the process where heat is produced by the system.

Operation at atmospheric pressure simplifies control and safety issues. Low pressure operation also allows for lighter weight equipment throughout the system than in a high pressure demonstration system.

The MAGNIC hydrogen production reactor design is based on empirical optimization of the solid surface area and the reaction slurry volume. An important parameter value is the maximum amount of solid MAGNIC which can be used in the reactor without frothing, which occurs when excess fuel is loaded in the reactor. At boiling conditions, this causes byproducts to become entrained in steam and hydrogen exiting the reactor.

The reactor is a one meter long, twenty centimeter water-jacketed cylinder. A polypropylene filter inside the reactor controls any frothing and byproduct entrainment while providing adequate area for gas/steam escape.

The brine heat exchanger recovers additional heat from the discharged brine leaving the RO desalination unit. Immersion heaters simulate heat from a fuel cell, based on 50% efficiency for the fuel cell and an assumption of an 80% efficient heat exchange between the fuel cell and the brine. A customized bubble condenser is used for H_2 gas drying and heat recovery. Parametric test are being applied to optimize the size of the bubble condenser.

The desalination unit is capable of producing 600 gallons per day (25 gph) potable water operating under standard conditions (25°C, 3.5% NaCl). The unit centers around three reverse osmosis membranes. In addition to the membranes, the desalination unit consists of three high pressure membrane housings, a low pressure pump (10-20 psi), a high pressure pump (800 psi), filters, a salinity probe, and associated monitoring and safety equipment.

The pictures in Figures 4 and 5 show the assembled unit. In Figure 4 the components of the reactor, identified counterclockwise from the bottom left of the skid, are the small centrifugal pump, the bubble condenser, the high pressure pump, the brine heat exchanger (flat plates at bottom right, fins are sandwiched between them), the reverse osmosis desalination unit high-pressure housings, the temperature/pressure indicators and heater control panel, the desalination unit control panel, and the main power disconnect. The low pressure pump is in the rear of the skid behind the reverse osmosis desalination unit high-pressure housings.

In Figure 5, the reactor is seen in the bottom left hand corner. The heater simulating fuel cell waste heat recovery is located behind the reactor. The tank above the reactor is the 20 liter source of 3.5% NaCL solution for the reaction.

Plates of MAGNIC 7-8 mm thick have been used for initial reactions. Similar plates have been used previously in a higher pressure system, with positive results. Under similar, atmospheric conditions, the reaction of the plates provided stable hydrogen production, and maintained constant reaction temperature. Other fuel geometries may be tested, such as 5 x 20 millimeter rods.

The exposed fuel surface area is maintained by proper initial fuel configuration with even distribution throughout the bottom of the reactor. MAGNIC flakes can be distributed in the reactor to provide even warming during startup.

A saltwater solution of 3.5% NaCl is nominal. Operating temperature is reached in five to fifteen minutes depending on the fuel geometry and temperature of water in the reactor jacket. Pump startup initiates desalination and rate and temperature monitoring Potable water production continues until hydrogen production ceases.

Data acquisition software is being used to monitor the reaction temperatures, reactor pressure, and hydrogen flow rate. System process variables are connected to the software through an input module which is monitored by a data acquisition board. The software is running on a 90 MHZ Pentium PC.

Table 1. System Variables Measurements

Inputs Monitored by Data Acquisition Software	reaction duration, hydrogen flow rate, reactor pressure, temperatures throughout the system (TC*x* in Figure 3)
Data Recorded by Personnel	water production rate, brine flow rate, reverse osmosis system pressure, time from reaction start to system readiness for new charge of MAGNIC

Conclusions

With the completion of the prototype unit, RTI has demonstrated the feasibility of a desalination system based on the MAGNIC hydrogen production process and maximized the amount of water produced for system weight. The demonstration system consists of a jacketed reactor, a bubble condenser, heaters(for fuel cell heat recovery simulation), and a brine heat exchanger. These units are integrated with a modular reverse osmosis desalination unit. The MAGNIC reactor system is designed to operate with 2 kg MAGNIC for one hour. The hydrogen produced by the MAGNIC can provide 3 kWh of electrical energy when used in a fuel cell operating at 50% efficiency. Heat energy produced by the MAGNIC reaction and fuel cell operation is recovered by the desalination feed water through several forms of heat exchange. Methods of heat recovery are incorporated in the reactor jacket, the bubble condenser, the brine heat exchanger, and fuel cell heat exchange. By warming the desalination feed water, the flux of potable water through the reverse osmosis membranes increases. This appears to be the best method for waste heat utilization since it adds little weight to the system, uses no complicated equipment, and increases water production. Compared to a diesel-powered unit, the integrated demonstration unit can increase mass efficiency by 34%, based on increases in water production (or decreases in feed water for a fixed rate of production) per unit of system mass. Calculations indicate that an optimized unit can increase mass efficiency 48% over a diesel powered unit.

Acknowledgments

The authors would like to thank Dr. Richard Paur, Dr. Gerald Iafrate, and the Army Research Office without whose support and assistance this work would not have been possible.

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Figure 1. Effect of temperature on water flux and salt removal

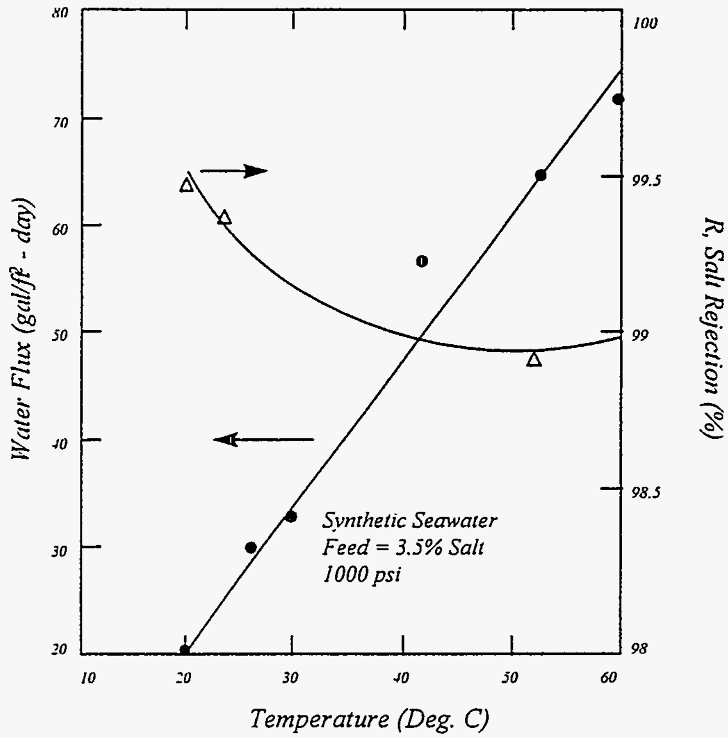


Figure 2. MAGNIC and Diesel Comparison

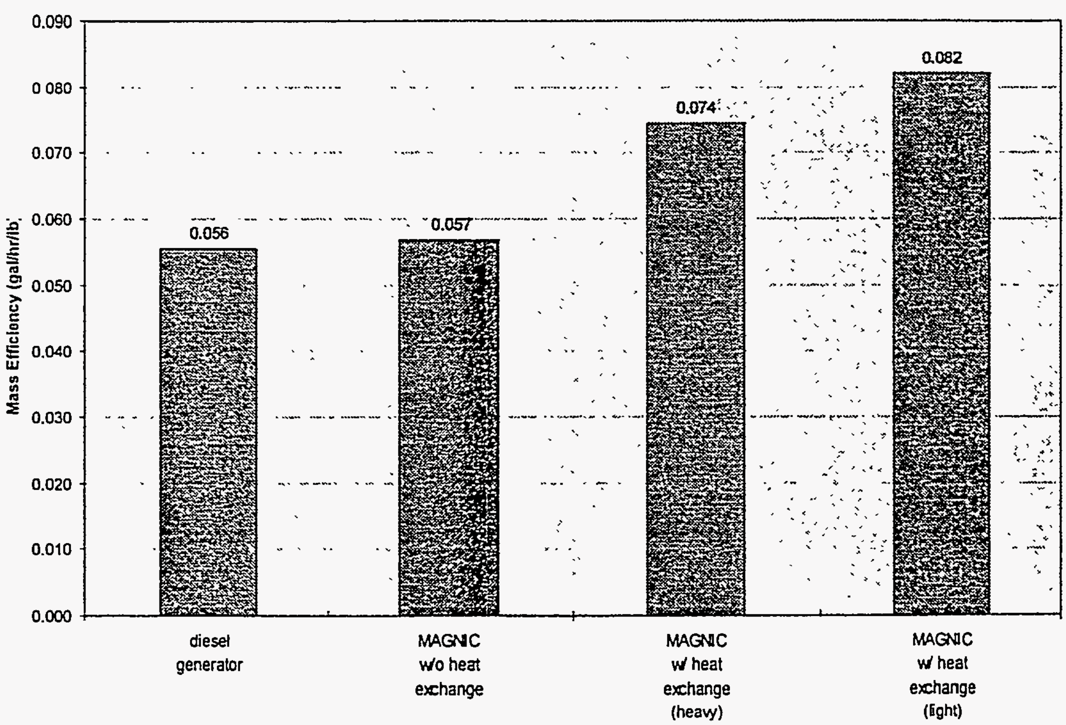


Figure 3. System Flow Diagram

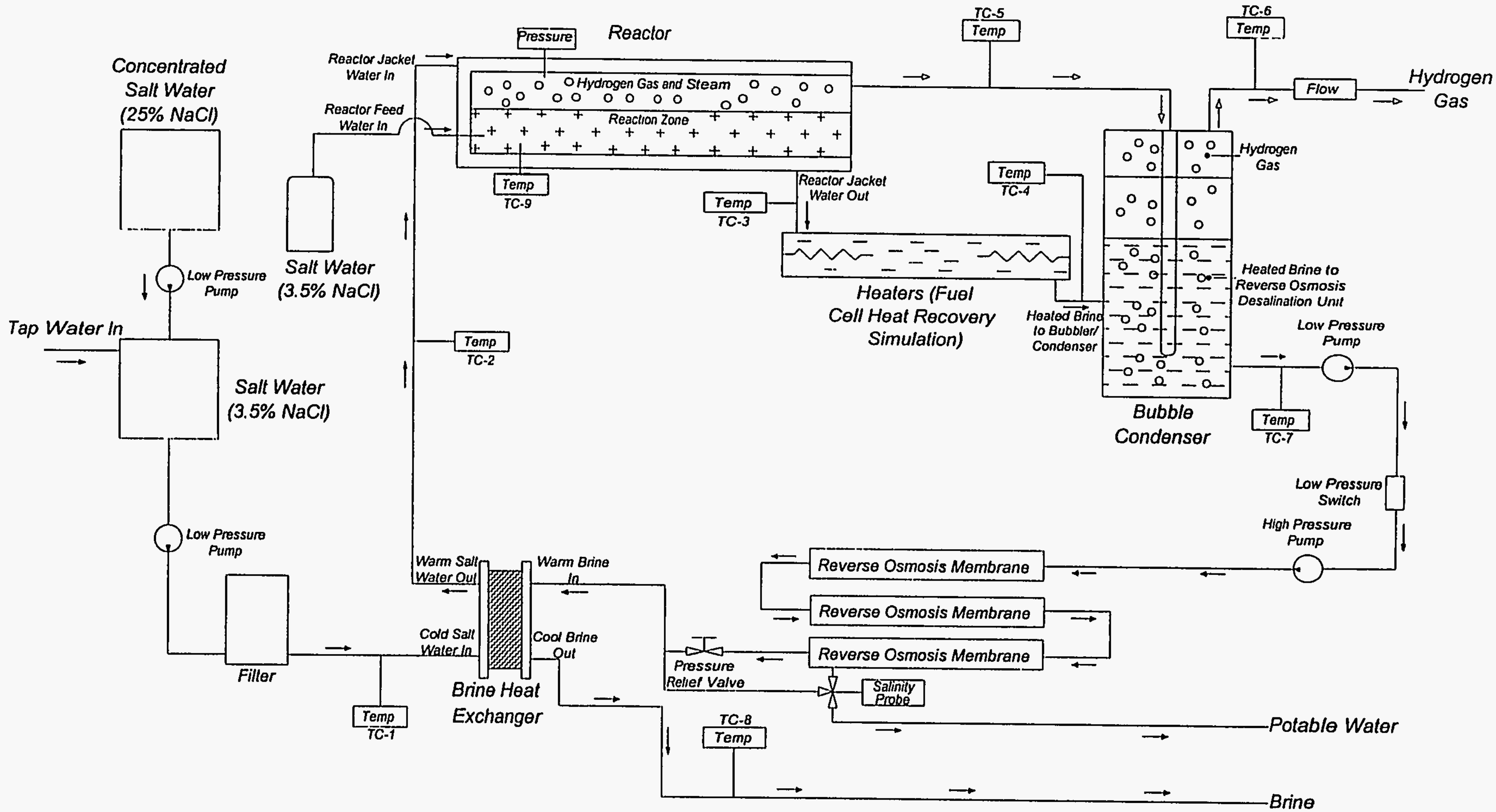


Figure 4. System Front View

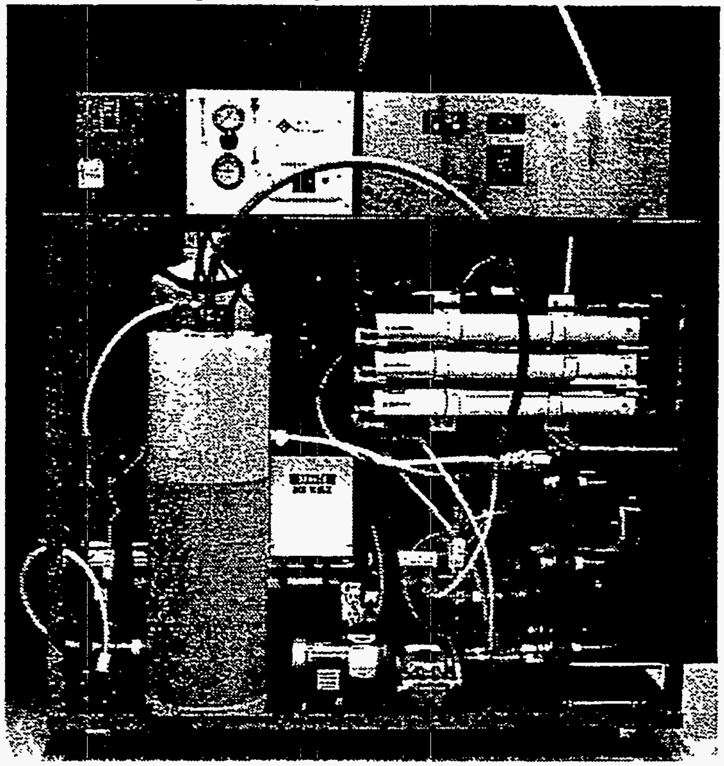
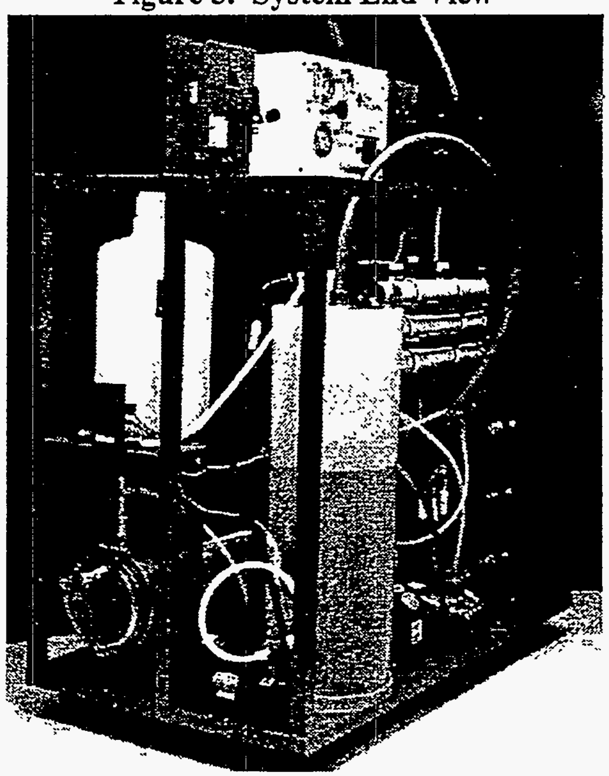


Figure 5. System End View



Composite Metal Membranes for Hydrogen Separation Applications

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Abstract

A novel multilayer metal membrane has been developed that can be used for the separation of hydrogen from feed streams with near perfect selectivity. The membrane is comprised of very thin layers of fully dense palladium film deposited on both sides of a thin Group V metal foil, ion-milled prior to sputtering of the palladium. Palladium loadings are kept low using the thin film deposition technology: 0.0012 grams of palladium per square centimeter of membrane is typically used, although thinner coatings have been employed. This membrane operates at temperatures on the order of 300°C and is capable of high rates of hydrogen flow. Flows are dependent on the pressure differential applied to the membrane, but flows of 105 sccm/cm^2 and higher are regularly observed with differentials below one atmosphere. Long term testing of the membrane for a period in excess of 775 hours under constant conditions showed stable flows and an 85% hydrogen recovery efficiency. A system has been successfully applied to the hydrogen handling system of a proton exchange membrane fuel cell and was tested using a pseudo-reformate feed stream without any degradation in performance.

Introduction

The use of hydrogen gas has become more important in recent years to a variety of high technology areas. The steady depletion of limited-resource fossil fuels, such as light crudes and natural gas, and the associated pollution problems have made hydrogen based energy systems more attractive. In the microelectronics industry, there is a growing need for ultra-high purity gases as the line resolution continues to shrink and impurity tolerance levels become more stringent. Further, ultra-high purity hydrogen gas is needed for ferrous and nonferrous metals processing, chemical and polymer synthesis, and petrochemical processing. These applications, as well as others requiring hydrogen recovery and separation, have created and sustained an interest in hydrogen separation techniques.

The most popular metal used for membrane based hydrogen separation has been, and continues to be, palladium and its alloys. As a result, the hydrogen/palladium system has been thoroughly studied, starting well over one hundred years ago.(Graham, 1866) While palladium is an attractive material because of its catalytic ability to dissociate molecular hydrogen into atomic hydrogen at its surface, several persistent problems remain. First, palladium undergoes a phase transformation which is dependent on the hydrogen concentration in the metal at temperatures below 300°C.(Ho et al 1978; Wicke et al 1978) Further, expansion and contraction of the lattice with varying hydrogen contents leads to embrittlement and fracture of palladium. Some control of this problem can be gained by alloying the palladium with silver. Inclusion of silver has been shown to significantly reduce the critical temperature and pressure for the phase transformation.(Shu et al 1991) While the addition of silver does increase the lifetimes of the membranes, it does not help to significantly reduce the cost of these expensive materials, another problem of palladium based membrane systems. Furthermore, the bulk transport of hydrogen in face-centered cubic metals, such as palladium and its alloys, is considerably lower than in a number of body-centered cubic refractory metals.(Alfeld and Völkl 1978) Zirconium, niobium, tantalum, and vanadium all have significantly higher bulk hydrogen permeabilities than does palladium.(Steward 1983) However, the direct replacement of palladium with these cheaper refractory metals is hindered because these metals passivate to form surface oxides layers, and the surface reaction limits the hydrogen flux. (Buxbaum and Marker 1993)

To exploit the rapid bulk diffusion of hydrogen atoms in the refractory metals, a composite structure can be fabricated where palladium is placed on each side of the refractory metal chosen for its ability to transport hydrogen and to offer structural integrity for the composite membrane. This construction allows the dissociation of the molecular hydrogen into atomic hydrogen by the palladium surface layer, rapid transport of the atomic hydrogen through the refractory metal, and reassociation into molecular hydrogen on the opposite palladium surface. Such a structure has several advantages. First, greater overall hydrogen fluxes are possible because the diffusion is not limited by the fcc structure of the palladium. Because of this, the membrane can be thicker providing improved mechanical/structural properties while still providing acceptable, and even improved, gas fluxes. Second, since the refractory metals are significantly less expensive than palladium, these membranes are much more economical because only two thin layers of palladium are needed. Further, while the Group V metals are subject to hydrogen embrittlement, this regime is only a problem well below room temperature.(Owen and Scott 1972; Schober and Wenzl 1978) Should the palladium layer develop defects, such as those caused by the palladium phase transformation, the membrane would still be functional because the defect would only expose a minute area of the refractory metal. This composite membrane structure is illustrated in Figure 1.

These advantageous properties have been employed by other groups and a number of patent applications have been filed and granted over recent years.(Buxbaum June 1, 1993; Edlund August 18, 1992; Edlund February 28, 1995) However, these groups did not address the problems of surface oxides and contamination on the refractory metals. This group recognized that the hydrogen fluxes could be improved by eliminating the boundary layers to obtain a highly clean surface on the refractory metal and by depositing an exceptionally pure palladium layer with particular crystallographic orientations. A patent application has been filed on this process and material (Peachey et al) and a full description of the initial work has been given elsewhere.(Peachey et al 1996)

Experimental

The fabrication of the composite membrane was done according to a set procedure using foils commercially purchased as light tight. The foil was mounted into a vacuum chamber which was then pumped down to the range of 10^{-6} torr. The foil was then cleaned using an argon ion gun to remove the native surface oxide layer. Without breaking the vacuum, layers of palladium of various thicknesses were sputtered onto the front and back of the foil. Deposition thickness was monitored using a quartz crystal monitor, and the foil was kept at ambient temperature during cleaning and deposition. The deposition thickness could be closely controlled using this technique and allowed low palladium loadings to be obtained. For example, at 5,000Å per side the palladium loading for the membrane was 0.0012 g/cm^2. The composite membrane was fully dense with no residual porosity in either the palladium coating or the metal foil. The quality of the deposition and the starting foil was checked by occasionally using scanning electron microscopy of the cross-section to check for porosity. No porosity was observed and the deposition was found to have good adhesion to the foil.

The membrane test system consisted of a membrane holder unit in which the membrane was sealed between the feed and permeate streams. The feed flows were composed of reagent grade hydrogen and ultra high purity argon and were controlled using mass flow controllers so that mixtures of various compositions could be used. The pressure on the feed side of the membrane was controlled by either pumping using a turbo pump or restricting the flow of the exhaust from the feed side. The permeate flow passed through a mass flow meter to determine the flow rate of gas through the membrane. The pressure on the permeate side of the membrane was also controlled either by pumping or by restricting the permeate flow. The composition of both the feed and permeate gas streams could be analyzed using a Residual Gas Analyzer (RGA). Leaks could be detected by the significant presence of argon in the permeate gas stream, indicating that argon was leaking through or around the seal of the membrane. Figure 2 shows a layout of the membrane testing system.

Results and Discussion

Intrinsic Membrane Properties

To demonstrate the ability of the membrane to only allow hydrogen to pass through, an experiment was set up where a feed gas mixture of equal parts of hydrogen, helium, and argon were introduced into the system. The permeate gas stream was monitored for composition using the RGA. The helium signal is present at intensities over four orders of magnitude below that of the hydrogen signal, no argon signal was discernible from the background. Based on this data, the permeate stream would be approximately 99.998% hydrogen, with the balance helium; this value corresponds to a hydrogen:helium selectivity of 49,999:1. However, the helium signal is in the lower range of detection of the RGA, and the certainty of its value is not high. As a result, the actual hydrogen purity may be higher than was calculated from the raw numbers. The slight presence of helium is not totally unexpected because the palladium film and vanadium foil were polycrystalline. Thus, some flow of helium could take place along the grain boundaries, especially with its small size. Also, any flaws in the seal around the membrane might allow a small amount of helium to leak through.

If the properties have been properly engineered, the composite membrane must also show increased performance to that seen by pure palladium. This was tested by comparing a multilayer metal membrane with a thickness of 0.5 μm of palladium on both sides of a 40 μm vanadium foil to a sheet of palladium foil with a thickness of 40 μm. Both membranes were tested at 300°C membrane temperature, 200 sccm feed flow rate, and an identical feed pressure range to produce a fair comparison. The results are shown in Figure 3. From this, it is possible to see that the use of the composite membrane provides far superior performance in terms of the membrane flow rate compared to that of pure palladium. At a pressure differential of just over half an atmosphere, i.e., 20 $torr^{0.5}$, the flow rate per area through the composite membrane was 105 $sccm/cm^2$ compared with 6 $sccm/cm^2$ for the palladium foil. Thus, the composite membrane showed an improvement of a factor of almost twenty in the flow rate over the pure palladium membrane. This increase shows that it is indeed possible to increase the hydrogen flow by replacing the bulk palladium that has low transport rates with a material that has much higher transport rates.

The long term performance of the membrane must be properly addressed because the membrane must be able to withstand long periods of operation without degradation. The flow rate as a function of time in a 575 hour test is shown in Figure 4; this experiment was run at a membrane temperature of 300°C, feed pressure of 600 torr (ambient pressure in Los Alamos, NM), permeate pressure of 17 torr, a hydrogen flow rate of 100 sccm and an Ar flow rate of 35 sccm. The flow rate per area of membrane was stable at 7.78 sccm per cm^2 which is a low flow rate for this membrane system. However, that value corresponded to an 84% efficiency, i.e., 84% of the hydrogen in the feed stream was transported across the membrane. The experiment ended when the hydrogen D-cylinder emptied and could have conceivably continued for many more hours. This membrane was tested for an additional 200 hours under a variety of flow rates and feed pressures prior to the 575 hour test, making the total testing time 775 hours.

Another area of interest is the determination of the limiting step within the membrane for hydrogen transport. The overall transport process can be broken into three steps that must occur at or in the membrane. The first step is the molecular hydrogen adsorption onto the palladium surface and dissociate into atomic hydrogen. The next step is the atomic hydrogen diffusion into, through, and out of the bulk metals. Finally, the atomic hydrogen re-associates into molecular hydrogen on the downstream palladium layer and desorbs from the surface. If the transport process is limited by either step one or three, then the flow rate of hydrogen through the membrane is a linear function of the hydrogen pressure differential between the feed and permeate sides. If the bulk diffusion of the atomic hydrogen limits the flow rate, the transport rate becomes governed by Sievert's law and is a linear function of the differential of the square root of the hydrogen partial pressure. Based on a series of experimental conditions, it was determined that the flow rate was best fit by using the square root of the differential pressure, as the data presented in Figure 3. Because the hydrogen permeability of palladium is several orders of magnitude lower than vanadium, it is expected that the palladium is limiting the transport rate, and thinner palladium should yield higher flow rates.

A comparison of membranes with two thicknesses of palladium is shown in Figure 5: 0.5 μm Pd/40 μm V/0.5 μm Pd and 0.1 μm Pd/40 μm V/0.1 μm Pd. In this Figure, the flow rate per area for the 0.1 μm deposition thickness is slightly higher than that from the 0.5 μm thickness, indicating that the resistance to flow was lowered by decreasing the palladium thickness. Also, it is worth noting that the state of the art for palladium membranes actually uses a palladium-silver alloy, instead of pure palladium. These alloys show approximately a factor of two improvement in hydrogen permeability compared with pure palladium.(Shu et al 1991) Changing to a palladium alloy for the deposited layers should also increase the flow rate through the membrane.

Applications

The membrane may be applied to a number of different areas and technologies that require ultra-high purity hydrogen or high efficiency hydrogen recovery. Among these applications are semiconductor processing, commercial gas purification, metals processing, chemical and polymer synthesis, exhaust stream recovery, and environmental remediation. However, a technology of particular interest is that of proton exchange membrane fuel cells (PEMFC). A major drawback of the PEMFC is that the anode of the fuel cell is easily poisoned by the presence of CO in the range of parts per million within the hydrogen stream. As a result, either an ultra-high purity hydrogen supply is needed or an impure gas supply must pass through shift and partial oxidation reactors to effectively oxidize the CO to CO_2. The use of a membrane separation system could replace the need for the shift and PROX reactors because the membrane would only allow hydrogen to pass and would exclude any CO from the anode.

A PEMFC was operated at Los Alamos National Laboratory in the configuration described above, where a pseudo-reformate gas mixture was introduced into a separation system before entering into the fuel cell. The pseudo-reformate gas supply was simulated for a CH_3OH reformate feed and composed of 1% CO, 24% CO_2, and 75% H_2. The membrane system was operated at an external temperature of 315°C. The PEMFC was a 5 cm^2 single cell, and the results are shown in Figure 6. The performance of the fuel cell showed a current density of 600 mA/cm^2 at 0.6 V. In contrast, the presence of only 100 ppm CO in the hydrogen fed directly into the anode suppressed the current density at this voltage to about 60 mA/cm^2, one tenth the cell performance. This application shows that the membranes have very high selectivity between H_2 and CO, as can be further evidenced by the degradation in the performance of the fuel cell at even 20 ppm CO.

Conclusions

A novel multilayer metal membrane has been developed that can be used for the separation of ultra-high purity hydrogen from impure feed streams. The membrane is comprised of very thin layers of dense palladium film deposited on both sides of a thin metal foil. One of the palladium layers provides the catalytic activity to break the molecular hydrogen into atomic hydrogen. The metal foil is selected for its ability to transport atomic hydrogen and provides some structural stability for the membrane. The other palladium layer re-assembles the atomic hydrogen into molecular hydrogen.

The membrane was tested using mixtures of hydrogen, helium, and argon to show that hydrogen permeation with high H_2:He selectivity was possible. Flows through the membrane were almost a factor of twenty higher than that of pure palladium with the same total thickness. The composite membrane showed a flow rate per area of 105 sccm/cm^2 with a half atmosphere differential. The membrane showed stable flows under consistent conditions 575 hours, and the same membrane was run for 775 total hours without breaking or deteriorating. The limiting transport mechanism was identified to be the diffusion of the hydrogen through the bulk metals, rather than the adsorption onto the palladium surface. Further, the flow rate per area could be increased by decreasing the palladium thickness.

The uses for this membrane center around areas which require ultra-high purity hydrogen or need hydrogen recovery from an impure gas stream. A membrane system has been successfully applied to a PEMFC, where it would replace the shift and PROX reactors that are needed to remove CO from the hydrogen supply. The membrane system was tested using a pseudo-reformate (CH_3OH) feed stream containing 1% CO without any degradation in the fuel cell performance. When the same fuel cell was run with as little as 20 parts per million carbon monoxide, the fuel cell showed a serious reduction in performance.

Acknowledgments

The authors wish to thank Mahlon Wilson and Shimshon Gottesfeld of Los Alamos National Laboratory for the fuel cell measurements.

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Figure 1. The multilayer metal membrane is composed of thin layers of palladium on the top and bottom of a Group V metal.

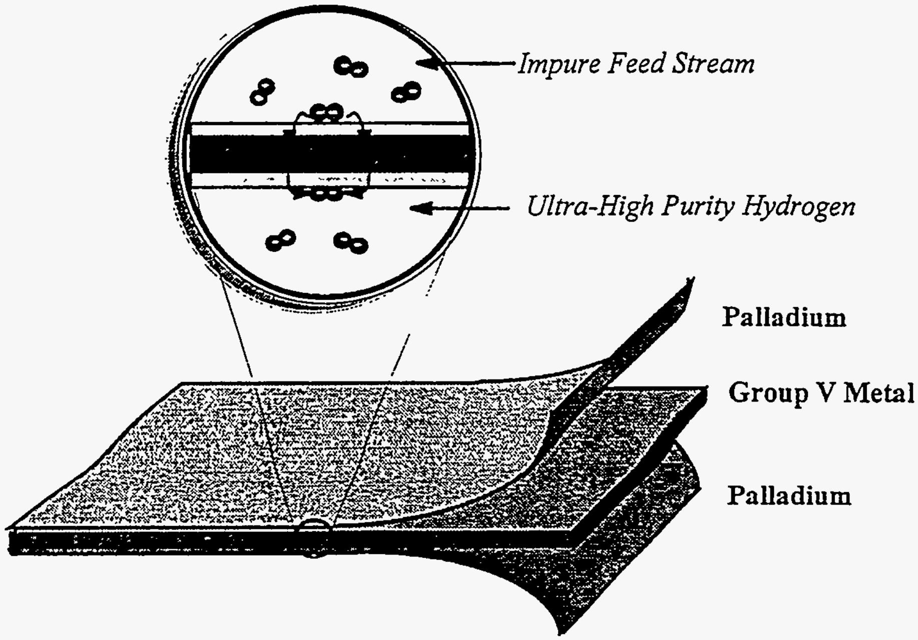


Figure 2. The testing system can test the membrane under a variety of conditions.

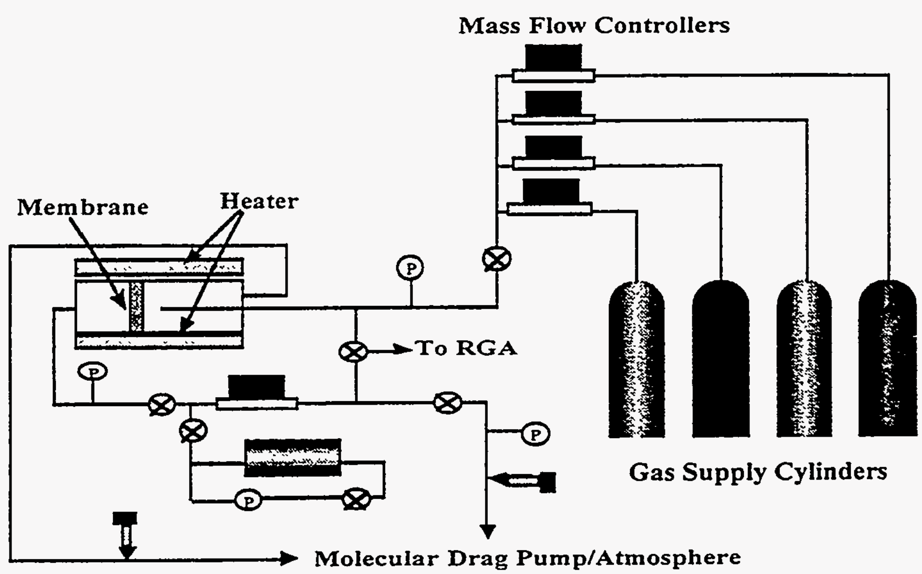


Figure 3. The composite membrane shows an order of magnitude increase in performance over a pure palladium membrane.

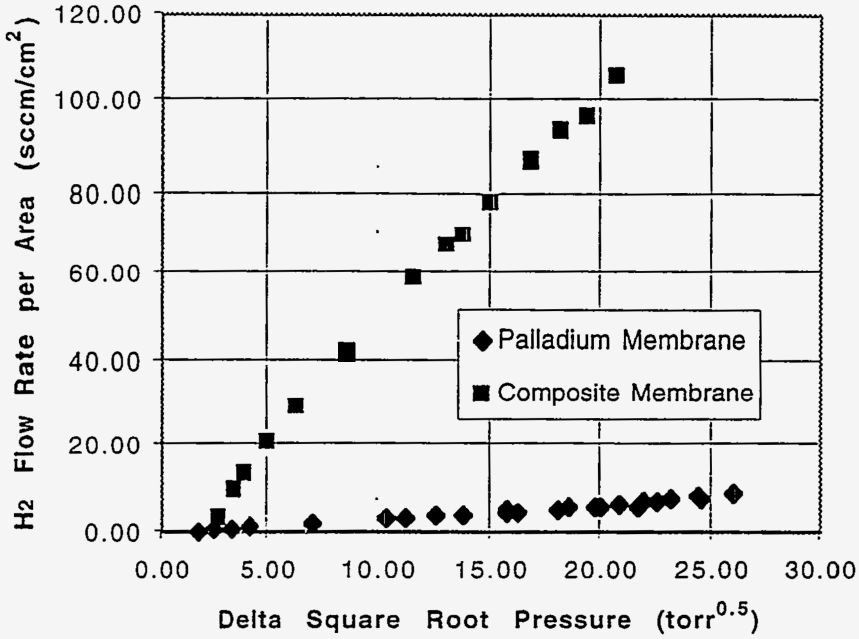


Figure 4. The hydrogen flow is stable at 7.78 sccm per cm^2 membrane and 84% efficiency in this 575 hour test.

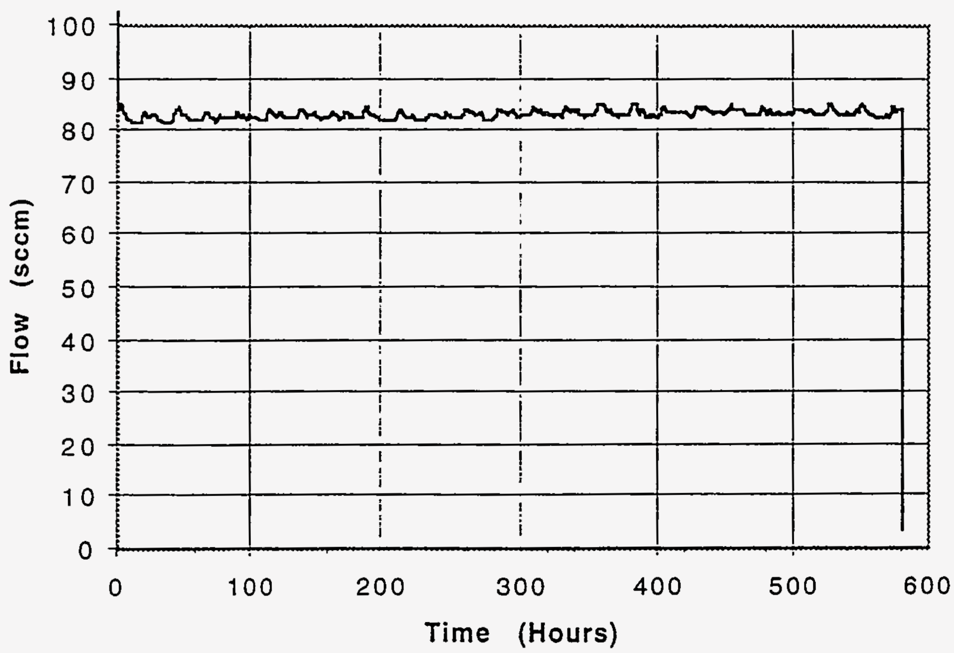


Figure 5. The performance of the membrane with 1,000Å of palladium on each side is slightly better than that with 5,000Å.

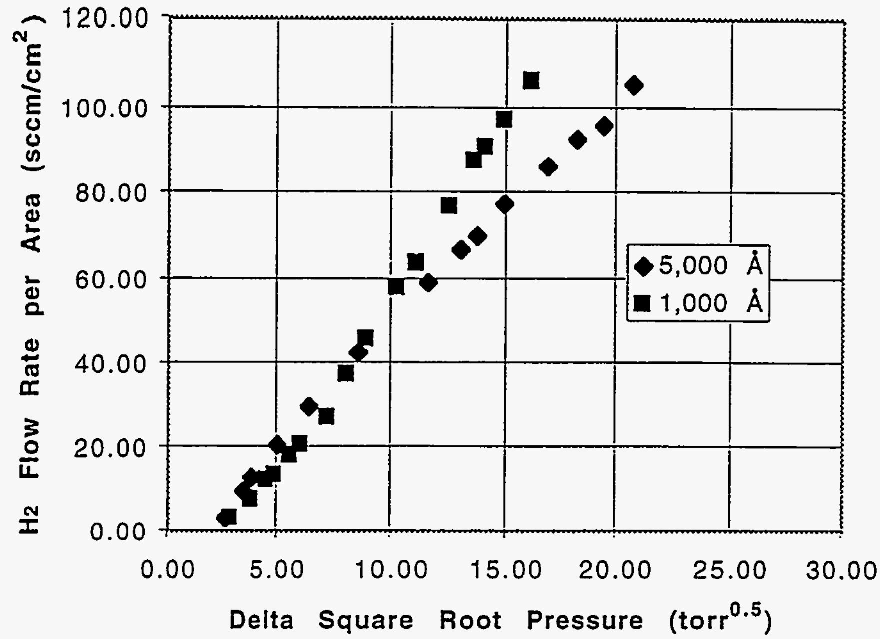
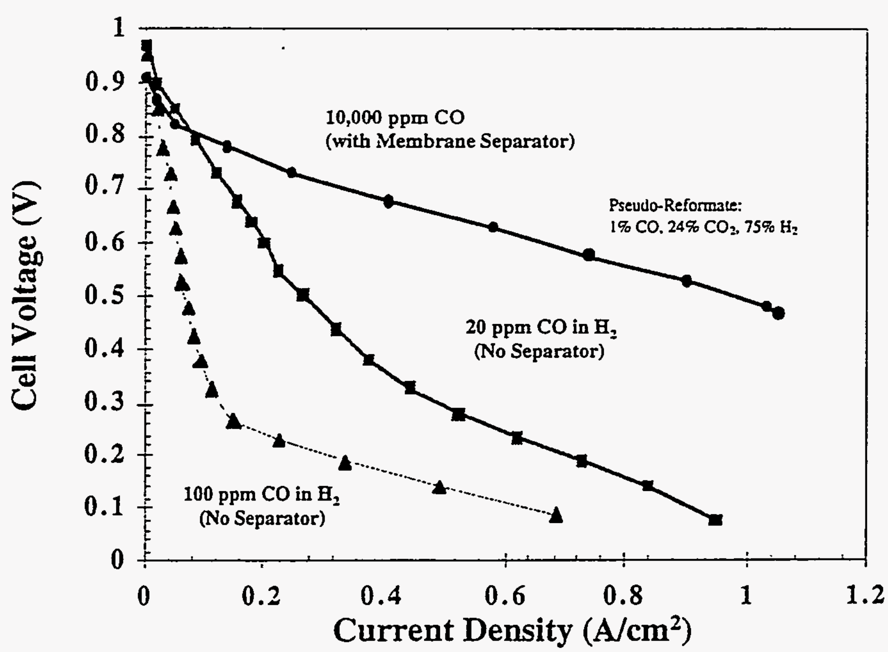


Figure 6. Current-Voltage curves depicting a single cell PEMFC operating at 80°C on (a) pseudo-reformate (1% CO) fed through a hydrogen membrane separator, (b) 20 ppm CO in hydrogen, and (c) 100 ppm CO in hydrogen.



HYDROGEN PRODUCTION FROM WATER: RECENT ADVANCES IN PHOTOSYNTHESIS RESEARCH

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The great potential of hydrogen production by microalgal water splitting is predicated on quantitative measurement of the algae's hydrogen-producing capability, which is based on the following: (1) the photosynthetic unit size of hydrogen production; (2) the turnover time of photosynthetic hydrogen production; (3) thermodynamic efficiencies of conversion of light energy into the Gibbs free energy of molecular hydrogen; (4) photosynthetic hydrogen production from sea water using marine algae; (5) the potential for research advances using modern methods of molecular biology and genetic engineering to maximize hydrogen production.

ORNL has shown that sustained simultaneous photoevolution of molecular hydrogen and oxygen can be performed with mutants of the green alga *Chlamydomonas reinhardtii* that lack a detectable level of the Photosystem I light reaction. This result is surprising in view of the standard two-light reaction model of photosynthesis and has interesting scientific and technological implications. This ORNL discovery also has potentially important implications for maximum thermodynamic conversion efficiency of light energy into chemical energy by green plant photosynthesis. Hydrogen production performed by a single light reaction, as opposed to two, implies a doubling of the theoretically maximum thermodynamic conversion efficiency from ≈10% to ≈20%.

The following publications may consulted for additional information contained in this talk:

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E. Greenbaum, J. W. Lee, C. V. Tevault, S. L. Blankinship, and L. J. Mets, "CO_2 Fixation and Photoevolution of H_2 and O_2 in a Mutant of *Chlamydomonas* Lacking Photosystem I," *Nature* **376**, 438-441 (1995).

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GENERAL SESSION IV:

Opportunities for Partnership in the Utility Market

Electric Industry Restructuring Impacts on Utility RD&D

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NHA Annual Meeting

March 1997

Utility Restructuring

- California Utility Restructuring -
  The Basics
- Special Funding for RD&D -
  The “PGC”
- Municipal Utility Issues -
  SMUD’s Programs
- The opening of New Market Opportunities

Names and Players

- AB 1890 - California's Omnibus Electricity Restructuring Bill; September 1996
- California Public Utility Commission
  - Applies AB 1890 to Investor Owned Utilities
- Municipal Boards
  - Apply AB 1890 to Municipal Utilities
- California Energy Commission
  - Applies AB 1890 to RD&D and Renewable Resource Projects

More Names

- LDC's - Local Distribution Companies
- PowEx - Electricity Commodity Market
- ISO - Independent (Transmission) System Operator
- CTC - Competition Transition Charge
- PGC - Public Good (Fund) Charge

AB 1890 Provides for

- 20% min Rate reduction by April 2002
- Separate monopoly utility transmission from competition in Generation Market
- All customers to choose from competing electricity suppliers
- Open, nondiscriminatory, and comparable access to Transmission and Distribution Services.

AB 1890

- Transition Starts 1/1/98 - Is Fully Open Market by 12/31/2001
- Strongly encourages IOU's to Divest Generation Assets
- Encourages and provides pathway for IOU's to recover stranded investment through CTC (1998-2001)
- Establishes Public Good Fund Charge

Public Good Fund

Research, Environmental, and Low-Income Funds

- Article 7 Requires IOU's to collect more than $475 Million per year for
  - Energy Efficiency
  - Renewable Energy
  - Research, Development, & Demonstration
  - Low Income Assistance
- Funds to be given to CPUC / CEC for disbursement

Article 8, Publicly Owned Utilities

385. (a) Each local publicly owned electric utility shall establish a nonbypassable, usage based charge on local distribution service not less than the lowest expenditure level of the three largest electrical corporations in California on a percent of revenue basis...

Article 8, Publicly Owned Utilities

to Fund Investments by the utility and other parties in any or all of the following:

(1) Cost effective demand-side management services to promote energy-efficiency and energy conservation.

(2) New investment in renewable energy resources and technologies... which promote those resources and technologies.

(3) Research, development, and demonstration programs for the public interest to advance science or technology which is not adequately provided by competitive and regulated markets.

(4) Services provided for low-income electricity customer, including but not limited to targeted energy efficiency service and rate discounts.

(3) Research, development, and demonstration programs for the public interest to advance science or technology which is not adequately provided by competitive and regulated markets.

1998 Public Good Funding

Energy Efficiency	$ 228	Million
Renewable Resources	$ 110	
Research & Develop.	$ 64	
Low Income	$ 73	
Total	$ 475	Million

Renewable Energy Fund

- CEC (within AB1890 Guidelines) determining who gets it, and how
- Draft allocates: 45% Existing, 30% New, 10% Emerging (PV), 15% Consumer-side Accounts
- CEC will recommend to Legislature by 3/31/97

R D & D

Working Group formulating Allocation and Administration Guidelines

- Draft Plan — April 15, 1997
- Final Plan — June 25, 1997
- Funds start to collect — Jan '98
- First $'s Awarded — Summer '98

SMUD's Public Good Fund

40% Greater than AB 1890 Minimum

Two Parts of SMUD's Public Goods Charge :

- **New Renewables**

  $ 3.7 million per year

- **Research & Development**

  $ 1.9 million per year

Research & Development

- Clean Generation Research
- Customer Advanced Technologies
- Electric Vehicle (R&D)

Public Good Fund Concept
vs
Minimum Renewable %

- Both have same goal
- Will outcome be Synergistic or Counter Productive ?
- National Marketing Plans must embrace both

Where to Get More Information

- RD&D and Renewable Energy Info

  www.energy.ca.gov

- Investor Owned Utility Directives & Info

  www.cpuc.ca.gov

- SMUD and Municipal Utility Info

  www.smud.org

Hydrogen Program Structure

- **Core Research and Development**
  - **Production**
  - **Storage**
  - **Utilization**
- **Technology Validation**
- **Analysis and Outreach**

Hydrogen Production: Goals

Fossil Derived Hydrogen Goals

- **FY1999 Demonstrate 20% reduction in energy cost using sorbent enhanced reforming Process Development Unit (PDU)**
- **FY2000 Demonstrate improved reforming efficiency to achieve 25% reduction in capital cost with Ion Transport Membrane Technology**

Photobiology R&D Goals

- **FY 2000 Demonstrate biological shifting of carbon dioxide to hydrogen in an Engineering Development Unit**
- **FY 2002 Demonstrate hydrogen production for two step microalgal process in a PDU**

Storage and Utilization: Goals

- **FY 1999 Demonstrate a storage system with desorption temperature of 150 degrees C and a weight percent greater than 5.5.**
- **FY 1997 Demonstrate 46% efficiency Hydrogen ICE**
- **FY 1999 Demonstrate a reversible fuel cell system with electricity produced at $0.06 per kWh**
- **FY 2000 Commercialize hydrogen sensor based on palladium solubility**
- **FY2000 Develop design/safety handbook for hydrogen systems with IEA**

Technology Validation: Goals

- **To support industry in the development and demonstration of hydrogen systems in the utility and transportation sectors**
  - **Renewable/Hydrogen Utilities**
  - **Clean Hydrogen Corridors and on-board storage systems**

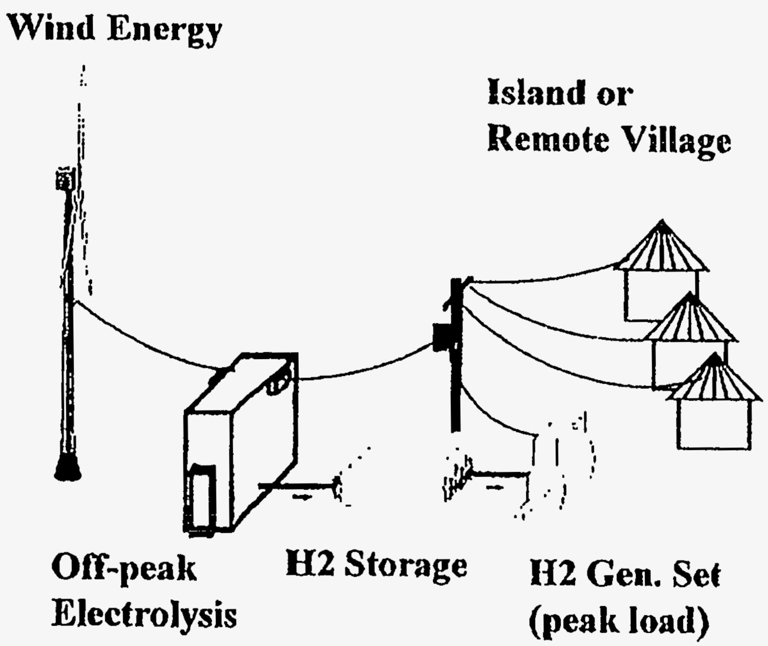
DOE Technology Validation Activities Supporting Hydrogen Pathways

- Integration with Renewable systems for distributed and dispatchable utility applications,
- Clean Hydrogen Corridors,
- Palm Desert, and blended-fuel tests and evaluations
- Solicitations:
  - NOI (near-term applications, biomass, hydrogen production options awarded)
  - PRDA (storage and fuel cell systems)

Near-term Opportunities for Hydrogen

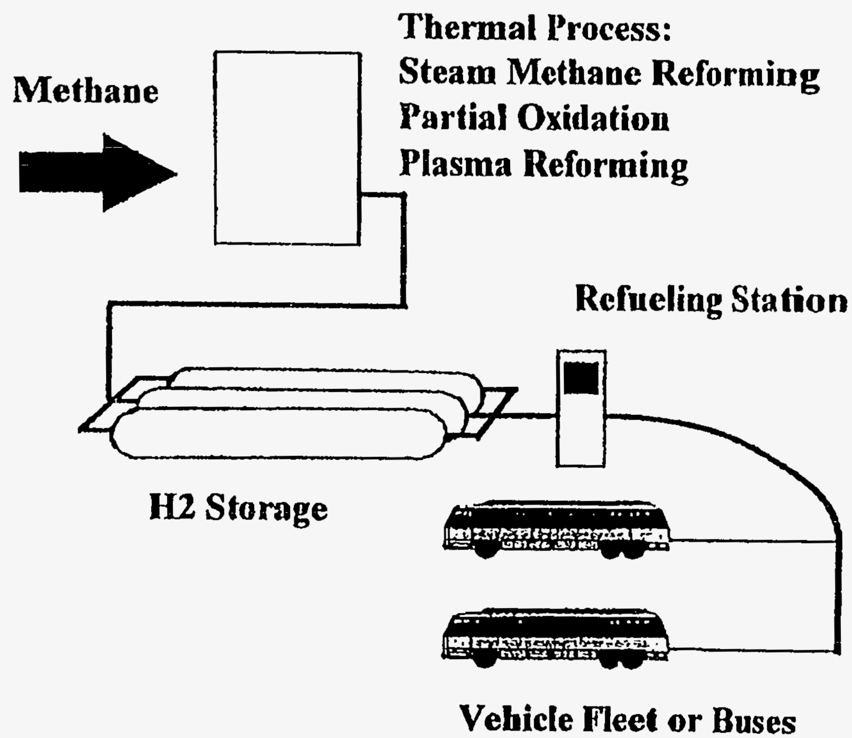
Utility Sector

(Remote Village Technology Validation)

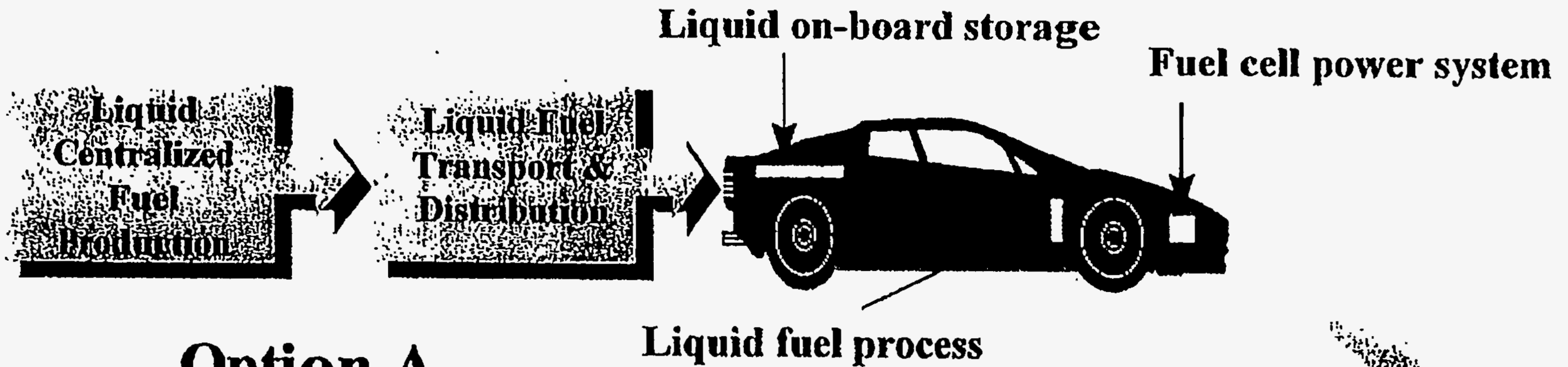


Transportation Sector

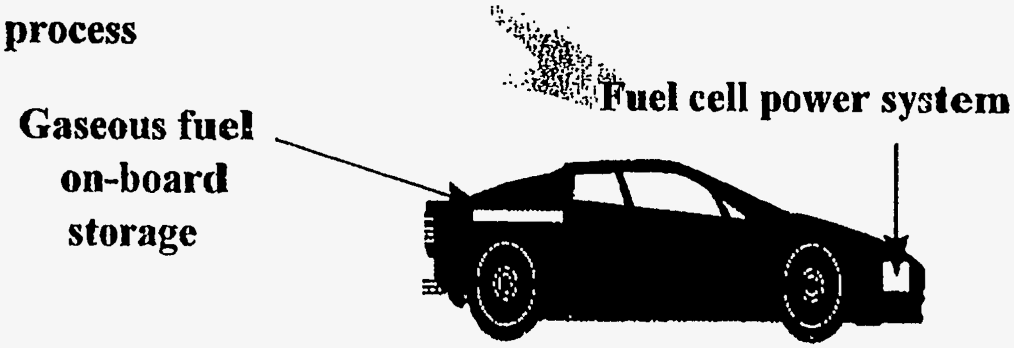
(Distributed Fueling Station Technology Validation)

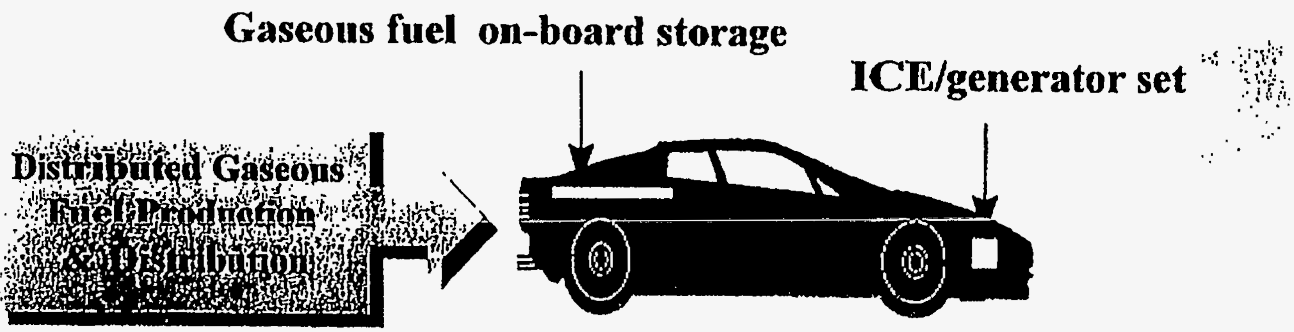


Alternative Vehicle System Options



Option A





Option B

Option B -- Hydrogen to Markets

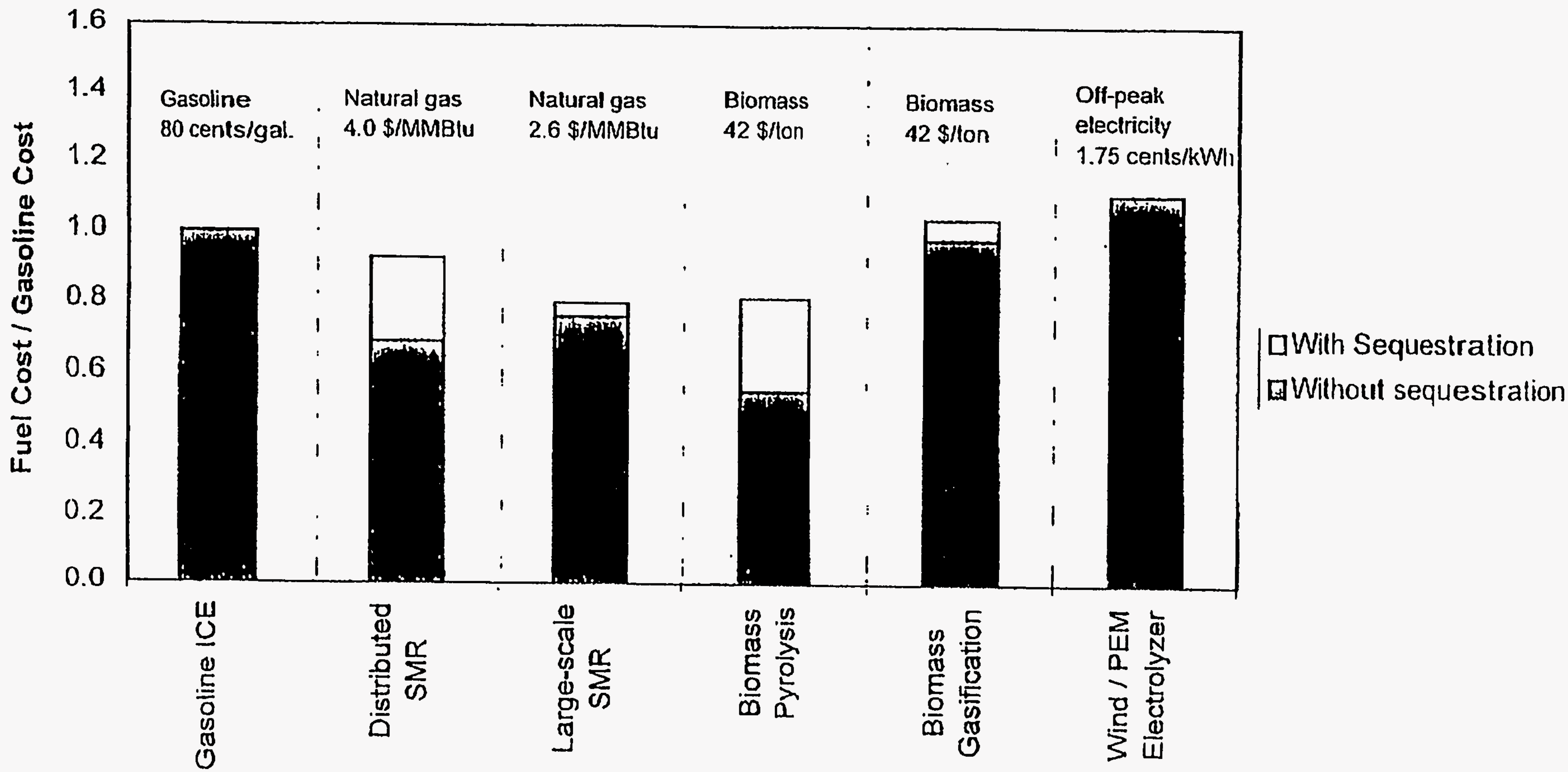
Advantages of Option B

- Low cost, domestic resource
- Low C/H2 ratio
- Higher performance
- Simpler system
- Compatible with carbon sequestration

Disadvantages of Option B

- No infrastructure
- Safety liability

Cost of Hydrogen Delivered to a Vehicle at Pressure Compared to Gasoline (near-term vehicle efficiencies)



Gasoline vehicle efficiency 28 mpg, gasoline cost $0.80/gallon, FCV efficiency 93 miles per kg.

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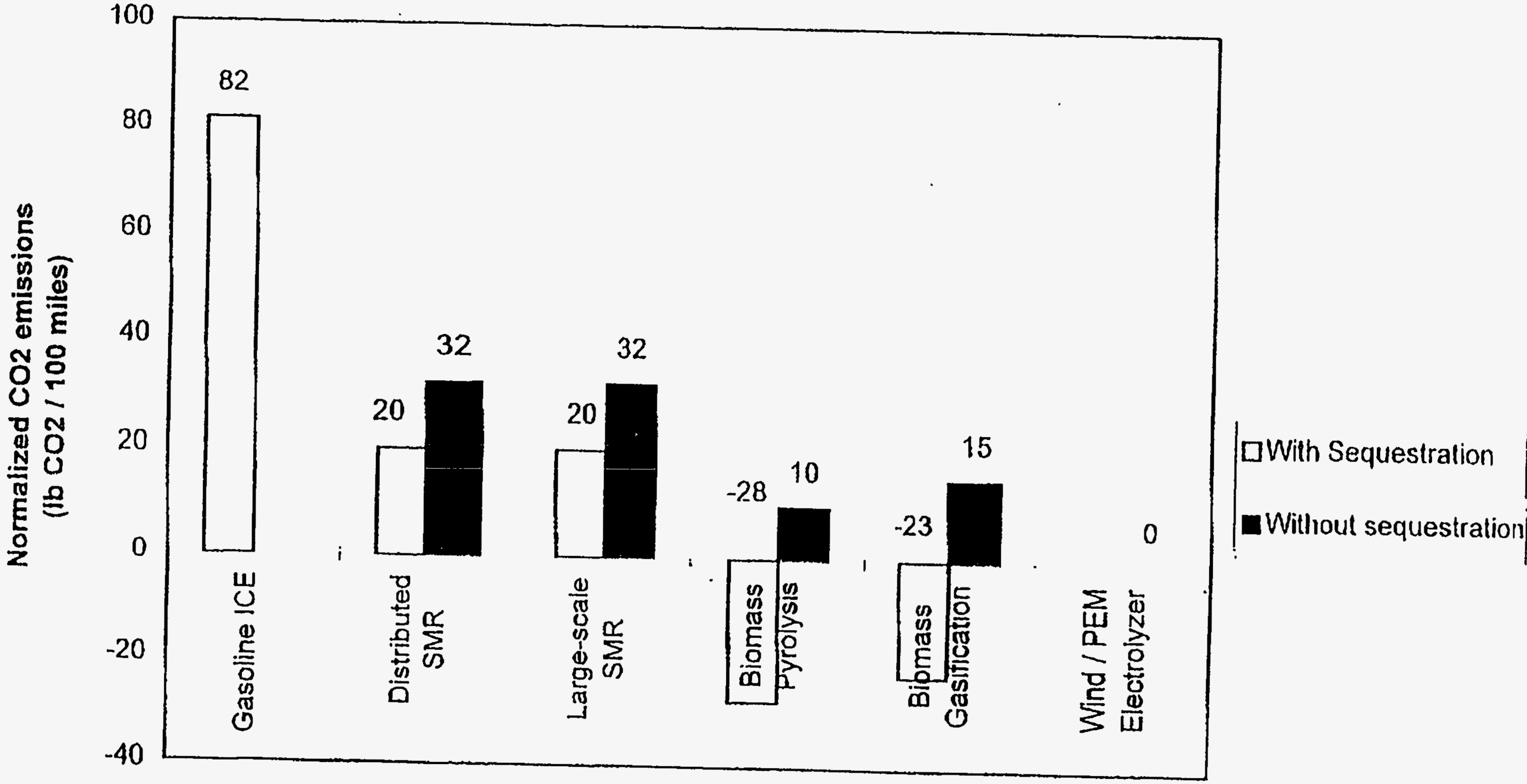
Full Life Cycle Carbon Dioxide Emissions for Hydrogen Options Compared to a Gasoline ICE (near-term vehicle efficiencies)



Gasoline ICE efficiency 28 mpg, FCV efficiency 93 miles per kg H2

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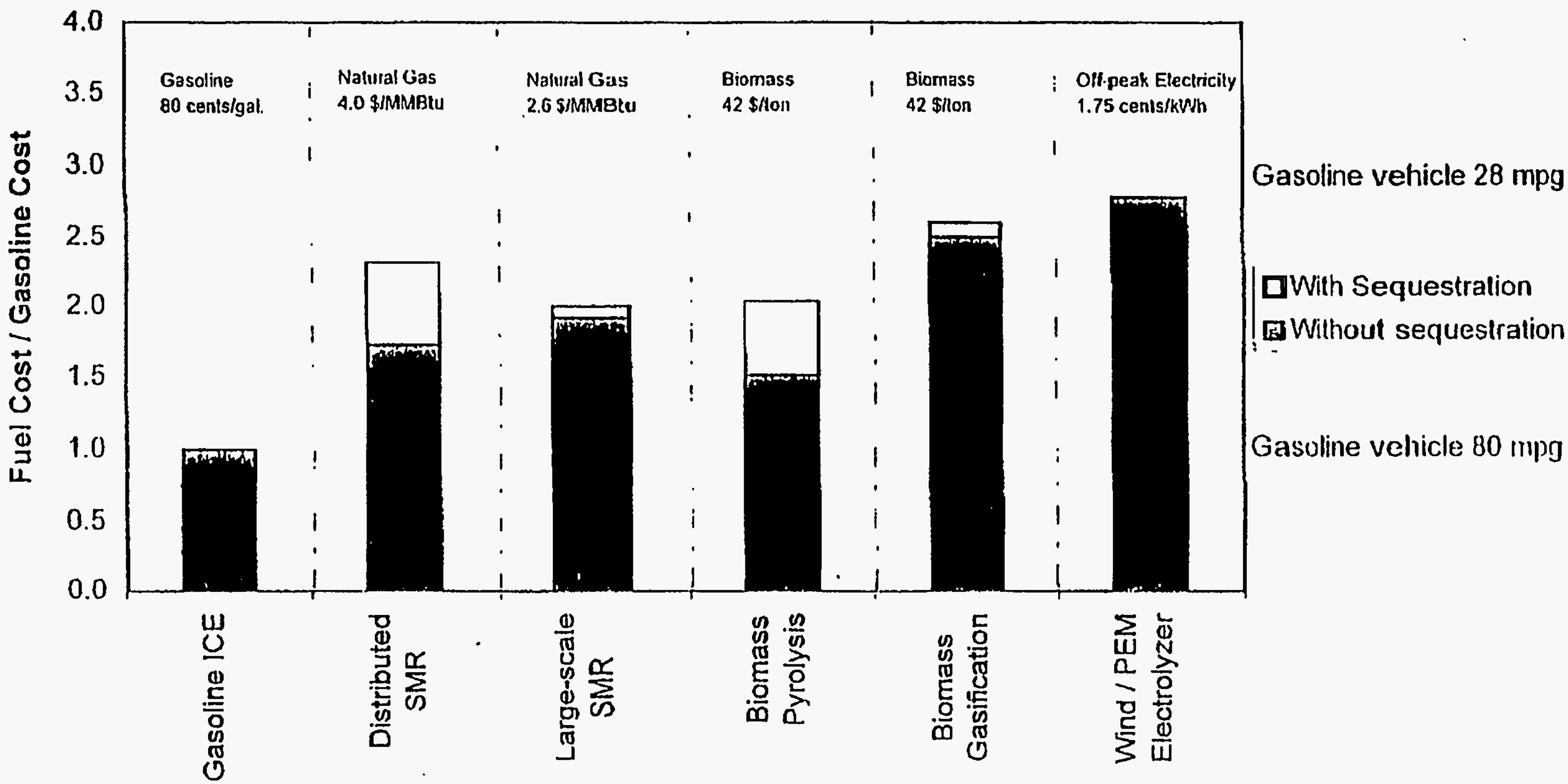
Cost of Hydrogen Delivered to a Vehicle at Pressure Compared to Gasoline (advanced vehicle efficiencies)



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FCV efficiency 106 miles per kg.

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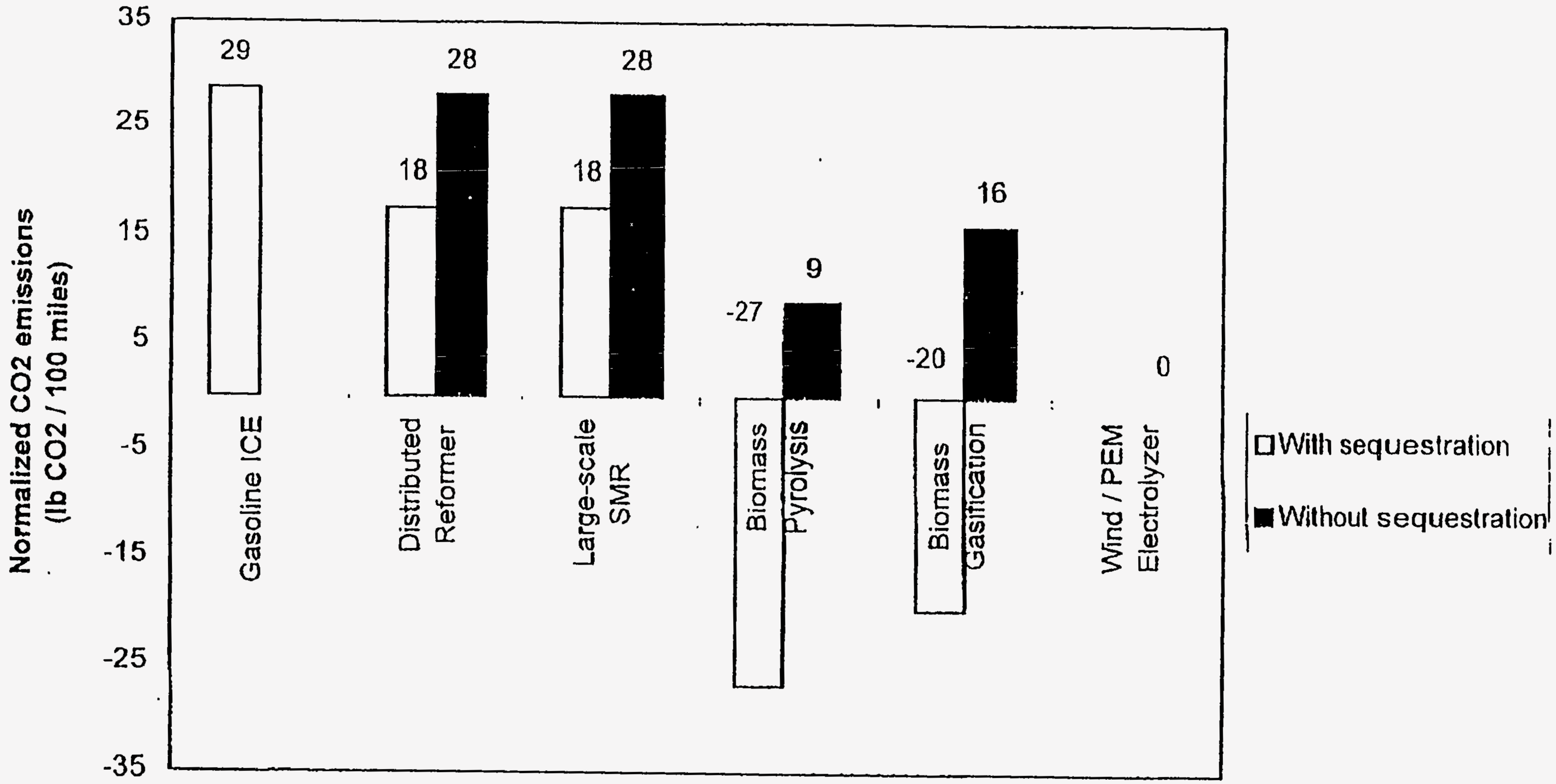
Full Life Cycle Carbon Dioxide Emissions for Hydrogen Options Compared to a Gasoline ICE (advanced vehicle efficiencies)



Gasoline ICE efficiency 80 mpg, FCV efficiency 106 miles per kg H2

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List of Solicitation Awards

SCOPE OF WORK	INDUSTRY
<u>Near-term Application</u>	
Integrated Hydrogen PEM Fuel Cell Systems	International Fuel Cells (IFC)
Fuel Cell Power Systems for Remote Applications	Teledyne Brown Energy
An Integral PV Electrolysis Metal Hydride Hydrogen Generating System	Energy Conversion Devices
Feasibility Study of Industrial Fuel Cell Vehicles	Southeastern Technology Center
An Integrated Hydrogen Energy System for Niche Markets in Florida	Bruderly Engineering
<u>Biomass Gasifiers</u>	
Hydrogen Power From Integrated Biomass Gasification and Molten Carbonate Fuel Cells	MC Power/IGT
Hydrogen Production by Supercritical Water Biomass Gasification	General Atomics
<u>Hydrogen Production</u>	
Integrated Hydrogen Generator System	IFC/Praxair
Filling up With Hydrogen 2000	Electrolyzer Corporation

Summary

- Many opportunities exist in utility and transportation sectors for hydrogen energy systems in the near-, mid-, and long-term
- Research, development, and validation activities will help to achieve hydrogen price goals make hydrogen technologies competitive in the marketplace
- Global Climate Change is a potential significant driver for the development of hydrogen systems
- A full transition toward a hydrogen economy can begin in the next decade.

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Commercializing Proton Exchange Membrane Technology to Enable Low Cost Distributed Hydrogen Production

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Presented at the
National Hydrogen Association's
8th Annual U.S. Hydrogen Meeting
March 13, 1997

Commercializing Proton Exchange Membrane Technology to Enable Low Cost Distributed Hydrogen Production

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Abstract

Advances in power generation technology, coupled with restructuring of the power industry itself, will mean lower power costs to everyone. Power intensive processes, including electrolysis of water into pure hydrogen and oxygen, will be major beneficiaries. One particularly appealing means of generating hydrogen to meet the needs of distributed hydrogen markets is Proton Exchange Membrane (PEM) technology.

PEM technology has a three decade lineage beginning at General Electric and evolving at United Technologies Corp., with successful deployment into a host of military and aerospace life support applications. Recently, a group has left United Technologies to form PROTON Energy Systems to pursue commercial market opportunities for the technology.

PROTON is presently focused on becoming the leading supplier of PEM-based electrolytic hydrogen generating equipment to the established hydrogen industrial gas market. In this regard, PROTON has introduced its first product series, the HOGEN™ 300, which will produce 300 standard cubic feet per hour of very pure hydrogen. PROTON's plan for low cost manufacturing, coupled with falling power prices, will enable hydrogen to be generated at the point-of-use with all-in costs significantly lower than conventionally delivered hydrogen. PROTON's units will be sized to meet the on-site needs of industrial gas markets today and will provide a design base that can transition to serve the needs of a decentralized hydrogen infrastructure tomorrow.

Introduction

We are all of us caught up in technology revolutions, often seeing their impacts well before recognizing the underlying forces at work. By now, most of us appreciate and understand how Moore's law—which says the cost of computational power falls by half every 18 months—will profoundly influence our lives. We see the effect of that powerful force in all manner of every day activity.

The Revolution Underway in the Power Industry

A less obvious but no less pervasive force is at work in the power industry. Less than 10 years ago, the "going price" of a large power generating plant was $ 900 per installed Kilowatt (Kw). Today's price for a gas fired combined cycle plant is $450. And the efficiency of today's plants is 54%, versus 38% only a decade ago.

As a consequence of these cost reductions, the life-cycle cost of electricity from today's plants is less than 3 cents per Kwh, versus 6 or 7 cents/Kwh just a decade ago. Power prices are falling and will stay low. These low costs are beginning to find their way into retail rates; industry restructuring now underway in a growing number of states is driven by the political and economic urge to see these lower costs channeled directly to end use customers. It is nothing short of extraordinary that the most pervasive, capital intensive system that touches our daily lives—the electric power network—is about to deliver end user price reductions on the order of one-half.

Reexamining the Economics of Electrolysis

What, you may ask, does any of this have to do with hydrogen? Maybe more than any of us realize. The impact that I am here to discuss relates to the fact that a proven technology will be rendered commercially viable as a result of this quantum drop in power costs. Electrolysis—using electricity to separate water into hydrogen and oxygen —takes about 14 Kilowatt hours (Kwh) for each 100 standard cubic feet (scf) of hydrogen produced. In many U.S. markets, end use hydrogen prices are in the range of $1.00-1.25 per 100 scf. Little wonder that electrolysis had scant commercial appeal when delivered power costs were 7 or 8 cents per Kwh. But at 4 cents per Kwh or less, the picture changes dramatically.

The Figure on the next page shows the fairly simple story behind why electrolysis deserves a new look. And you can now understand a big part of the reason why we have formed PROTON Energy Systems to pursue the commercial opportunities embodied in that picture.

PROTON is a classic example of a company created to commercialize technology that was developed initially for military and aerospace applications. That technology—involving the use of Proton Exchange Membranes (PEM's)—has been used primarily to generate oxygen on spacecraft and submarines for life support applications. A proton exchange membrane electrolyzer not only splits water into oxygen and hydrogen, it also draws the hydrogen ions through its membrane, resulting in near perfect separation of the two gases.

PEM technology has a rich heritage with demonstrated reliability. The General Electric Company invented PEM technology in the 1960's; the Hamilton Standard division of United Technologies, Inc. acquired and has advanced the technology over the past decade or so. What makes PROTON unique is that four of our people have worked with this technology for the bulk of their careers. We know how to build these systems.

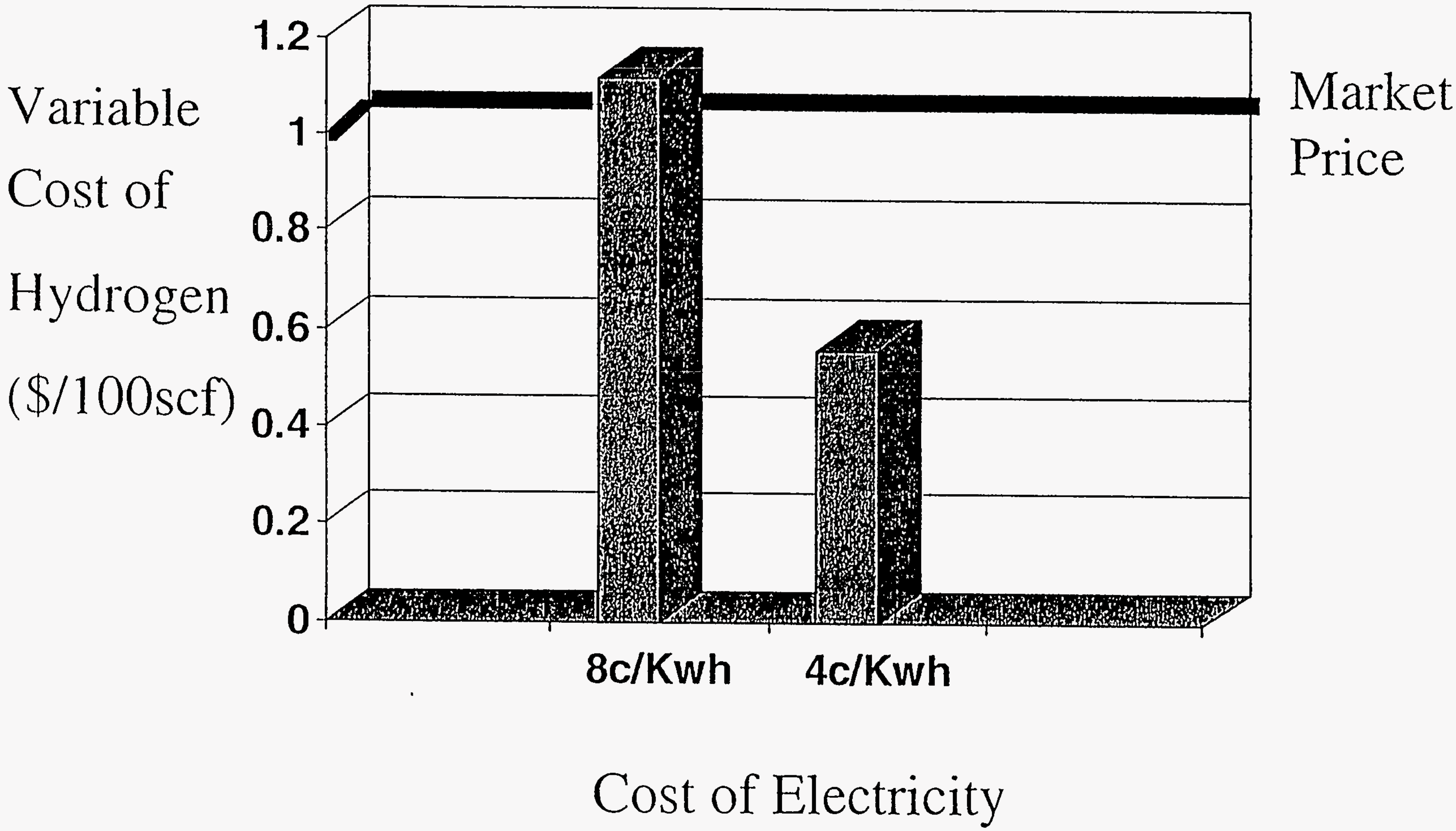
PROTON was incorporated in August of last year, and has raised nearly $4 million of venture funding. We plan to deliver our first commercial scale units, against orders already in hand, by the end of this year. Our fundamental message to this audience today is that we are moving headlong at commercial markets and not waiting for federal or other concessionary financing support.

My colleague Bill Smith will present a paper shortly that does justice to the task of explaining the inner workings and system design of a proton exchange membrane electrolyzer, including the specific units now in development at PROTON. In the limited time allowed for my presentation, I hope to create at least a working understanding of some of the exciting implications of this technology for the many markets that are of interest to all of us in the National Hydrogen Association.

Today's commercial gases market: our immediate target

PROTON's business focus is to move our technology into commercial applications as quickly as we know how. We will combine low cost manufacturing techniques with creative power purchasing to enable us to make hydrogen on site (at the point of use) for less than the cost of supplying hydrogen through conventional distribution channels.

Commercial Viability of Electrolysis



Using the existing power delivery system to make gases on site with electrolysis may offer lower logistics costs than using trucks and large storage tanks to do the job. The typical hydrogen gas tube truck weighs over twenty tons but carries only 500 pounds of gas.

If we can make hydrogen on-site for less than $1.00 per 100 scf,, we will be below the vast majority of gaseous hydrogen market prices. And as the Figure on the next page shows, our declining cost structure during the next few years should make us competitive even with a significant portion of the liquids market.

We plan to work with existing industrial gas marketers rather than compete against them. Our units will be economically "invisible" to the end user, but for one important fact: Our units use lots of electricity. If we pool our power needs with those of our on site customer, we make him a bigger, more sophisticated power buyer. We put him in a position to lower his power costs as well as his supplier's hydrogen costs.

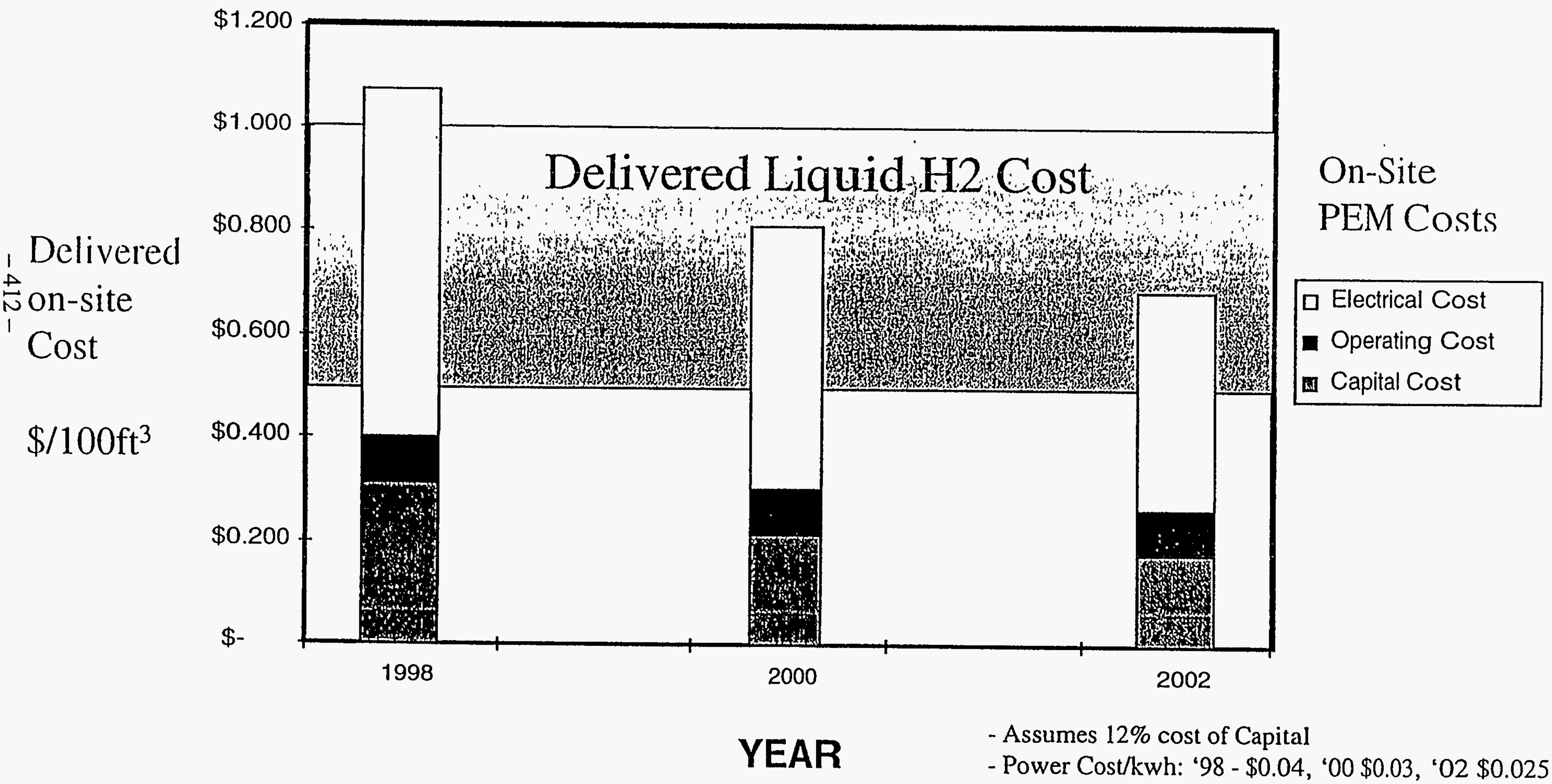
Fostering Tomorrow's Hydrogen/Energy Markets: our ultimate goal

The Chrysler and Ballard/GPU announcements have generated renewed excitement about the timing and scope of fuel cell commercialization. We at PROTON are watching these developments with keen interest for two reasons. First, our PEM technology is at the core of a great many fuel cells now in development. Any success we achieve in driving down costs of PEM electrolyzers will often translate into lower fuel cell costs as well.

Second, we believe we may have the best approach for solving the hydrogen refueling challenge. If there is a "conventional wisdom" regarding how to meet the energy needs of fuel cells, it is through "on-board" reforming of conventional fossil fuels. That approach almost certainly makes the most sense for stationary applications, but we seriously question the viability of onboard refineries as a source of hydrogen on moving vehicles.

Yes, Chrysler is the latest to bless on board reforming. But our careful reading of Chrysler's announcements reveals that they favor on-board refining not so much because they see technical superiority in this approach vs. externally-supplied hydrogen, but because Chrysler sees no realistic means of delivering hydrogen any other way. They are skeptical, quite properly, of the prospect of liquid hydrogen truck fleets blanketing our highways to deliver hydrogen to corner filling stations. But there is a whole different way to deliver hydrogen—by wire rather than by truck. That's our ultimate advantage—we use the existing power network to replace more expensive and far less safe

Projected On-site Hydrogen Cost using PEM Technology



- Assumes 12% cost of Capital
- Power Cost/kwh: '98 - $0.04, '00 $0.03, '02 $0.025
- 400 psi product H2
- no oxygen credit assumed

highway-based transport. Last year at this conference, Air Products suggested that PEM-based distributed hydrogen would cost about $3.00 per pound. With the manufacturing cost breakthroughs that PROTON hopes to achieve, our number is actually just about $2.00 per pound.

The logical evolution of our PEM distributed hydrogen generators doesn't end with the local filling station. It ends with the home garage. Our units scale very well to small sizes; they will be far more economical than small scale reformers for meeting home hydrogen demand, whether for automotive fuel cell or stationary fuel cell needs.

Our ultimate product is a Unitized Regenerative Fuel Cell (URFC). A URFC can operate as either an electrolyzer or a fuel cell. When plugged into the home's water and power supplies, it makes hydrogen . Later, when electricity is needed (whether to turn motors of a vehicle or to power the home's electrical system), the unit operates in reverse mode—stored hydrogen is delivered to the same membrane and migrates back toward the water side, giving up electrons in the process. A single cell stack that makes hydrogen and generates power has clear size and weight advantages, with obvious value for transportation applications. Such a unit will also enable renewable power generating technologies (wind, solar, biomass) that are undergoing their own cost breakthroughs into the 4 cent/KWh range.

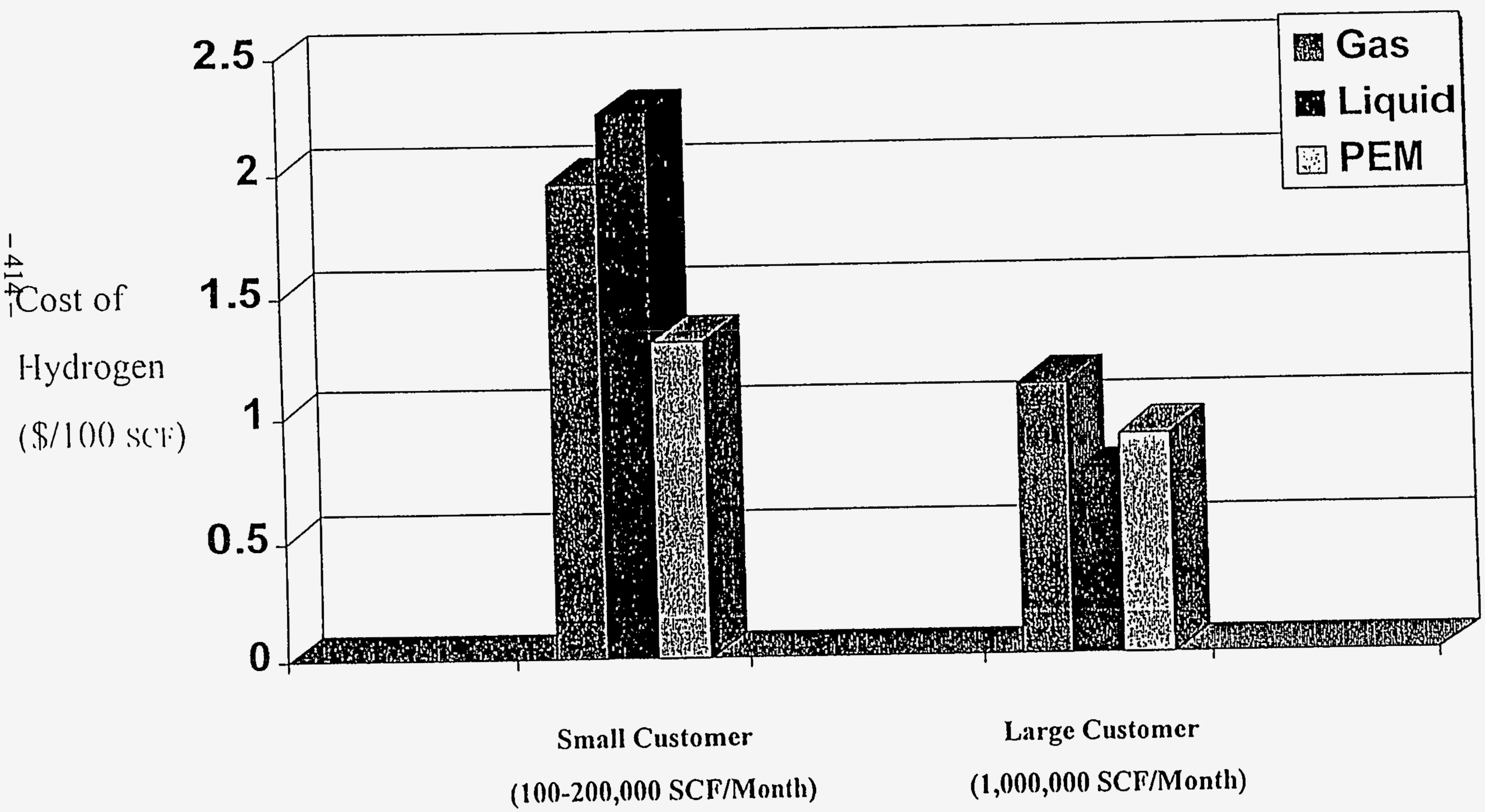
We expect that within two years we will be offering unitized regenerative fuel cells having 40 % thermal efficiency at prices approaching $1,200 per Kw. And we envision significant further cost reductions thereafter.

Electrolyzer design features

To wrap up, our immediate focus is on proving the viability of making industrial gases using PEM electrolyzers. Our principal hurdle is to make these units at sufficiently low capital costs to pass the very clear price tests in the gas marketplace. We believe that we have an inherent advantage over other ways of making hydrogen, particularly where relatively small quantities of gas (say 300-500,000 scf per month or less) are involved. As our third Figure (next page) suggests, we don't expect to be cheaper than large steam reformers, but we scale down to meet smaller applications a whole lot better than reformers do.

Our units are solid state. There is very little to go wrong with them, so long as they get fed with good clean water. Our design is to use potable water and do the additional demineralization with commercially available systems.

PEM Technology Wins in Smaller Hydrogen Markets



customer needs, and enables us to make and store gas during off peak power periods while meeting on peak customer gas needs. Eliminating the need for mechanical compression further enhances reliability and cost effectiveness.

Our units also make very high purity gas. This purity is an additional factor underlying our commercial viability, because many customers need and will pay a premium for purity.

In closing, PROTON is here as an "early mover" into markets made newly attractive by the falling price of electricity. We have very high hopes for ourselves, and are excited at the prospect of contributing to the growth of hydrogen markets that form a common interest of members of the National Hydrogen Association.

Arizona Utility Market Changes Affecting Hydrogen Energy, and APS Involvement

Herb Hayden

Renewable Resources Program Coordinator

Arizona Public Service Company

National Hydrogen Association Annual Meeting

March 13, 1997

Presentation Outline

- **Deregulation of Utilities**
- **APS Environmental Involvement**
- **Arizona Regulatory Solar Proposal**
- **Transportation, Air Quality and Alternative Fuels in Arizona**

Deregulation of Utilities

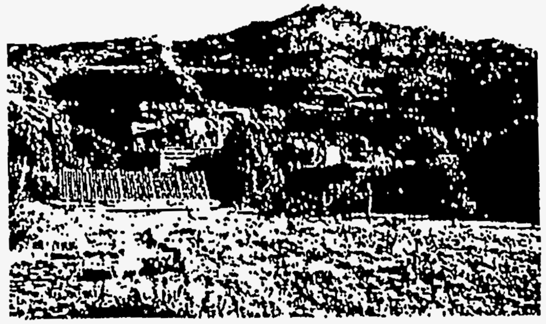
- **Wholesale prices will decrease**
  - generation prices of 1.5c - 3c/kWh, @ >10 MW
  - for some customers, retail prices could rise
- **Planners will seek shorter investment horizons**
  - increased uncertainty in markets and technology
  - seek 10 year or less term, rather than 20-40 years
- **Opportunities for renewables will remain**
  - some customers will choose to buy renewable energy
  - regulatory support remains for renewables & environment

APS Environmental Involvement

- Solar Development Program
- Environmental Showcase Home
- Grand Canyon Partnership
- Mexico Village Wind/Solar Project
- Global Climate Change: Climate Challenge
- Signatory to CERES principles
- Support of 1990 Clean Air Act Reauthorization
- Arizona Air Quality task forces

APS Solar Services

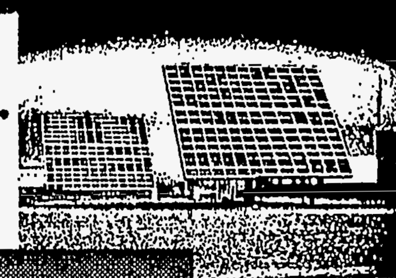
- **Remote Solar Electric Service**
  - in remote areas where power lines are costly or not available
  - kWh storage is costly, an opportunity for H_2 if efficient and low cost



- **Residential Solar Energy Option, 2Q97**
  - offers customer option for solar power
  - as part of their regular service,
  - from various APS plants to be built
  - sold in 100 W shares of solar plant output
  - costs about $3/mo. above regular rates

Solar Technology Development

- **APS STAR Site - Test And Research**
  - field testing of solar since 1988
  - PV modules, trackers, hybrid systems
- **Support of mass-producable, low cost solar**
  - High Concentration PV
    - 500x reduction of PV area using Fresnel lenses
    - 23% efficient cell, 18% efficient system
  - Solar Dish Stirling,
    - uses a large dish-shaped mirror
    - Stirling engine uses heat to turn generator
    - 40% efficient engine, 25% system



Arizona Regulatory Solar Proposal

- **Recent rule by Arizona Corporation Commission**
  - new solar to provide 1% of all kWh sales in AZ
  - phased implementation, 1999 - 2003
  - note that rule could be altered or delayed

- **200 MW of solar estimated to meet mandate**
  - APS estimates cost to range from 12c - 25c /kWh
  - DOE/CSTRR received proposals as low as 6c/kWh

Transportation and Air Quality in Arizona

- **Phoenix area is designated 'serious' for nonattainment of EPA standards**
  - CO, particulates, O_3, NO_x, VOCs
  - penalties include loss of highway funds, more permitting requirements, offsets
- **APS support of improving air quality**
  - sponsor of annual 'APS Electrics' EV races since 1990
  - participant in regional air quality task forces
  - encourage employee use of mass transit, trip reduction
  - Grand Canyon & other customers with EV busses
  - lead the Businesses for Clean Air Challenge

APS

Arizona State Support for Alternative Fuel Vehicles

- **Existing tax credit of $500/vehicle**
  - up for increase to $1000 this year
  - may be increased to $5000 in some cases
- **Grants for fueling stations**
  - up to $100,000 for public stations
  - $1000 for home refueling equipment
- **Proposed grant for AFV busses**
  - 50/50 cost share, up to $5M/yr. total

Electric H_2 Cost for Vehicles

- **Costs of Electrolytic H_2 v. Gasoline Gallon**
  - $2.00/gal energy cost, @ 4c/kWh
    - 120,000 Btu/gal / 3412 Btu/kWh = 35 kWh /gal
    - 35 kWh/gal * 4c/kWh / 70% eff. = $2.00 /gal
  - $3.14/gal equipment cost, @ $1000/kW, 10 yr.. life
    - $1000/kW * 22% /yr..* 35kwh/gal / (8760 hr./yr. * 0.4 CF * 0.7 eff.)
    - ($2.57 @ 20yr., at 18% /yr..)
  - $5.14 /gal total cost ($4.57 @ 20yr)
- **CO_2 produced using coal generation ~100 lb/gal, using natural gas generation ~60 lb/gal**

Closing the Cost Gap

- **Total cost could be $2.15 /gal.**
  - Energy cost could be $1.50 /gal using 3c/kWh
  - Equipment cost could be cut to $0.65/gal
    - find $500/kW electrolyser
    - increase capacity factor to 80%
    - relieve taxes on income and property
- **Effective cost could be $1.07 /gal.**
  - use Fuel Cell vehicle, cut fuel use in half or better
  - also add ZEV value in sensitive areas
- **H_2 energy storage would have better near-term value as an alternative to lead-acid batteries**

APS

Summary

- **Hydrogen and solar energy equipment costs need to be very low to compete directly in US utility and transportation markets**
- **CO_2 would be increased if off-peak electricity is used to make H_2 (but there may be an interim rationale to develop H_2-fuel equipment)**
- **Remote power may be an important early market**
- **APS has a broad involvement and commitment to energy services and the environment**

APS

GENERAL SESSION V:

Advanced Technologies

HOGEN™

PROTON EXCHANGE MEMBRANE HYDROGEN GENERATORS: COMMERCIALIZATION OF PEM ELECTROLYZERS

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Alexandria, VA

HOGEN™ PROTON EXCHANGE MEMBRANE HYDROGEN GENERATORS: COMMERCIALIZATION OF PEM ELECTROLYZERS

by

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Abstract

PROTON Energy Systems' new HOGEN series hydrogen generators are Proton Exchange Membrane (PEM) based water electrolyzers designed to generate 300 to 1000 Standard Cubic Feet Per Hour (SCFH) of high purity hydrogen at pressures up to 400 psi without the use of mechanical compressors. This paper will describe technology evolution leading to the HOGEN, identify system design performance parameters and describe the physical packaging and interfaces of HOGEN systems.

PEM electrolyzers have served U.S. and U.K. Navy and NASA needs for many years in a variety of diverse programs including oxygen generators for life support applications. In the late 1970's these systems were advocated for bulk hydrogen generation through a series of DOE sponsored program activities. During the military buildup of the 1980's commercial deployment of PEM hydrogen generators was de-emphasized as priority was given to new Navy and NASA PEM electrolysis systems.

PROTON Energy Systems was founded in 1996 with the primary corporate mission of commercializing PEM hydrogen generators. These systems are specifically designed and priced to meet the needs of commercial markets and produced through manufacturing processes tailored to these applications. The HOGEN series generators are the first step along the path to full commercial deployment of PEM electrolyzer products for both industrial and consumer uses. The 300/1000 series are sized to meet the needs of the industrial gases market today and provide a design base that can transition to serve the needs of a decentralized hydrogen infrastructure tomorrow.

TM HOGEN is a Trademark of Proton Energy Systems Inc.

Introduction

Electrochemical devices which utilized proton exchange membranes were invented in the early 1950's and rapidly incorporated in critical military and aerospace power and life support applications. Early PEM fuel cells developed by General Electric satisfied rigorous mission performance requirements for NASA's Gemini spacecraft supplying power for 7 successful manned missions (Butler, 1996). In the course of the Gemini program, 250 cell stacks were built for development, test and flight achieving over 5000 total hours of space flight operation. These PEM fuel cells (Figure 1) met rigorous mission requirements but had limited life capability. The styrene-based materials used for the proton exchange membrane degraded rapidly, often permitting only a few hundred of hours of acceptable performance.

The introduction of DuPont's Nafion®, a perfluorinated ionomer, allowed electrochemical cells to be operated for much longer time periods thereby opening up many practical applications. Based on this enhanced life capability, Nafion materials have been instrumental in oxygen generation systems manufactured for the United States and Royal Navies for submarine life support (Figures 2 and 3, Smith 1994). Furthermore, Nafion has revolutionized the chlor-alkali industry significantly lowering the cost of producing chlorine and caustic soda from brine, Figure 4, (Quah 1995.)

Leveraging off this strong aerospace and industrial heritage, proton exchange membrane technology has become a key enabler in commercial water electrolysis based hydrogen production. To date, over 20,000 laboratory scale PEM electrolyzers generating up to 1.5 SCFH hydrogen, (Figure 5) have been sold. Electrolyzers which contain these cells have continually gained market share previously dominated by hydrogen gas delivered in cylinders.

Despite a long and rich history of development for military and space applications, PEM water electrolysis technology, for large scale applications, was not aggressively commercialized. Responding to this opportunity, Proton Energy Systems was founded in 1996 with the mission of supplying market priced commercial PEM products. PROTON is currently developing low-cost units having hydrogen generation capacities of 300 SCFH and 1000 SCFH at delivery pressures of up to 400 psi. These hydrogen-oxygen generators (HOGEN™) units can be deployed anywhere to provide a point-of-use infrastructure. HOGEN units will find use in diverse markets including materials processing, food processing, microelectronics, transportation and energy. Initial HOGEN units will begin In-Service Evaluation testing in October 1997 with production deliveries starting in the first quarter 1998.

® Nafion is a registered trademark of E. I. DuPont De Nemours and Company

Background

The Nafion membrane is a perfluorosulfonic acid polymer in the proton form. This material has a Teflon backbone with pendant vinyl ether groups. These vinyl ether groups are terminated with a sulfonate anionic group which is in equilibrium with a proton. This structure is shown in the Figure 6. Membrane ionic conductivity required for electrochemical cell operation is provided by the mobility of hydrated protons ($H^+ \cdot nH_2O$). These protons move directly through the polymer sheet by successively changing place with a proton located at an adjacent sulfonic group. The sulfonic groups are fixed and do not move, thus their concentration remains constant within the solid polymer electrolyte. The solid polymer membrane is the only electrolyte required; there are no free acid or caustic liquids, and the only liquid used within the module is distilled water.

The ability to support ionic current flow allows the PEM cell to function in a manner to complete the electrochemical circuit. In the PEM cell, thin layers of catalyst are applied to each side of the membrane forming the anode and cathode electrodes of the cell. This assembly, Figure 7, supports the reaction: $2H_20 \rightarrow 2H^+ + 2e^- + O_2$ at the anode and the reaction: $2H^+ + 2e^- \rightarrow H_2$ at the cathode. In this reaction the gaseous oxygen evolves directly at the anode, the H^+ protons are conducted through the membrane to the cathode where they combine with electrons supplied by the external circuit to evolve hydrogen.

PEM Technology Heritage

NASA

Following the first use of PEM fuel cells aboard the Gemini spacecraft NASA sponsored the development of numerous PEM electrochemical systems including prototype fuel cell systems compatible with space shuttle mission requirements, electrolyzers for life support applications and electrolyzers for generation of propulsion reactants for space station reboost. Through these developments PEM technology has proven its capability in rigorous ground testing simulating space mission duty cycles and interfaces. This most recently has included highly successful testing of the Hamilton Standard PEM oxygen generator at NASA Marshall Space Flight Center which is designed for oxygen generation required for manned life support aboard the Space Station.

Navy

The extended deployment of strategic deterrent submarines necessitated the onboard generation of respirable oxygen. This need led to the development of a high pressure potassium hydroxide (KOH) electrolyzer in the 1950's. Further refinements in the 1960's prompted the production of a semi-automated, 20 MPa KOH electrolyzer. In the 1970's, the U.S. Navy and General Electric began development of a proton exchange membrane cell capable of generating oxygen at up to 1,600 milliamperes per square centimeter of cell surface area. Hamilton Standard acquired this technology in the mid-1980's and incorporated it into a system capable of safely generating oxygen at variable pressure and flow rate.

The introduction to the United States nuclear submarine fleet of PEM water electrolyzers for oxygen generation provided a substantial increase in oxygen generator safety and reliability. The polymeric electrolyte material utilized in this unit provided a rugged pressure barrier to prevent mixing of generated hydrogen and oxygen gases in the electrolysis module. This, combined with automatic shutdown and control features, allows the unit to be operated over wide parameter ranges with minimal interaction by a ship's crew.

Both the U. S. Navy and U.K. Royal Navy have sponsored the development of PEM water electrolyzers for oxygen generation in nuclear submarines. In the case of the Royal Navy, the PEM electrolyzer system, supplied by CJB Developments of Portsmouth England, is fully qualified with over 35 cell stacks delivered to date. Table I summarizes the in-use history of these U.K. Royal Navy electrolyzers (Arkilander 1996)

Table I Royal Navy Electrolyzer Experience

Description	Test Data
Land Tests	17,200 Hours
Sea Operation	154,400 Hours
Longest Running Unit at Sea	21,200 Hours
Number of Systems Presently at Sea (1996)	24
Reported malfunctions	0
Total Cell Operating Time	12,870,000 Hours

The U.S. Navy electrolysis system, which operates at pressures up to 3,000 psia, has passed all qualification testing, including shock, vibration and sea trials. This system, the Oxygen Generating plant (OGP) has been reported to have demonstrated long life in the laboratory and in the field. The fundamental electrolysis cell elements have been reported to have demonstrated well over 100,000 hours of life in single cell laboratory tests.

Chloralkali-The First Commercial Success of Large PEM Systems

The world's second highest electrical energy-consuming chemical process, next to the aluminum industry, is the electrolysis of brine (NaCl) into caustic soda and chlorine (Quah 1996). These chemicals together comprise the second largest volume of commodity chemicals produced worldwide. Traditionally brine has been electrolyzed using a process known as the Hall process using mercury amalgam cells or with asbestos diaphragm electrolyzers. These processes still remain predominate, but in the chloralkali industry today, membrane electrolyzers equipped with perfluorinated membranes such as Nafion are accepted as the state-of-the-art technology. In such a perfluorinated membrane system, a sodium ion is moved across the membrane in fashion identical to the protonic current flow described previously. Introduced commercially in the early eighties, membrane electrolyzers presently account for about 25% of the global chloralkali capacity. This 25% represents about 40 billion lbs/year of product chloralkali. In electrical energy terms chloralkali membrane systems today consume about 3 GW of power for electrolysis at 220 plants in 49 countries (Quah 1996). Membrane plants have become the accepted choice because of several key advantages over mercury and asbestos processes including:

- Lower initial investment costs
- Reduced operating costs
- Elimination of environmental concerns related to exposure to and waste disposal of asbestos and mercury
- Inherently higher quality products

Figure 8 charts the growth of membrane technology worldwide from 1987 to 1995. Although older technology plants continue in operation until they have reached their end-of-life, almost all new chloralkali plants built around the globe are membrane plants. Within the chloralkali industry, membrane systems are today accepted as commercially proven and are acknowledged as the preferred state-of-the-art choice.

PEM Laboratory Hydrogen Generation-A Thriving Commercial Venture

The production of very small (250 cc/min to 500 cc/min) hydrogen generators was initiated in the 1970's at General Electric who sold these small generators to gas chromatography customers who used these generators to replace gas in cylinders. This has become the preferred form of supply for the gas chromatography industry where over 20,000 PEM hydrogen generators have been sold. Today's leading laboratory scale hydrogen generator suppliers; Peak Scientific and Packard Instruments manufacture and sell PEM hydrogen generators as standard commercial products

PROTON's HOGEN Hydrogen Generators Leverage Proven Industrial and Aerospace Heritage

Years of Navy & NASA development have proven the reliability and durability of PEM electrolyzers in meeting vital life support needs under the most demanding mission requirements. Successful commercial deployment of PEM technology into chlroalkali industry and the laboratory generator markets have demonstrated the commercial viability of PEM products.

PROTON continues this tradition, evolving PEM technology into full-scale commercial applications for large scale hydrogen generation. The first two products being developed for commercial applications, at PROTON, are 300 SCFH and 1000 SCFH water electrolyzers -- the HOGEN 300 and HOGEN 1000. These hydrogen generators are designed to serve industrial gas markets for a wide range of applications including metals processing, electronics production, electrical generator cooling, hydrogenation of fats and oils and argon purification.

HOGEN System Design

Each cell element of a HOGEN hydrogen generator implements the water electrolysis reaction (Figure 7) to generate hydrogen and oxygen. To produce a cell stack, repeating cell elements are stacked in a bipolar filter press arrangement (Figure 9) stacking as many cells as are required for the desired generation rate. Initial HOGEN series cell stacks are designed to produce hydrogen at 400 psi and oxygen at near ambient pressure. This provides the hydrogen user with pressurized gas, suitable for buffer storage operations, without the noise, maintenance and power consumption of mechanical compression. It also allows the oxygen system design to be very safe and very simple using low pressure components circulating only low temperature deionized water.

A summary schematic of this system is shown in Figure 10. Water is introduced to the system from a potable water source. The water is then purified by an integral water treatment unit and supplied to the oxygen-side circulation loop. Water circulates on the anode (oxygen) side of the cell stack to both introduce water for the electrolysis reaction and to remove heat. This water loop is maintained at near ambient pressure while the hydrogen side is allowed to self pressurize to 400 psi. Oxygen is vented from the system as produced while the 400 psi product hydrogen is dried and delivered to the customer. Table II Summarizes key operating parameters of these system

Table II HOGEN 1000 Hydrogen Generator Operating Parameters

Output	1000 SCFH hydrogen
Hydrogen Purity	99.999+%
Outlet Pressure	400 psi (no compressor required)
Cooling	Air cooled
Water input	potable
Water Consumption	50 lbs./hr
Packaging	skid mounted
Environmental:	-40 to 120 deg F (powered)
Power Service Required	480V, 350A, 3-phase 60hz
Power Consumption (per100ft3)	14-18 kwh

Packaging

The HOGEN systems are designed to be delivered in a fully weatherized configuration, (Figure 11), with the only operations interface being power, water, and the hydrogen delivery line. No cooling loop connection is required. The form factor selected is that of a standard ISO shipping container ensuring the compatibility of the product with standard forms of worldwide shipment. The fully weatherized configuration allows the user to site the system in a location external to the user in an analog of traditional gaseous or liquid hydrogen trailer delivery.

Future Product Development

The HOGEN 300 and 1000 series electrolyzers form the foundation for a family of PEM products including electrolyzers and fuel cells. Advanced PEM electrolyzers will be sized and priced to meet distributed hydrogen infrastructure needs (Figure 12) and PEM Unitized Regenerative Fuel Cells, integral units that can reversibly operate in both electrolysis and fuel cell modes, will be introduced for energy storage applications.

Serial production of the HOGEN series hydrogen generators will provide both learning benefits and economies of scale that are directly applicable to a wide array of new electrolysis and fuel cell products. In this manner, production of PEM hydrogen generators for established, existing markets leverages the production of new, low cost PEM products for the emerging transportation and energy markets.

Conclusion

PROTON is bringing the advantages of PEM technology to the commercial hydrogen marketplace with near term products based on proven PEM electrolysis. PROTON looks forward to supporting the needs of the today's hydrogen market with these long-lived, reliable systems providing the basis for products and markets of the future.

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Figure 1 NASA Gemini 1 kW PEM Fuel Cell

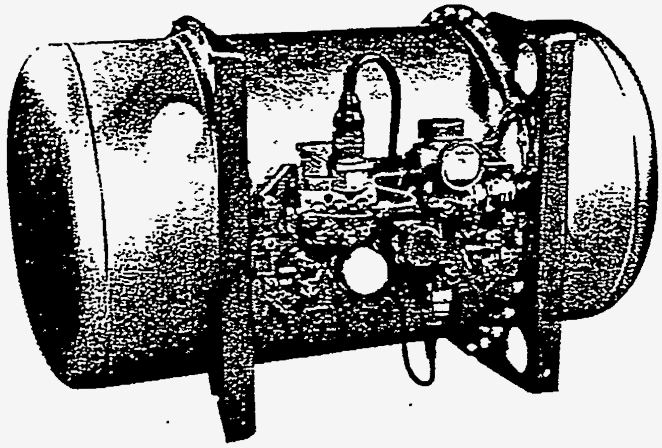


Figure 2 U. K. Mod Navy Submarine Low Pressure Electrolyzer

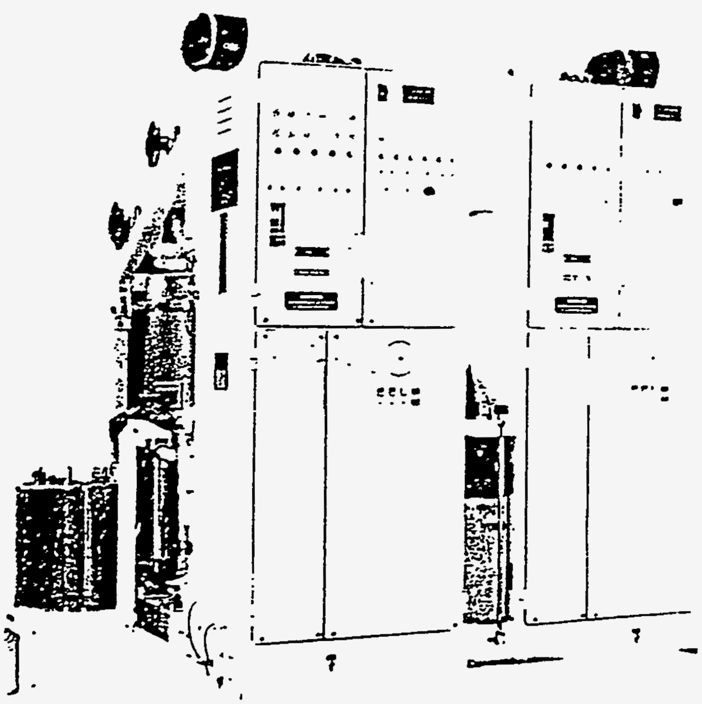


Figure 3 U. S. Navy High Pressure Oxygen Generating Plant

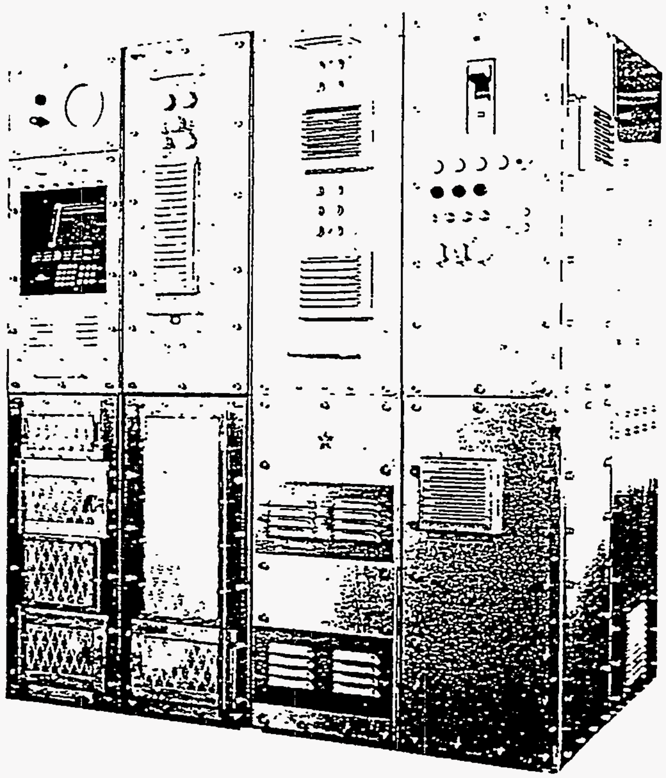


Figure 4 Chloralkali Facility

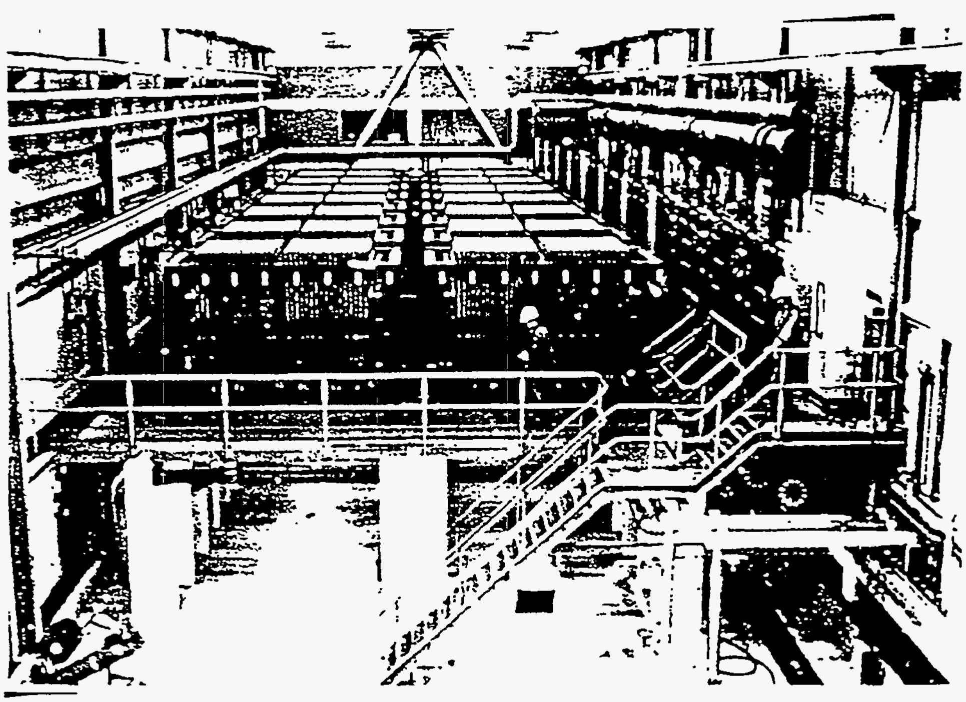


Figure 5 PEM Hydrogen Generator for Laboratory Applications

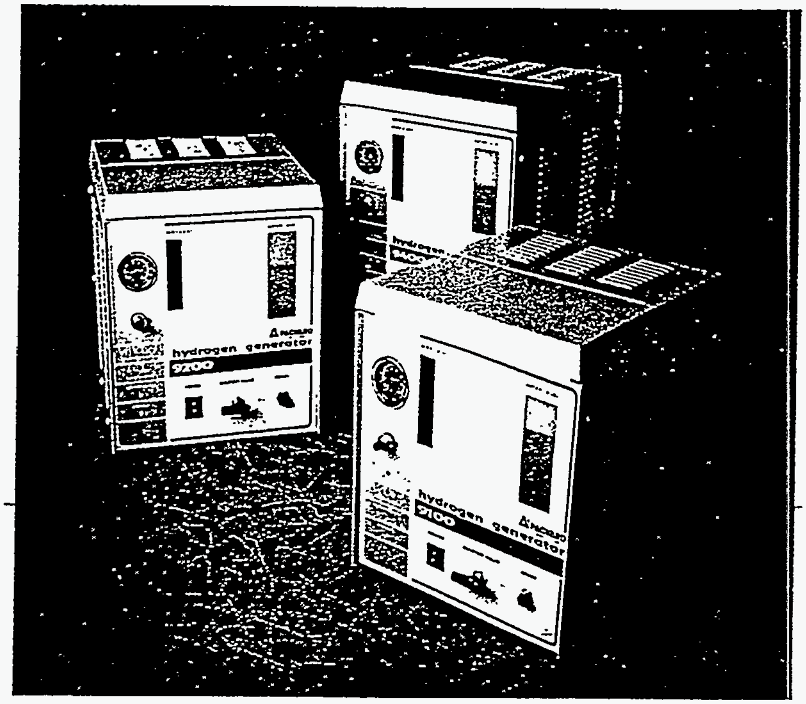


Figure 6 Proton Exchange Membrane: Proton Transport Function

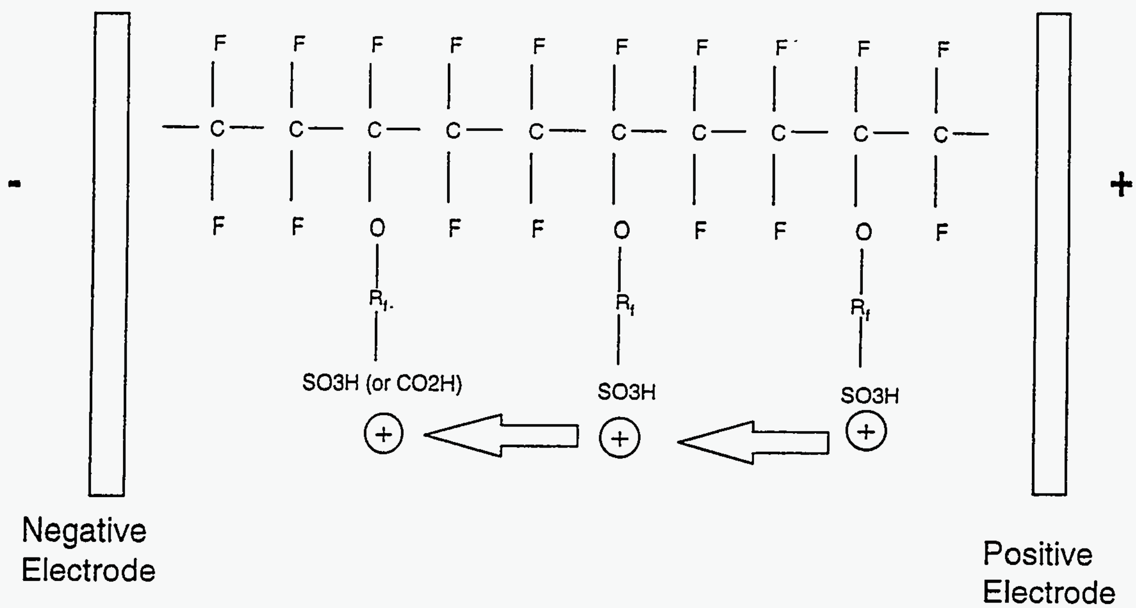


Figure 7 PEM Electrolysis Cell Reactions

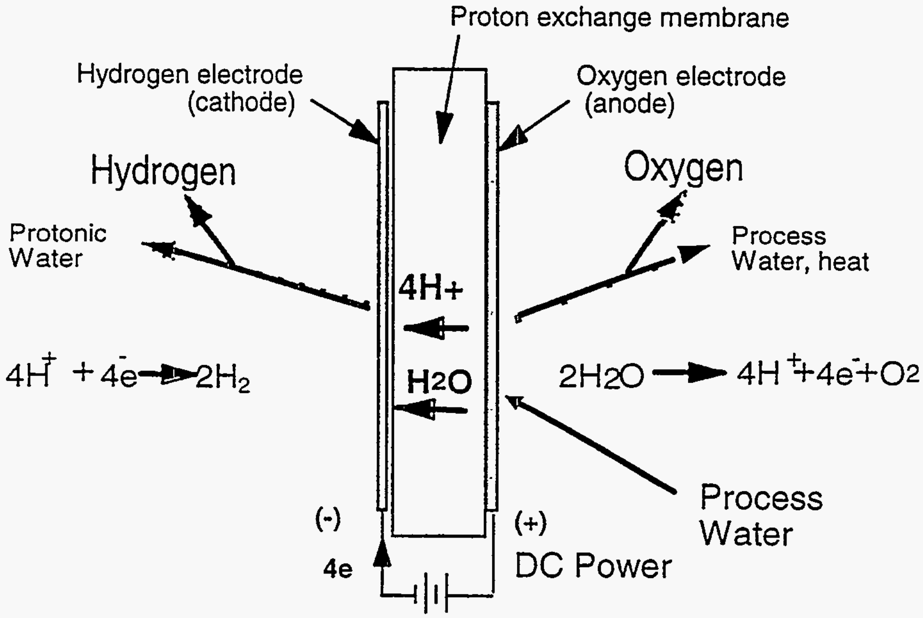


Figure 8 Chloralkali Industry Membrane Technology Penetration

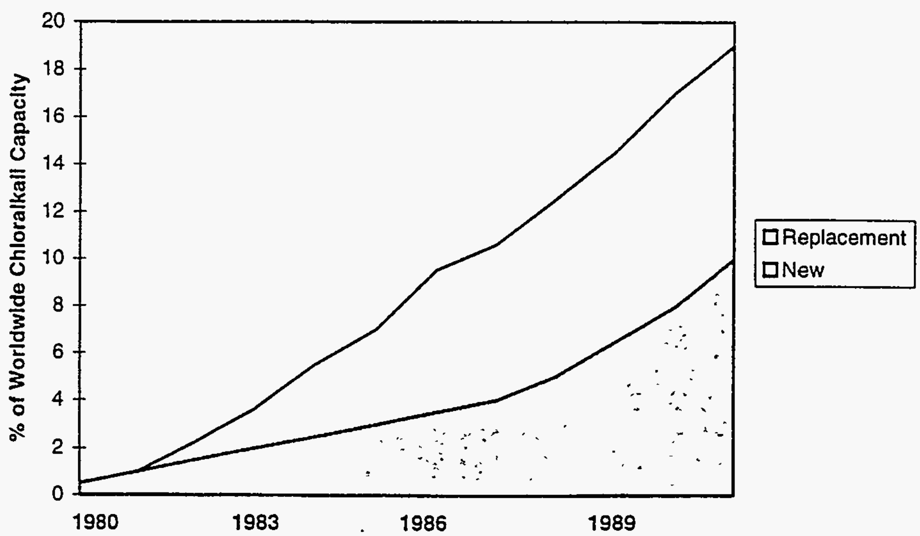


Figure 9 HOGEN PEM Cell Stack

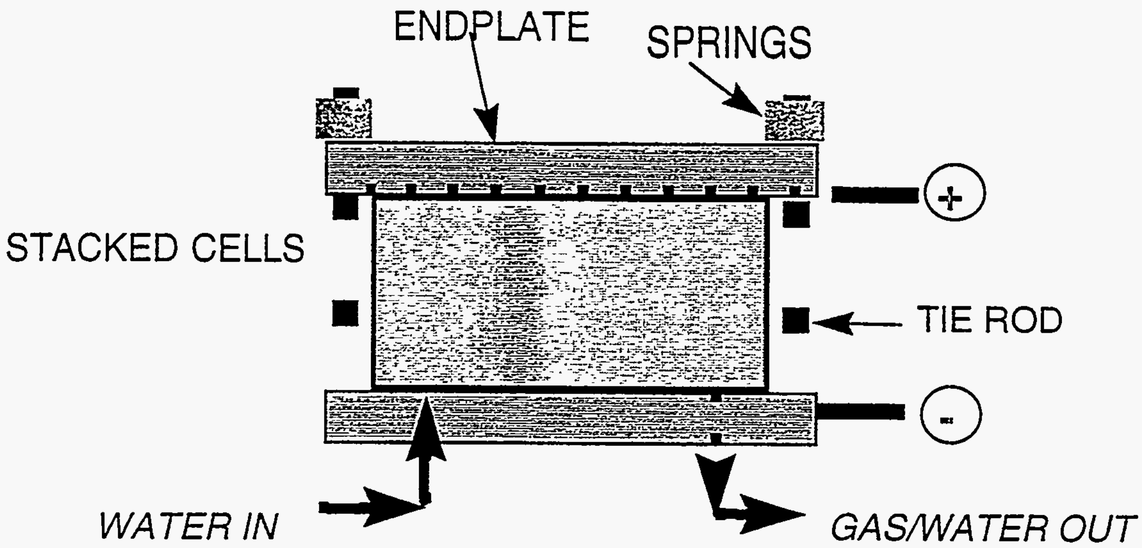


Figure 10 Simplified HOGEN Fluid Schematic

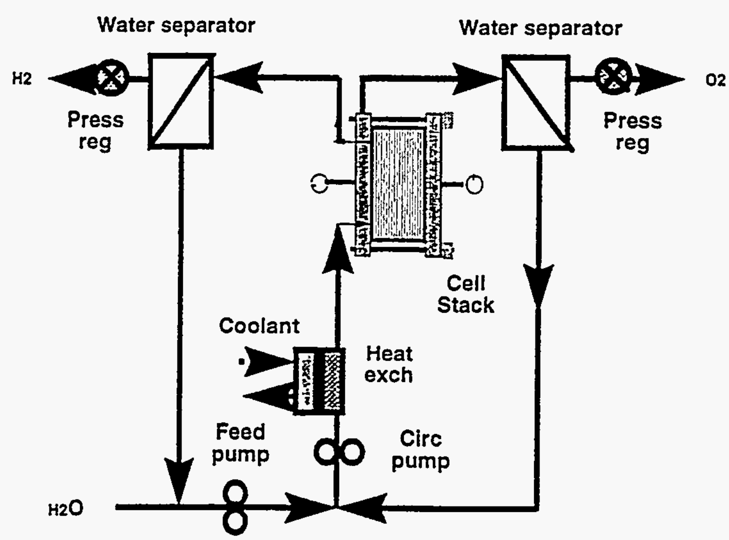


Figure 11 HOGEN Hydrogen Generator Physical layout

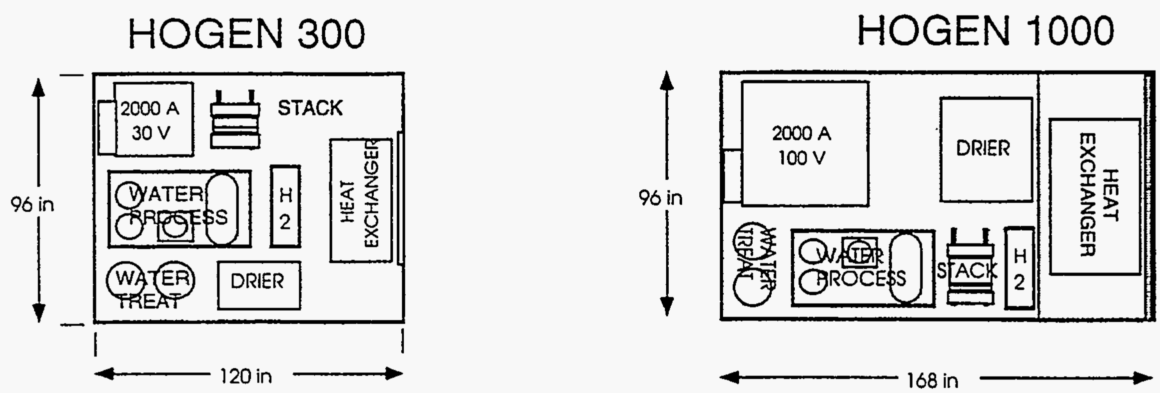
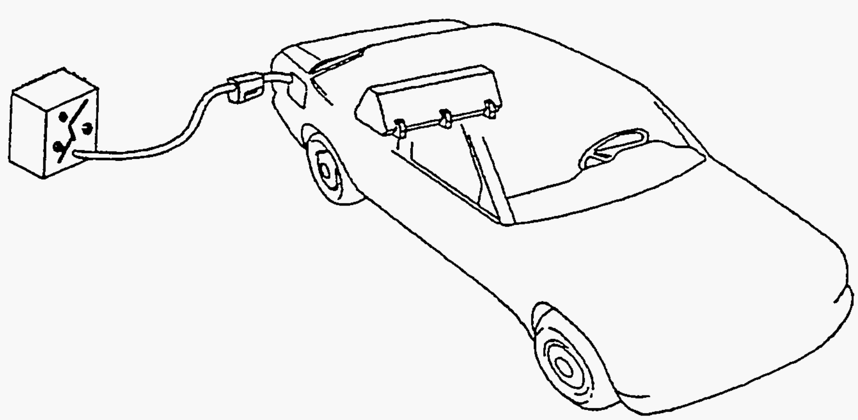


Figure 12

PROTON's Hydrogen Generators Create a Distributed Hydrogen Infrastructure



Making the Case for Direct Hydrogen Storage in Fuel Cell Vehicles

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Abstract

Three obstacles to the introduction of direct hydrogen fuel cell vehicles are often stated: 1) inadequate onboard hydrogen storage leading to limited vehicle range 2) lack of an hydrogen infrastructure, and 3) cost of the entire fuel cell system. This paper will address the first point with analysis of the problem/proposed solutions for the remaining two obstacles addressed in other papers[1,2].

Results of a recent study conducted by Directed Technologies Inc. will be briefly presented. The study, as part of Ford Motor Company/DOE PEM Fuel Cell Program, examines multiple pure hydrogen onboard storage systems on the basis of weight, volume, cost , and complexity. Compressed gas, liquid, carbon adsorption, and metal hydride storage are all examined with compressed hydrogen storage at 5,000 psia being judged the lowest-risk, highest benefit, near-term option.

These results are combined with recent fuel cell vehicle drive cycle simulations to estimate the onboard hydrogen storage requirement for full vehicle range (380 miles on the combined Federal driving schedule). The results indicate that a PNGV-like vehicle using powertrain weights and performance realistically available by the 2004 PNGV target date can achieve approximate fuel economy equivalent to 100 mpg on gasoline (100 mpg_{eq}) and requires storage of approximately 3.6 kg hydrogen for full vehicle range. This fuel economy significantly surpasses the PNGV goal of 80 mpg_{eq} and the required onboard storage quantity allows 5,000 psia onboard storage without altering the vehicle exterior lines or appreciably encroaching on the passenger or trunk compartments.

Background

In 1994, Ford Motor Company began a cost-shared program with the U.S. Department of Energy to develop direct hydrogen fueled Proton-Exchange Membrane (PEM) fuel cell power systems for automobiles[3]. The main focus of the R&D effort is development of lightweight, high performance, low catalyst loading fuel cell stacks and peripheral systems. However, recognizing that the direct hydrogen fuel cell automobile concept is only as strong as its weakest link, Ford asked Directed Technologies Inc.

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[1] "PEM Fuel Cell Cost Minimization Using 'Design For Manufacture and Assembly' Techniques," F.D. Lomax, Jr., B.D. James, Directed Technologies, Inc., presented at the 8th Annual U.S. Hydrogen Meeting, Arlington, Virginia, March 11-13, 1997.

[2] "Affordable Hydrogen Supply Pathways for Fuel Cell Vehicles," C.E. Thomas, I.F. Kuhn, Jr., B.D. James, F.D. Lomax, Jr., G.N. Baum, Directed Technologies, Inc., presented at the World Car Conference, Paper 97WCC061, Riverside, California, January 21, 1997.

[3] In Phase 1 of the program, Ford funded five fuel cell companies (IFC, MTI, Tecogen, Energy Partners, and H-Power) to develop prototype 10-kW stacks. Based on the performance of these stacks and the projection of full system performance, Ford competitively down-selected to two companies, IFC and MTI, to fabricate full 50-kW net PEM systems. Integration and testing of these bench top power systems is expected in late 1997.

(DTI) to examine three critical ancillary subjects: onboard hydrogen fuel storage, safety of hydrogen vehicles, and a plausible hydrogen infrastructure. The following paper describes the results of the onboard storage study and related work by DTI.

Storage Study Results

Since Ford is developing direct hydrogen fueled PEM power systems under their DOE contract, only storage systems producing pure undiluted H_2 gas are considered. Storage systems are divided into two main classes: mature systems, defined as those reasonably well characterized and able to be mass produced for an automobile within 10 years, and immature systems, defined as those not well characterized. Each mature system was conceptually designed and evaluated on the basis of weight, volume, cost, complexity, refueling impact, dormancy, and development risk. System attributes are summarized in Figure 1. The following conclusions were reached:

Liquid Hydrogen: LH_2 systems have the highest H_2 mass fractions and one of the lowest system volumes. along with near zero development risk, good fast fill capability, and acceptable safety characteristics. They would appear to be an excellent choice except for two adverse factors: dormancy and infrastructure impact. Dormancy concerns arise due to boil-off losses that will inevitably concern the average car owner, although daily use or proper planning for route or fleet applications can remove most if not all dormancy concerns. Infrastructure impacts are three fold: first, the liquefaction process is costly, second, small scale LH_2 production is impractical, and third, low volume distribution/dispensing of LH_2 is expensive. Consequently, LH_2 systems will not easily support a transition from anemic start-up to a robust H_2 economy. Overall, LH_2 storage is a most appropriate for a mature H_2 economy where the inherent difficulties (and high cost) of large scale remote LH_2 production and very small scale LH_2 dispensing are least encountered.

Carbon Adsorption: Current performance carbon adsorption systems simply are not competitive in terms of H_2 mass fraction, system volume fraction and refueling time. Carbon adsorption systems perform best at cryogenic temperatures, but if one accepts the dormancy and infrastructure penalties of cryogens, we conclude that the designer should store hydrogen as a liquid to obtain a high H_2 mass fraction. If goal level performance of room temperature adsorbents is achieved and if a means for fast filling (<5 minutes) the system can be devised. carbon adsorption systems will be a capable storage system for the FCV. In our opinion, the current carbon adsorption systems do not achieve adequate performance for initial incorporation into FCV.

Metal Hydrides: Metal hydrides can be subdivided into two categories: low dissociation temperature hydrides and high dissociation temperature hydrides. The low temperature hydrides suffer from low H_2 fraction (~2%). The high temperature hydrides require a fuel burner to generate the high temperature of dissociation (~300°C). Both systems offer fairly dense H_2 storage and good safety characteristics. Indeed it is the bad characteristics of dissociation (high temperature, high energy input) that create the good safety characteristics (no or slow H_2 release in a crash). Overall metal hydrides are either very much too heavy or their operating requirements are poorly matched to PEM vehicle systems. Without a dramatic breakthrough achieving high weight fraction, low temperature, low dissociation energy, and fast charge time, metal hydrides will not be an effective storage medium for PEM FCV.

Compressed Hydrogen Gas (CH_2): Compressed gas storage systems offer simplicity of design and use, high H_2 fraction, rapid refueling capability, excellent dormancy characteristics, minimal infrastructure impact, high safety due to the inherent strength of the pressure vessel, and little to no development risk. The disadvantages are system volume and use of high pressure. Integrating 340 liters (12 ft3) system volume for 6.8 kg (15 lbs)[4] usable H_2 will clearly challenge the designer, but we believe such a tank volume can be packaged into a "clean sheet" vehicle. In our opinion, the many advantageous features of compressed gas storage outweigh its larger volume. Compressed gas storage is supportable by small scale H_2 production facilities (on-site natural gas reforming plants, partial oxidation burners, and electrolysis stations) as well larger scale LH_2 production facilities. Thus a plausible H_2 infrastructure transition pathway exists. For these reasons, room temperature compressed gas storage is viewed as the most appropriate fuel storage system for PEM fuel cell vehicles.

Recent Compressed Pressure Vessel Developments

To further enhance the system performance of compressed hydrogen tank systems, in 1996 Ford funded an R&D team of Lawrence Livermore National Laboratory (LLNL), Aero Tec Laboratories Inc. (ATL) and EDO Fiber Sciences to expand on earlier work and demonstrate a light-weight tank liner for fiber wrapped pressure vessels. The new liner consists of a very thin (5 mil) laminated metallized polymeric bladder to function as a gas barrier and replaces the aluminum (0.1 inches) or plastic (0.25 inches HDPE) liners previously used. Use of the new polymeric liner reduces system weight by up to 30-40%. Experimental tanks produced with the new liner achieved a tank performance factor (P (burst) X internal volume /tank weight) of 1.6×10^6 inches with a projection of 2×10^6 inches for more optimized designs. Previous non-polymeric liner tanks have achieved only 1.3×10^6 inches.

Since the fiber wrapped pressure vessels are similar whether they store hydrogen gas or natural gas (NG), NG storage experience is relevant. In August 1996, a natural gas fueled passenger bus in the Los Angeles County Municipal Transit Administration (MTA) fleet experienced a cascade failure of two 24.8 MPa (3,600 psia) natural gas pressure vessels aligned beneath the buses floor boards. The two tanks ruptured in series with the first rupture occurring during refueling from damage caused by an improper installation or, ironically, from damage sustained by the tank during a safety inspection. No one was injured from the mishap although a maintenance worker was standing only a few feet away. There was no detonation nor combustion of the released natural gas. Substantial damage was done to the floor of the bus as well as a shattering of the windows of other busses in the refueling facility.

The NG tanks which ruptured are quite similar in design to those proposed for 34.5 MPa (5,000 psia) CH_2. However, the susceptibility of the initially ruptured tank was enhanced by its pure carbon fiber wrapping. Future hydrogen storage tanks will blend fiberglass with carbon to increase toughness and damage resistance. Secondly, the 2nd tank to rupture failed by being impacted on its end domes -- the structurally weakest part of the tank. Future tanks will have enhanced wrapping or energy absorbent material to reinforce the end-domes. Lincoln Composites Inc. NG tanks advertise an energy absorbent ToughShell™ material encasing the end-domes especially for this reason and a fiberglass/carbon fiber blend for abrasion and impact resistance. Indeed, Lincoln Composites is using this mishap to their commercial advantage, arguing that such an accident would not have occurred with their tanks.

Liquid Hydrogen and Compressed Hydrogen Volume Comparison

Figure 2 graphically compares the tank volumes of liquid and compressed storage of 3.6 kg hydrogen. As shall be discussed in the next section, onboard storage requirements are expected to decrease to 3.6 kg for future fuel cell vehicles. Both 34.5 MPa (5,000 psia) and 69 MPa (10,000 psia) compressed gas systems are displayed to reflect the reduced system volume made possible by high pressure. While 69 MPa systems are not currently being pursued for automotive applications due to perceived safety concerns and the added burden placed on the refueling infrastructure, at 69 MPa compressed gas is virtually the same system volume as liquid storage.

[4] The original hydrogen storage analysis was based on 6.8 kg, but more recent analysis shows that 3.6 kg is sufficient for PNGV-type vehicles, as discussed later in this paper.

To allow easier storage tank integration within the vehicle, two types of tank configuration are considered: cylindrical and rectangular. Cylindrical is self-explanatory and can utilize hemispherical or ellipsoidal end domes. Rectangular configuration means a grouping of several smaller diameter cylindrical tanks to yield an outer envelope approximately rectangular in shape. For compressed gas tankage, this arrangement is straightforward. However, for LH_2 tankage, innovative designs are needed to prevent buckling of the outer tank which must support the evacuated insulation chamber. The drawing in Figure 2 is only conceptual but more detailed design work is being conducted. Overall, the packaging advantages of rectangular LH_2 tanks are appealing but must be balanced against the extra weight, volume, and boil-off such configurations imply[5].

Future Vehicle Onboard H_2 Storage Requirement:

The storage system analysis was based on an onboard H_2 capacity of 6.8 kg, (15 lbs) usable H_2. This mass of H_2 came from early fuel cell system estimates and current chassis weight and parameters. However, as expected, should vehicle drag and weight parameters improve, the required onboard storage mass correspondingly declines. This trend is shown in Figures 3-5 for three classes of vehicles:

1) a very near-term vehicle (modified Aluminum Intensive Vehicle (AIV) Mercury Sable platform),
2) a Partnership for a New Generation Vehicle (PNGV) type vehicle featuring reduced drag and weight,
3) and a far-term future vehicle maintaining PNGV class weight but further reducing drag coefficient.

For PNGV-class vehicles, only 3.6 kg of usable H_2 must be stored onboard to achieves the required 600 km (380 miles) range on the Federal combined driving schedule. This greatly reduced H_2 storage requirement eases the packaging difficulties. Furthermore, 3.6 kg produces a 480+ km (300+ mile) range on the more realistic driving schedule approximated by increasing the velocity for each time step of the combined cycle by 25%. Prior to the introduction of PNGV-class chassis technology, heavier vehicles can still achieve useful ranges of 320+ km (200+ miles) -significantly surpassing electric vehicle ranges.

Vehicle Layouts:

Ford has also conceptually demonstrated that 3.6 kg of compressed H_2 gas can be packaged in a ground-up FCV, as shown in Figure 6. The layout vehicle, which complies with all appropriate vehicle safety and moving barrier crash test requirements, has a modified rear suspension and floorboard region where three longitudinal 34.5 MPa (5,000 psia) H_2 cylinders holding a total of 3.6 kg are placed. Thus the tanks are packaged within the vehicle with no compromise of trunk volume and minimal passenger compartment intrusion. While the layout is not ideal from the perspective of having three tanks rather than one (and the cost implications of three valves, three subsystems, and associated refueling logic and plumbing) this ground-up design shows that CH_2 storage can be successfully integrated within a passenger vehicle without appreciable intrusion.

The new Mercedes Benz A-class vehicle, shown in Figure 7, offers another option for hydrogen FCV's. While the Ford ground-up vehicle followed a minimal modification approach to storage system integration (the external lines, vehicle frame, and engine placement are quite traditional), the A-class begins with an entirely new construction paradigm. The passenger floor is raised to allow under floor drivetrain placement inside of an energy absorbing box frame. Although initially designed for an ICE or battery power supply, the high passenger compartment and non-sloping roofline of the A-class is well

[5] Compared to cylindrical configurations. rectangular LH2 tanks will have an adverse ratio of surface area to internal volume, leading to greater boil-off losses for the same insulation thickness.

suited for fuel cell power systems with a single laterally oriented compressed H_2 or LH_2 tank under the rear seat. This arrangement is not easy with more conventional vehicles unless the roofline is raised. Overall the A-class points out packaging possibilities made possible by complete vehicle re-design rather than adaptation of current ICE vehicle designs.

Summary of Conclusions:

- Both LH_2 and 34.5 MPa (5,000 psia) compressed H_2 are acceptable storage systems for fuel pure H_2 vehicles, based on weight, volume, cost, safety, development risk, and complexity.
- CH_2 offers infrastructure pathway advantages over LH_2 for the H_2 economy start-up.
- PNGV-class FCV's reduce the onboard H_2 storage requirement to 3.6 kg usable hydrogen for 600 km (380 miles) range on the combined Federal drive schedule.
- Ford has configured a representative ground up FCV storing 3.6 kg usable H_2 with little passenger and no trunk encroachment.
- Future vehicle designs offer additional packaging solutions.
- Onboard H_2 storage is not a limiting factor for direct H_2 fueled fuel cell vehicles.

Figure 1
Hydrogen Storage for PEM Fuel Cell Vehicle

			System Performance							
	Development Risk	Implementation Issues	Weight for 6.8 kg H2 (15 lbs)	Volume for 6.8 kg H2 (15 lbs)	Cost for 6.8 kg H2 (15 lbs)	Fuel Extraction	Refilling	Cyclic Life	Dormancy	Safety
Near/Moderate Term										
Compressed Gas- 34.5 MPa (5,000 psia)	Zero	Approp. Tank Safety Factor, Volume	Low 50.3 kg (111 lbs) 13.5% H2 by wt	Largest 323 liters (11.4 ft3)	Moderate/ High $548- $1,090	Gas drives air compr	Fast (<3 min)	Very High	Excellent	Good, Ultra strong high press tank
Liquid Hydrogen	Zero	Boiloff, LH2 Cost, Complexity	Low 43 kg (94 lbs) 16% H2 by wt	Moderate 187 liters (6.6 ft3)	Low/ Moderate $487- $815	Hi press gas drives air compr	Fast (5 min)	Very High	Constant boiloff	Cryo
Rechargable Hydride Mg Based (ionic)	High for low temp alloy	High Temp Complexity Low Cycle Life Poisoning	Very High 203 kg (448 lbs) 3.4% H2 by wt	Moderate 171 liters (6.0 ft3)	Moderate/ High ~$1500	290°C Heat heat source, internal heat exch, 10% unusable	Slow (20-60 min)	Low 100-1000, Poisoned if hydrogen < 99.98%	good	Slow release in accident
Others (covalent)	Low	Weight, Complexity, Low Cycle Life, Poisoning	Very High 592 kg (1305 lbs) 1.2% H2 by wt	Moderate 180 liters (6.3 ft3)	High ~$5000	90°C Heat heat source, internal heat exch, 10% unusable	Slow (20-60 min)	Low 100-1000, Poisoned if hydrogen < 99.98%	good	Slow release in accident
Carbon Adsorption Cryogenic/ Pressurized	Moderate	Cryo Refuelling	Moderate ~100 kg (~220 lbs) ~7% H2 by wt	Potentially Good 100-200 liters (3.5-7 ft3)	Moderate/ High ~$1300- ~$2700	Heater gas drives air compr	Slow (10-60 min)	Good	Constant boiloff	Cryo, Medium release in accident
Less Mature Options										
Cryo-Pressure H2 Tank	Very Low		Low 46 kg (102 lbs) 14.7% H2 by wt	Moderate 198 liters (7.0 ft3)	Modest $611	Hi press gas drives air compr	Fast (5 min)	Very High	Very Good	Good, Ultra strong high press tank
Iron-Water Hydride	Low	Low Temp. Reaction uncertain, Infra. Compatibility	High 189-330 kg (417-728 lbs) 3.6-2.1% H2 by wt	Moderate/ Good 164 liters (5.8 ft3)	Low/ Moderate	25-900°C heat needed	requires exchange of iron every refill	requires exchange of iron every refill	Very Good	Very Good
Microspheres	Moderate	Requires high quality heat & pressure at refilling center	Moderate ~159 kg (~350 lbs) ~4.3% H2 by wt	Large 524 liters (18.5 ft3)	unknown	>200°C heat needed to evolve H2	requires exchange of microspheres every refill	unknown	Constant H2 loss, half-life of approx. 110 days	Good

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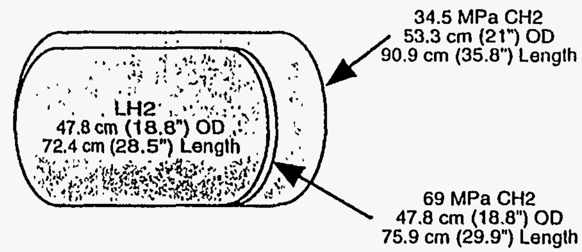
Figure 2
External Tank Dimensions for 3.6 kg of Hydrogen: Liquid Hydrogen and 34.5 MPa & 69 MPa Compressed Gas

One Tank: 3.6 kg Hydrogen

Cylindrical Envelope

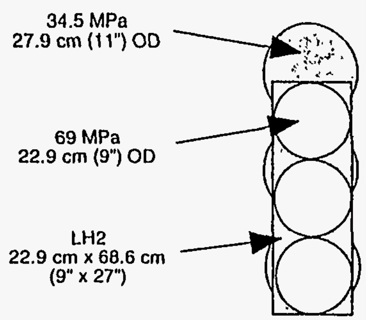


34.5 MPa = 5,000 psia
69 MPa = 10,000 psia

Rectangular Envelope

Each 34.5/69 MPa tank holds 1.2 kg Hydrogen

Side View



Top View

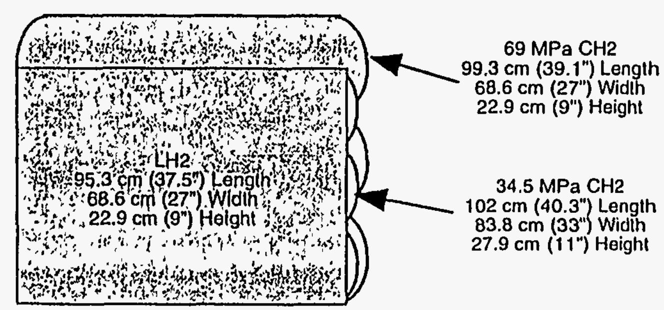


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Figure 3
Estimated Fuel Storage Requirements
for Future Fuel Cell Vehicles

Battery Augmented Fuel Cell Vehicles

		AIV Sable Fuel Cell Vehicle	PNGV-Like Fuel Cell Vehicle	Future Fuel Cell Vehicle
Test Weight (kg)		1344	1032	1032
Drag Coefficient		.33	.27	.20
Frontal Area (m^2)		2.13	2.08	2.00
Rolling Resistance		0.0092	0.0072	0.0072
Fuel Cell Max. Power(kW) (88.5 km/h@7% grade)		39.2	29.8	28.1
EPA	Urban	80.3 mpg	106.2 mpg	112.7 mpg
	Highway	84.8 mpg	113.7 mpg	135.8 mpg
	Combined	82.3 mpg	**109.6 mpg**	123.1 mpg
1.25xEPA	Urban	69.8 mpg	92.4 mpg	100.5 mpg
	Highway	62.5 mpg	82.4 mpg	102.9 mpg
	Combined	66.5 mpg	87.9 mpg	101.6 mpg
kg H2 for 380 miles of EPA Combined Cycle		4.7	**3.6**	3.1

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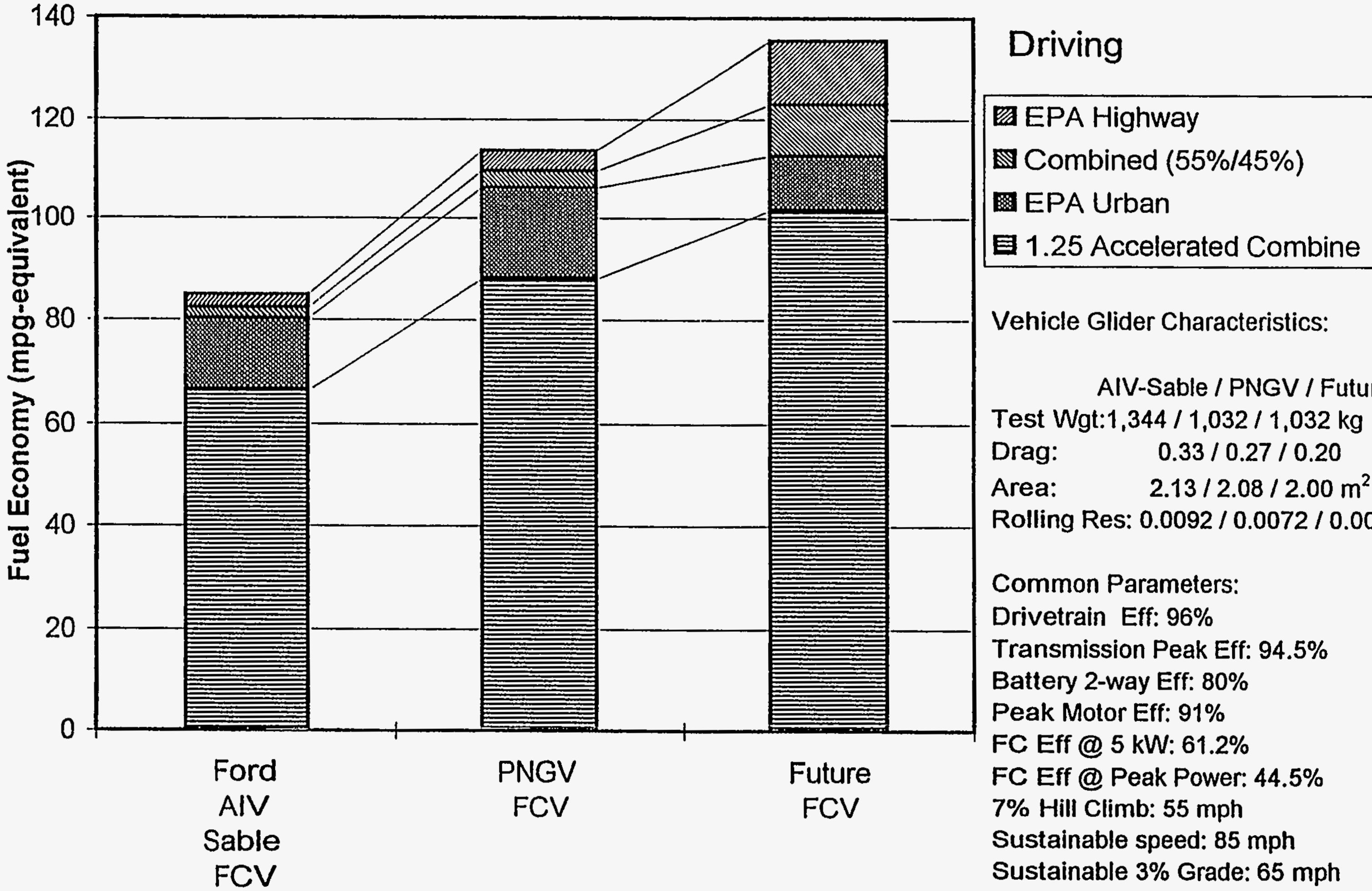
Figure 4 - Fuel Economy of Fuel Cell Vehicles



Vehicle Glider Characteristics:

AIV-Sable / PNGV / Future
Test Wgt:1,344 / 1,032 / 1,032 kg
Drag: 0.33 / 0.27 / 0.20
Area: 2.13 / 2.08 / 2.00 m^2
Rolling Res: 0.0092 / 0.0072 / 0.0072

Common Parameters:
Drivetrain Eff: 96%
Transmission Peak Eff: 94.5%
Battery 2-way Eff: 80%
Peak Motor Eff: 91%
FC Eff @ 5 kW: 61.2%
FC Eff @ Peak Power: 44.5%
7% Hill Climb: 55 mph
Sustainable speed: 85 mph
Sustainable 3% Grade: 65 mph
Accessory Power: 500 W

DTI: VEHICLE.XLS, Tab 'Range';O33 3/18/1997

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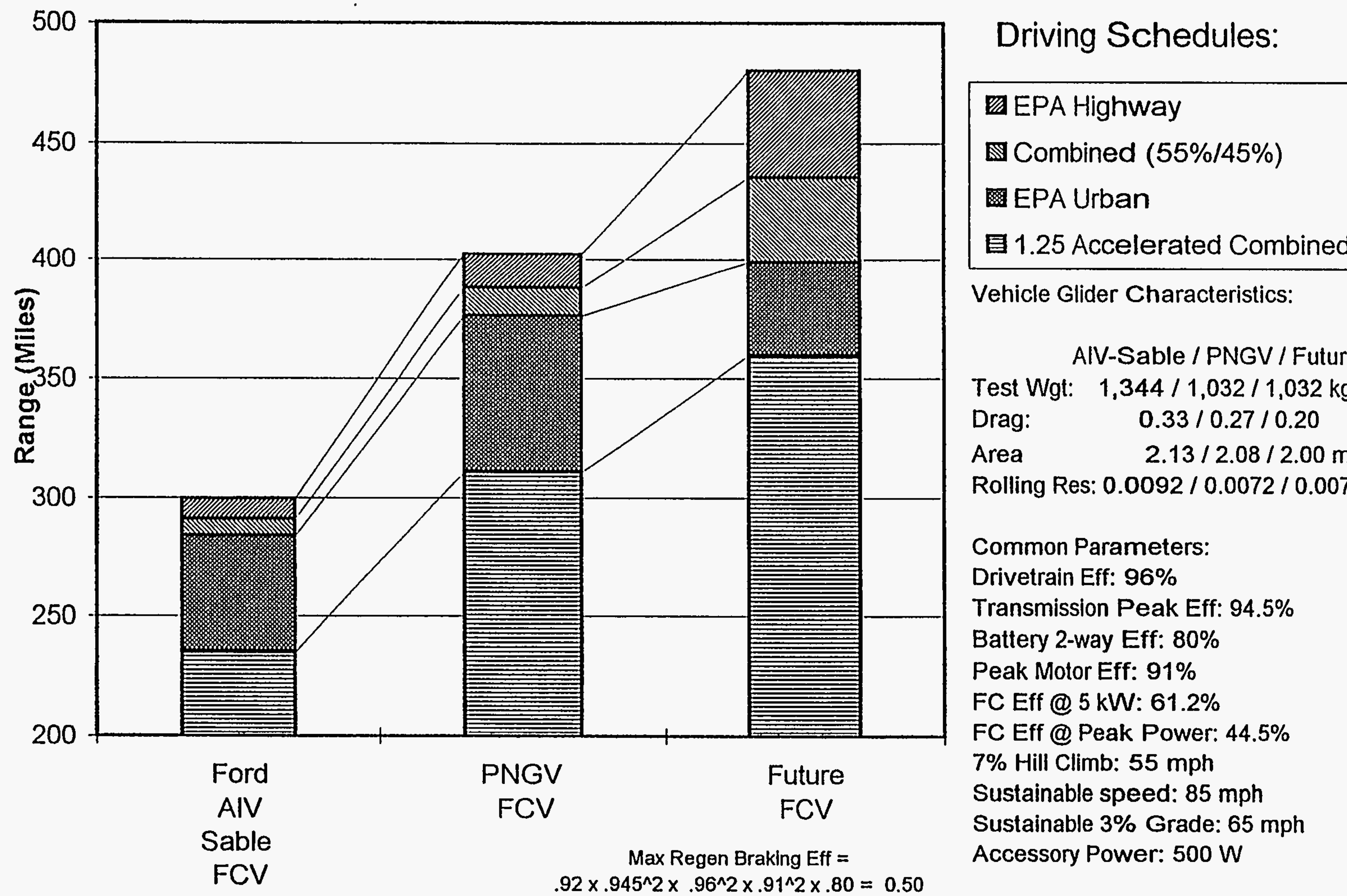
Figure 5 - Fuel Cell Vehicle Range
(on 3.58 kg of Hydrogen)



Max Regen Braking Eff =
.92 x .945^2 x .96^2 x .91^2 x .80 = 0.50

Vehicle Glider Characteristics:

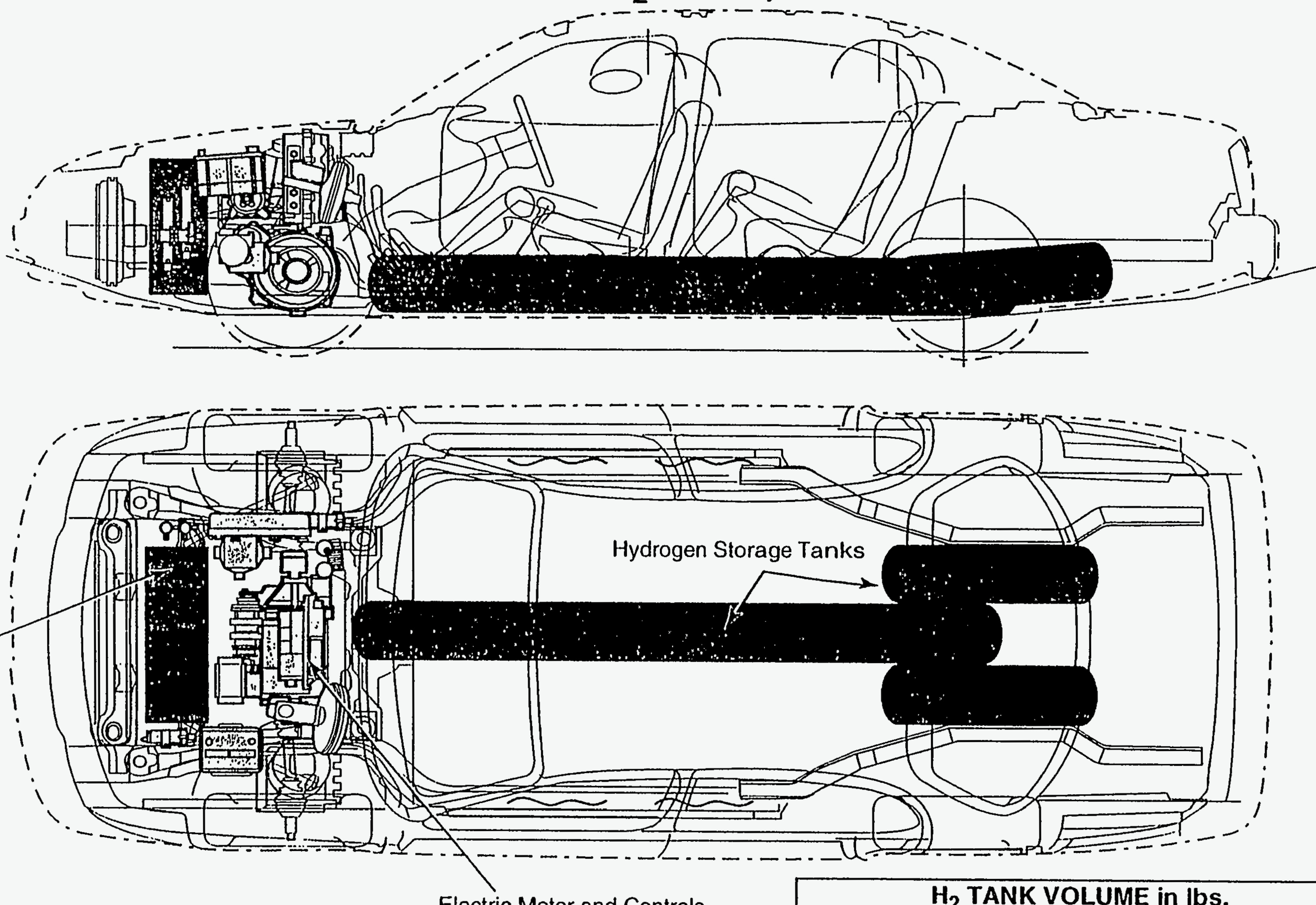
	AIV-Sable / PNGV / Future
Test Wgt:	1,344 / 1,032 / 1,032 kg
Drag:	0.33 / 0.27 / 0.20
Area	2.13 / 2.08 / 2.00 m^2
Rolling Res:	0.0092 / 0.0072 / 0.0072

Common Parameters:
Drivetrain Eff: 96%
Transmission Peak Eff: 94.5%
Battery 2-way Eff: 80%
Peak Motor Eff: 91%
FC Eff @ 5 kW: 61.2%
FC Eff @ Peak Power: 44.5%
7% Hill Climb: 55 mph
Sustainable speed: 85 mph
Sustainable 3% Grade: 65 mph
Accessory Power: 500 W

DTI: VEHICLE.XLS, Tab 'Range';E33 3/18/1997

Figure 6

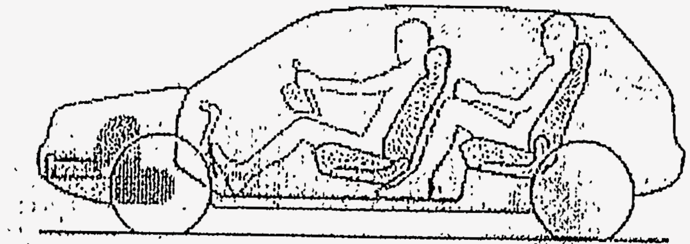
GROUND UP ZEV FUEL CELL VEHICLE
(Gaseous H_2 Tanks)



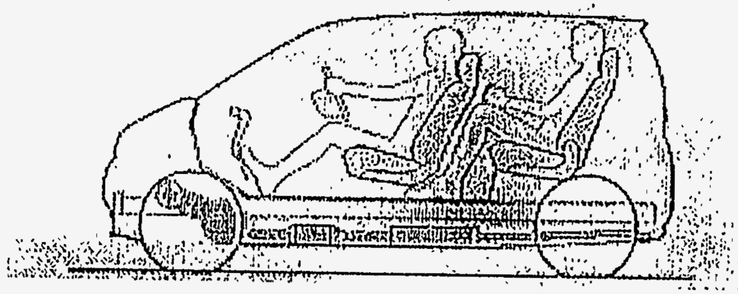
H_2 TANK VOLUME in lbs.		
	Per	Total
9.0" x 105" Long	5.0	5.0
9.0" x 35" Long	1.5	3.0
		8.0

FUEL CELL PROGRAM

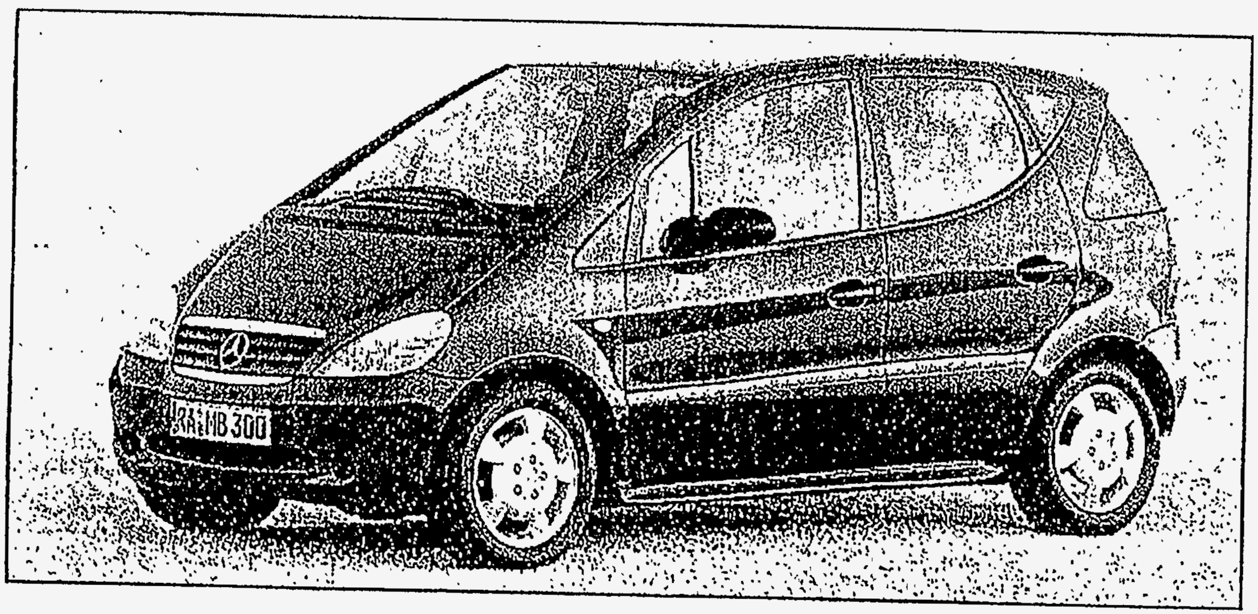
Figure 7 Mercedes-Benz A-Class Offers New Packaging Possibilities



Conventional
Configuration



A-Class Configuration
featuring "Sandwiched Floor"



A-Class Parameters

0.31 Drag Coefficient

172 cm (67.7 in.) width

356 cm (140 in.) total length

PEM Fuel Cell Cost Minimization Using "Design For Manufacture and Assembly" Techniques

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Introduction

Polymer Electrolyte Membrane (PEM) fuel cells[1] fueled with direct hydrogen have demonstrated substantial technical potential to replace Internal Combustion Engines (ICE's) in light duty vehicles. Such a transition to a hydrogen economy offers the potential of substantial benefits from reduced criteria and greenhouse emissions as well as reduced foreign fuel dependence. Research conducted for the Ford Motor Co. under a U.S. Department of Energy contract suggests that hydrogen fuel, when used in a fuel cell vehicle (FCV), can achieve a cost per vehicle mile less than or equal to the gasoline cost per mile when used in an ICE vehicle. However, fuel cost parity is not sufficient to ensure overall economic success: the PEM fuel cell power system itself must be of comparable cost to the ICE. To ascertain if low cost production of PEM fuel cells is feasible, a powerful set of mechanical engineering tools collectively referred to as Design For Manufacture and Assembly (DFMA) has been applied to several representative PEM fuel cell designs. The preliminary results of this work are encouraging,as presented below.

Methodology

The DFMA methodology, formalized by Boothroyd and Dewhurst of the University of Rhode Island[2], is the culmination of formalizing historic mechanical engineering practice regarding the design of inherently low cost components and the estimation of their manufacturing cost. The popularity and validity of the DFMA approach is demonstrated by the large number of companies, including Ford Motor Co., that employ it for design work. The techniques' central theme is that simplified design leads to low manufacturing and assembly cost. Thus, by eliminating costly design features and having each piece serve multiple functions, cost-optimized designs result. This result is achieved by evaluating plausible designs which minimize the required number of parts (and thus assembly costs) from the standpoint of their manufacturing and material costs. This level of detailed analysis requires careful consideration of the construction and design of the product (in this case a PEM fuel cell stack) and the judicious analysis of the product to identify the required manufacturing process steps, cost of these steps, direct cost of materials, and the costs attributable to overhead and profit. Additionally, it is customary to include a 10% contingency factor to ensure cost estimate conservatism. The total estimated cost of the product is reflected in the equation below:

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1 Also called Proton Exchange Membrane fuel cells

2 Product Design for Manufacture and Assembly, G. Boothroyd, P. Dewhurst, and W. Knight, Marcel Dekker, Inc., New York, 1994.

$$\text{Total Cost} = [\text{Material Cost} + \text{Manufacturing Cost} + \text{Assembly Cost}] \times \text{markups} \times \text{contingency}$$

To assess the projected PEM fuel cell stack cost at high manufacturing volumes (500,000 units/year), specific cell designs must be selected. This includes materials of construction as well as general physical dimensions, including any surface features which must be manufactured such as textures, grooves, flow manifolds, gasketing glands, etc.. Figure 1 summarizes four generic fuel cell constructions investigated in the study. All cell designs are amenable to conventional construction techniques such as injection molding and stamping: new manufacturing processes are not required. However, the mating of high production rate manufacturing processes and low cost fuel cell stack materials has not been experimentally demonstrated. Nor has the actual engineering been performed to develop the manufacturing hardware (i.e. mold and dies) to accomplish the processing assumed here. Thus, the fuel cell designs and manufacturing concepts proposed here can best be described as reasonable mechanical engineering extrapolation from accepted engineering practice.

Schematic assembly drawings of two of the representative cell types are presented in Figures 2 and 3. The drawings convey the general level of detail required in the notional designs as well as the physical configuration of typical types of PEM fuel cell hardware.

Figure 1. Cell designs investigated

Attribute	Unitized Metallic	3-Piece Metallic	Amorphous Carbon	Carbon Composite
Material	316 Stainless Steel	316 Stainless Steel	Carbon Black/Pitch	Carbon Fiber/Polymer
Processing	1)Stamp from coil, forming 3-D surface, 2)pierce/blanking to form manifolds and exterior dimensions 3) Heat-stake injection-molded gaskets	1) Pierce/blank separator 2) roll-form anode and cathode flow-fields, shear to length 4) Heat-stake injection-molded gaskets	1)Injection mold "green" plate 2)carbonize plate in oven 3)surface-grind plate to ensure flatness	1)Injection mold plate

In addition to cell design, stack architecture is an important design variable. Architecture specifically refers to the ratio of active cells to cooler cells in the stack, as well as to the physical layout of the stack. The results presented here are for a high-voltage PEM fuel cell with 420 electrochemically active cells each having an active area of 258 cm^2. The power output of such a stack based on electrochemical performance of 1.076 amps/ cm^2 at 0.6 volts per cell is roughly 70 kW gross. Such a stack would provide appropriate voltage characteristics (252-400 vdc) for use with electric traction drives commonly envisioned for fuel cell vehicles. Stack costs discussed below are for stacks with two active cells for each cooler cell. This arrangement ensures that each active cell is in direct contact with a cooler cell, helping to ensure proper thermal management of the cells. However, the optimal frequency of cooler cells is not known. Consequently, a sensitivity analysis of the stack cost per gross kilowatt versus the ratio between the cooler cells and active cells was conducted and is discussed below.

Arranging 420 cells in one long stack is unwieldy. Thus, a notional design for an Integrated Stack Package (ISP) was conceived to package the stack in a more structurally sound fashion as well as providing acceptable characteristics for stack assembly, finished product safety, and durability. A schematic assembly drawing of the ISP is shown in Figure 4 and consists of two 210 cell substacks arranged in parallel but connected electrically in series. Both substacks are fed by a common air manifold down the center of the ISP and are encased by a single stack housing which serves as both an air manifold and a protective case.

The Membrane Electrode Assembly (MEA), the actual electrochemically active portion of the cell, received particular scrutiny in this study. Special attention is warranted because current prices for ion-exchange membranes for use in the PEM fuel cells are very high. In fact, small quantities of the perfluoronated sulfonic acid polymer are more expensive per unit mass than gold. A notional production process train to make large volumes of MEA was formulated based on the open literature, and this process train shown in Figure 5 was used as a basis for estimating the MEA cost. The most surprising result of this detailed study is that the cost of the MEA, which includes platinum catalyst and carbon paper electrodes, fell to approximately $50 per square meter including markups and contingency. This cost is much lower than the current price, and reflects low catalyst loading (0.25 mg per square centimeter of MEA) as well as high volume manufacture of the membrane and electrodes. Indeed, the electrode costs may be reduced below the value used here, resulting in even further cost reduction. Specifics of the MEA process train will be presented in the poster session of this conference.

Summary of Preliminary Results

The main conclusion from the study is that multiple fuel cell designs manufactured using conventional methods are able to meet established fuel cell stack cost goals (<$30/kW). As presented in Figure 6, cost per gross kW varies from $19/kW for the injected molded composite fuel cell design to $27/kW for the three-piece metallic design. Figure 6 also breaks down the total cost per kW into the cost of various components. Even at the low MEA costs developed in this study, the MEA still accounts for a significant fraction of the fuel cell stack cost. Furthermore, MEA cost is dominated by platinum catalyst cost indicating that stack cost may most easily be reduced through further reductions in catalyst loading, as long as performance is not adversely affected.

The repeat mechanical components (the separator/bipolar plates and cooler plates) account for a relatively small fraction of the total cost of the PEM fuel cell stack, which contrasts sharply with previous cost estimates based on machined graphite repeat parts. Since machined graphite parts are inherently higher cost than the materials and techniques examined here and are ill suited to mass production, they were not even considered in the high volume cost study.

Figure 7 shows the sensitivity of PEM fuel cell stack cost to the stack architecture. It is clear from the figure that increasing the number of cooling cells increases the stack cost, an effect which is amplified for the cell constructions with high mechanical component costs. While experience has shown[3] that a large number of coolers is important to ensure peak PEM performance, it is possible that configurations with two or three active cells to each cooler cell may not sacrifice performance. Consequently, the sensitivity analysis results of Figure 7 are presented here to quantify the potential cost savings.

An important final conclusion is that because PEM fuel cell stack costs are dominated by the MEA, the electrochemical performance of the fuel cell stack has a very important direct effect on the cost of the power system per gross kW. Much research is being devoted to increasing the electrochemical performance of PEM fuel cells. The stack and system designers must always be careful to consider the cost ramifications of operation at degraded performance, and should consider the system cost in their design practice.

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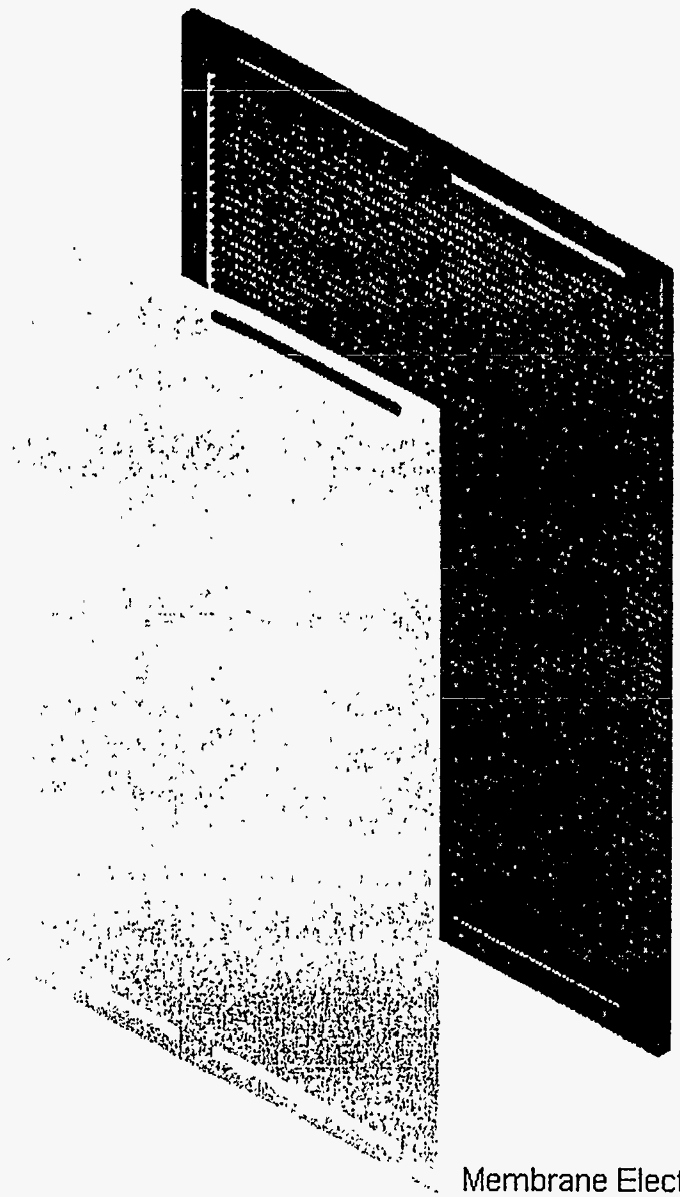
3 The patented designs of Ballard Power Systems and International Fuel Cells attest to this point.

Figure 2: Unitized, Molded Cell Cell Assembly Schematic



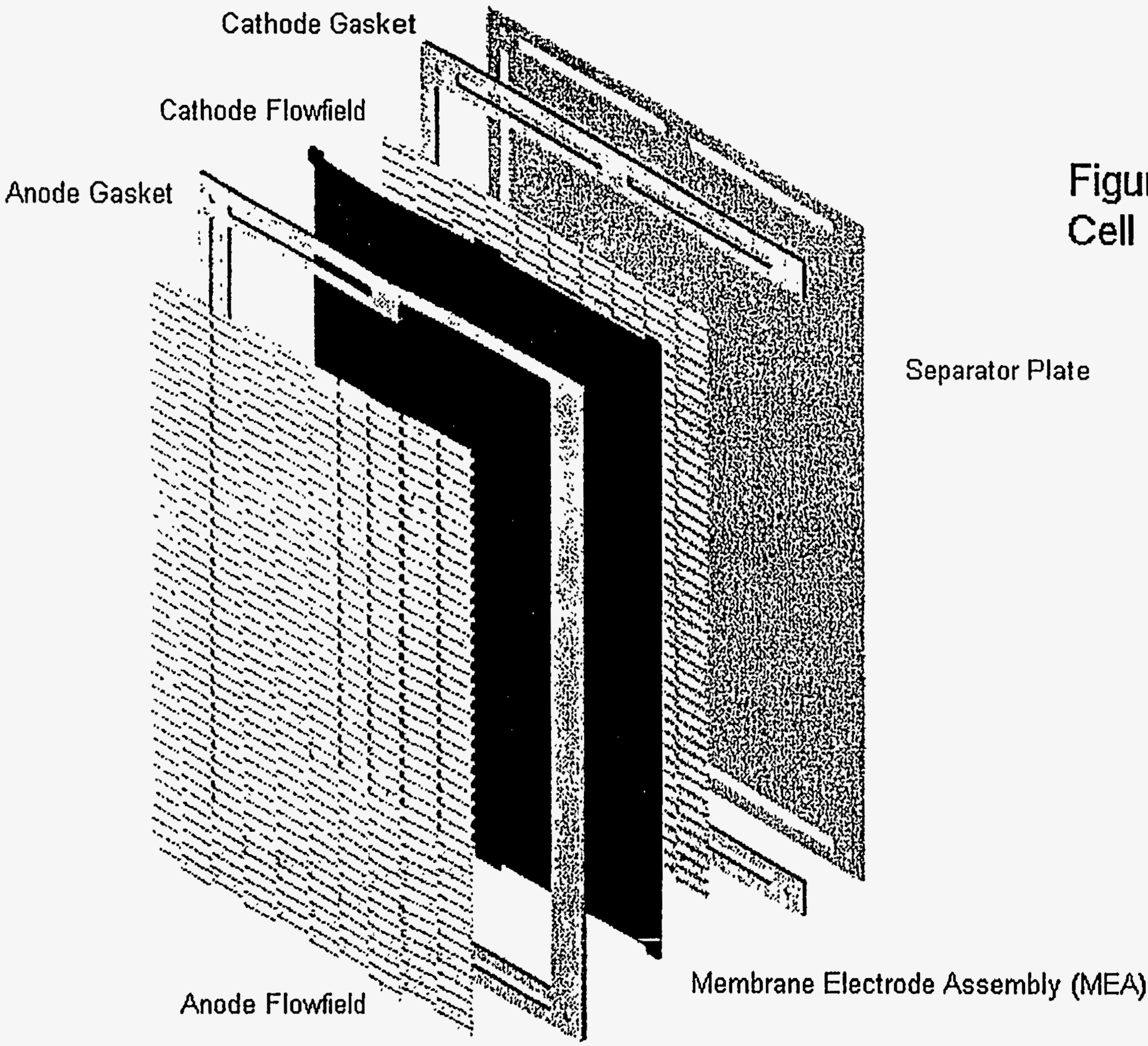
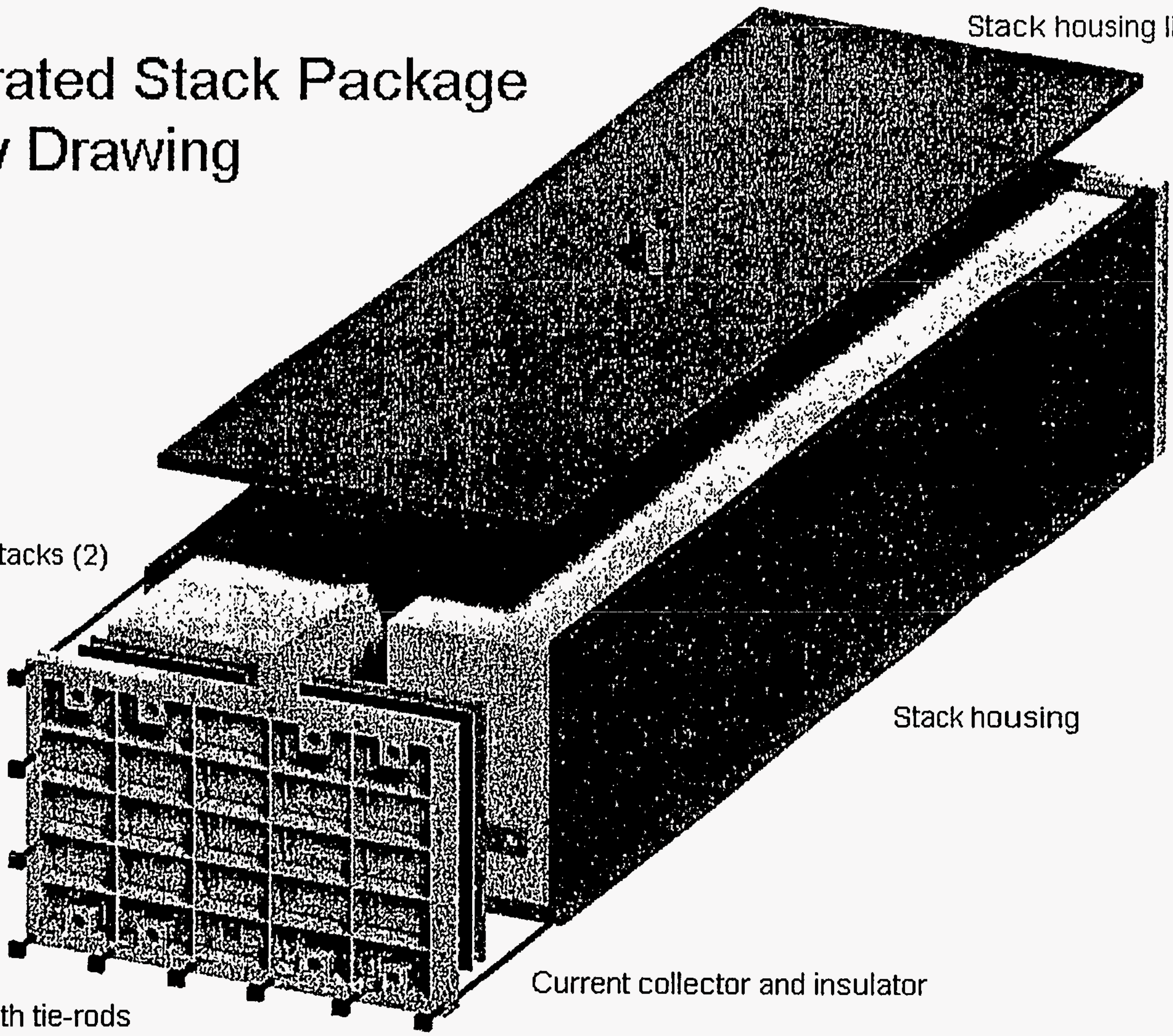


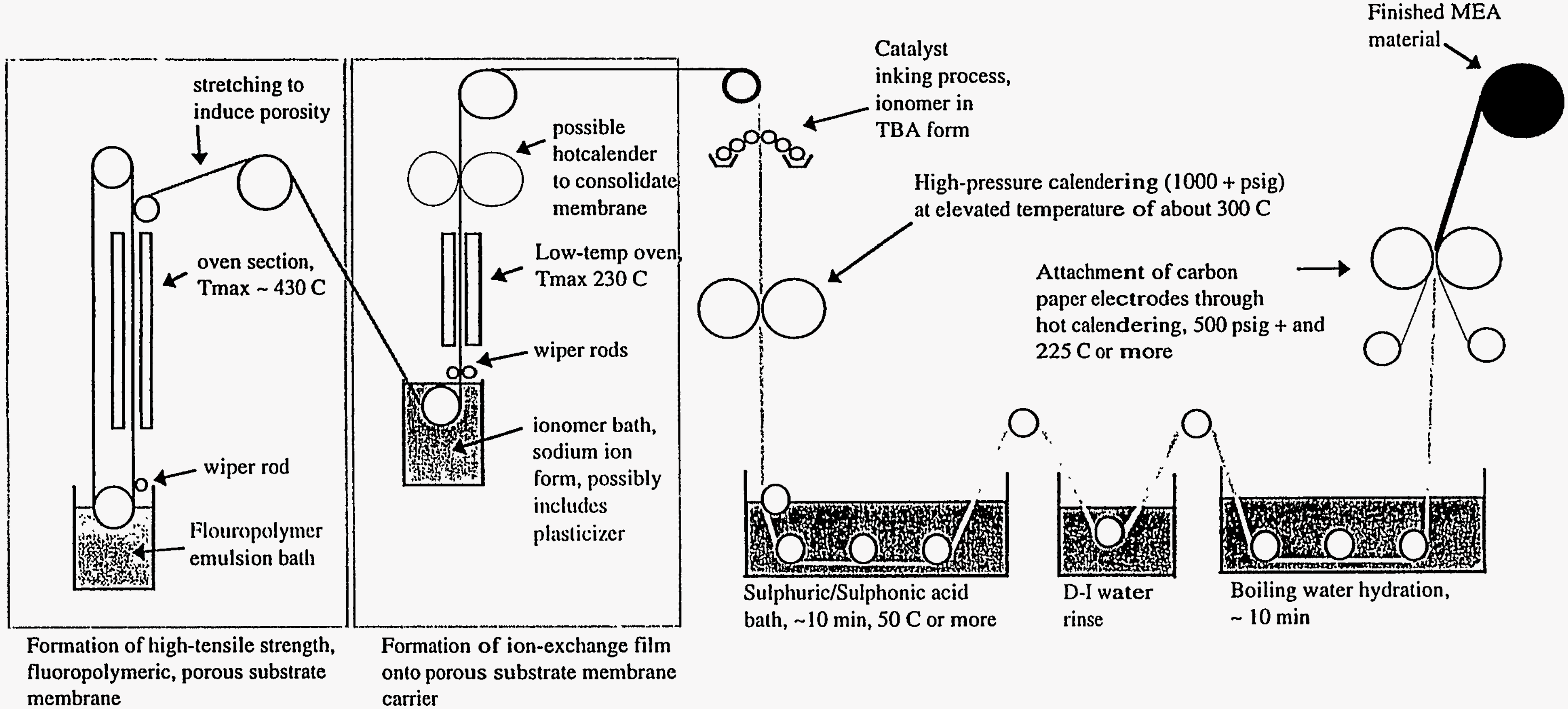
Figure 3: Three-piece Metallic Cell Cell Assembly Schematic

Figure 4: Integrated Stack Package (ISP) Assembly Drawing



Schematic View, Not to Scale

Figure 5: Proposed Membrane Electrode Assembly Integrated Process Train (Wet Process)



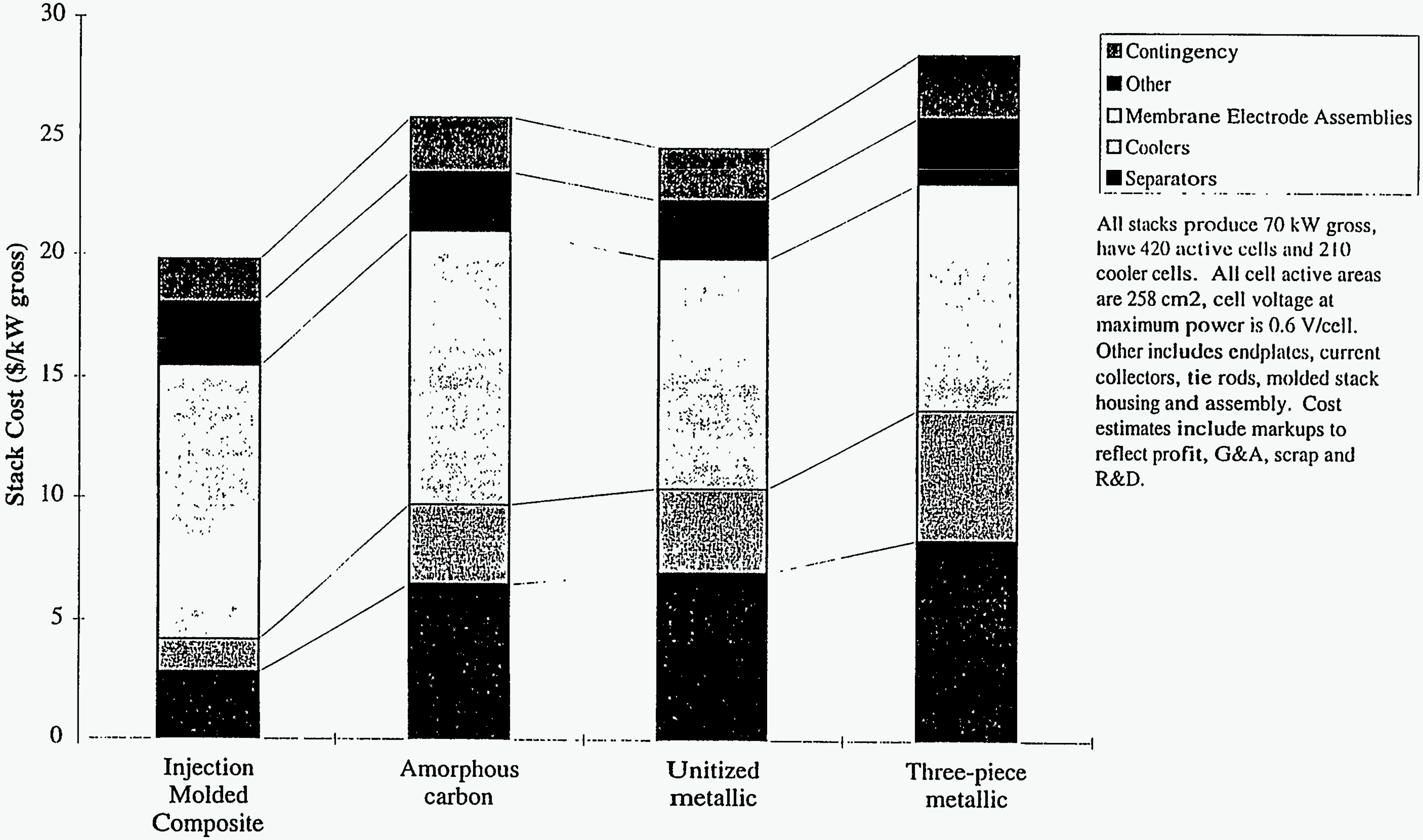
Initial bath casting onto a continuous, high-temperature polymer belt. Feed rate limited to 10 - 30 fpm by size of practical oven. Substrate membrane is peeled from the continuous belt then stretched. Stretching of partially crystallized fluoropolymer (50% - 70%) along the axis of the substrate membrane with or without additional heating. Stretching will increase the linear feed rate by a factor of 2 or greater, and result in a highly-porous substrate membrane of controlled thickness. Ionomer emulsion or solution is cast onto the web then dried and cured in an oven or hot-calendered to ensure proper consolidation. Because the ionomeric material requires lower temperatures than the fluoropolymer, high speeds should be attainable. The result is a composite ion-exchange membrane with the ionomer in the sodium ion form.

Metering bars or equivalent means are employed to add the appropriate amounts of both anodic and cathodic ink in an emulsion with the tetrabutyl ammonium (TBA) form of the ionomeric material and a carrier of dimethyl sulfoxide or other appropriate material. The inked membrane is then hot-calendered at a temperature and pressure sufficient to effect proper mating between the catalysts and the membrane. The membrane is then protonated, rinsed, and hydrated. The final step is hot calendering the carbon paper electrodes to the catalyzed membrane, which might also include hydrophobic doping with a fluoropolymer.

Based upon open literature, non-proprietary

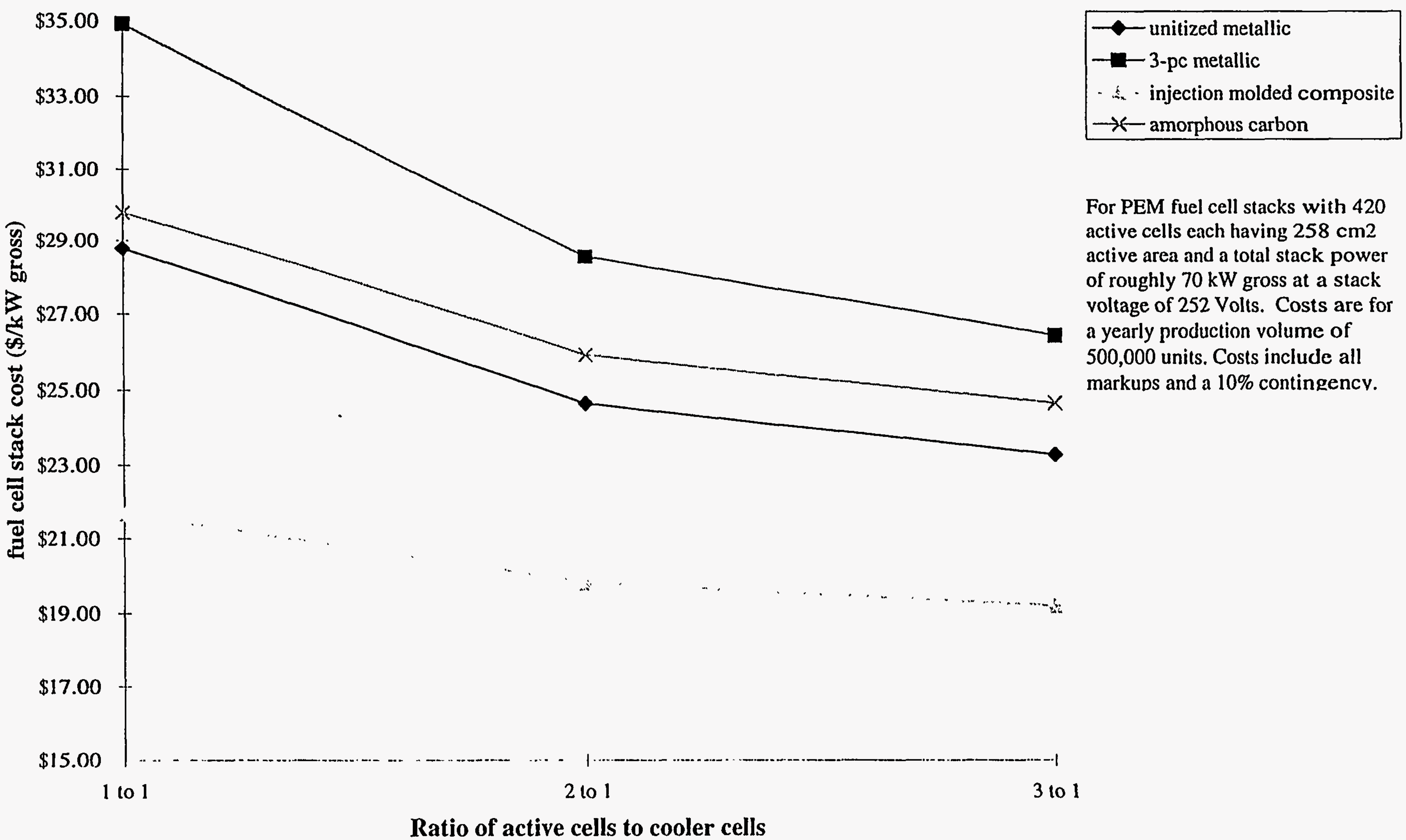
DIRECTED TECHNOLOGIES, INC.

Figure 6: Fuel Cell Stack Cost Estimates for High Volume Production (500K units)



All stacks produce 70 kW gross, have 420 active cells and 210 cooler cells. All cell active areas are 258 cm2, cell voltage at maximum power is 0.6 V/cell. Other includes endplates, current collectors, tie rods, molded stack housing and assembly. Cost estimates include markups to reflect profit, G&A, scrap and R&D.

Figure 7: PEM Fuel Cell Stack Cost vs. Stack Architecture



For PEM fuel cell stacks with 420 active cells each having 258 cm2 active area and a total stack power of roughly 70 kW gross at a stack voltage of 252 Volts. Costs are for a yearly production volume of 500,000 units. Costs include all markups and a 10% contingency.

Acknowledgments

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HYDROGEN AS A FUEL FOR FUEL CELL VEHICLES: A TECHNICAL AND ECONOMIC COMPARISON

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Abstract

All fuel cells currently being developed for near term use in vehicles require hydrogen as a fuel. Hydrogen can be stored directly or produced onboard the vehicle by reforming methanol, ethanol or hydrocarbon fuels derived from crude oil (e.g. Diesel, gasoline or middle distillates). The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure.

In this paper, we compare three leading options for fuel storage onboard fuel cell vehicles:

* compressed gas hydrogen storage
* onboard steam reforming of methanol
* onboard partial oxidation (POX) of hydrocarbon fuels derived from crude oil

Equilibrium, kinetic and heat integrated system (ASPEN) models have been developed to estimate the performance of onboard steam reforming and POX fuel processors. These results have been incorporated into a fuel cell vehicle model, allowing us to compare the vehicle performance, fuel economy, weight, and cost for various fuel storage choices and driving cycles. A range of technical and economic parameters were considered.

The infrastructure requirements are also compared for gaseous hydrogen, methanol and hydrocarbon fuels from crude oil, including the added costs of fuel production, storage, distribution and refueling stations.

Considering both vehicle and infrastructure issues, we compare hydrogen to other fuel cell vehicle fuels. Technical and economic goals for fuel cell vehicle and hydrogen technologies are discussed. Potential roles for hydrogen in the commercialization of fuel cell vehicles are sketched.

Introduction

All fuel cells currently being developed for near term use in vehicles require hydrogen as a fuel. Hydrogen can be stored directly or produced onboard the vehicle by reforming methanol or hydrocarbon fuels derived from crude oil (e.g. Diesel, gasoline or middle distillates). The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure.

While most in the fuel cell vehicle community would agree that widespread public use of hydrogen fuel cell cars is the ultimate aim, there is an ongoing debate about the most direct path to this goal. Much of this debate centers around which fuel to use and when to use it.

In this paper, we compare three leading options for fuel storage onboard fuel cell vehicles (see Figure 1):

* compressed gas hydrogen storage
* onboard steam reforming of methanol
* onboard partial oxidation (POX) of hydrocarbon fuels derived from crude oil

with respect to vehicle performance, fuel economy and cost, and infrastructure requirements.

To examine vehicle design trade-offs, models of onboard fuel processors have been developed. These have been coupled to Princeton's fuel cell vehicle simulation model. This allows us to calculate vehicle performance, fuel economy and cost for a variety of cases.

Capital costs for hydrogen refueling infrastructure development are estimated for various near term hydrogen supply options, and the cost of delivered hydrogen to the consumer is calculated. The overall infrastructure costs per car (including both onboard fuel processors and off-board refueling systems) are compared.

Finally, potential roles for hydrogen in the development of fuel cell vehicles are discussed.

Comparison Of Alternative Designs For Fuel Cell Vehicles

Model Of Fuel Cell Vehicles

A computer model for proton exchange membrane fuel cell vehicles has been developed (Steinbugler 1996, Steinbugler and Ogden 1996, Steinbugler 1997). This program allows us to estimate the performance, fuel economy and cost of alternative fuel cell vehicle designs.

Input parameters to the model include:

* the driving schedule [the Federal Urban Driving Schedule (FUDS), Federal Highway Driving Schedule (FHDS) or others may be used]
* vehicle parameters (the base vehicle weight without the power train, the aerodynamic drag, the rolling resistance, vehicle frontal area, accessory loads),

*	fuel cell system parameters (fuel cell current-voltage characteristic, fuel cell system weight),

*	peak power battery characteristics (behavior on charging and discharging. weight), and

*	fuel processor parameters (conversion efficiency, response time, weight, hydrogen utilization in the fuel cell).

First, the fuel cell system and peak power device are sized according to the following criteria:

*	The fuel cell system alone must provide enough power to sustain a speed of 55 mph on a 6.5% grade.

*	The output of the fuel cell system plus the peak power device must allow acceleration for high speed passing of 3 mph/sec at 65 mph.

These criteria are consistent with the goals set by the Partnership for a New Generation of Vehicles (PNGV).

Once the components are sized. the vehicle weight is calculated, (accounting for any extra structural weight needed on the vehicle to support the power system). Then the fuel economy is calculated for a desired driving schedule. At each time step of the driving schedule the road load equation [1] is solved to find the total power P_D needed from the vehicle's electrical power system (fuel cell plus peak power device).

$$P_D = P_{aux} + (mav + mgC_Rv + 0.5\,\rho\, C_D\, A_F\, v^3)/\eta \qquad [1]$$

where:

P_D = total electrical power demanded of vehicle's power system (Watts)
P_{aux} = power needed for accessories such as lights and wipers (Watts)
m = vehicle mass (kg)
a = vehicle acceleration (m/s^2)
v = vehicle velocity (m/s)
g = acceleration of gravity = 9.8 m/s^2
C_R = rolling resistance
ρ = density of air (kg/m^3)
C_D = aerodynamic drag coefficient
A_F = vehicle frontal area (m^2)
η = efficiency of electric motor, controller and gearing

If the fuel cell alone cannot supply the power needed, the peak power battery is called upon. Power demanded is allocated between the fuel cell and battery in a way that both accounts for fuel processor response time and aims to maintain the battery at a target state of charge. (The program is set up to keep the battery near its ideal state of charge, by recharging from the fuel cell during driving.) Knowing the fuel processor efficiency, the fuel consumed in each time step can be estimated. Fuel consumption is summed over the drive cycle and divided into the distance travelled to give a fuel economy, expressed in miles per equivalent gallon of gasoline.

Fuel Storage Capacity and Range

The vehicle range is allowed to vary, but all fuel storage systems are assumed to weigh 50 kg. We assume that 7.5% hydrogen by weight can be stored in a compressed gas tank at 5000 psia. For gasoline and methanol, 13 gallons of fuel are stored in a 12 kg tank.

Model of Fuel Cell System

The fuel cell is modelled based on current-voltage curves for existing PEM fuel cells (Steinbugler and Ogden 1996). For hydrogen-air fuel cells operated at 3 atm, with cathode stoichiometry of 2, the voltage current relation is given by [Steinbugler 1997]:

$$V = 0.787 - 0.0533 \log i - 0.148\, i + V_{comp/exp} - V_{reformate} \qquad [2]$$

where:

V = voltage output in volts
i = current density is amps/cm^2

$V_{comp/exp}$ = voltage correction for power consumed/generated by net air compression/expansion.
= -0.08 for hydrogen
= +0.067 for methanol steam reforming
= 0 for gasoline POX

$V_{reformate}$ = voltage penalty due to H_2 dilution when operating on reformate
= 0 (hydrogen)
= 0.06 i for methanol reformate
= 0.128 i for gasoline/POX

This expression is valid for $0 < i < 1.5$ amps/cm^2.

Both the power produced by the fuel cell and the power required for cathode air compression are proportional to the flow of hydrogen through the fuel cell (or the current drawn from it.) Thus in order to properly account for the net auxiliary power (compression-expansion) we apply a constant voltage drop of $V_{comp/exp}$ to the polarization curve, as shown in Eq. 1.

The output of PEM fuel cells varies with the concentration of hydrogen in the anode feed gas. For compressed gas hydrogen storage, the feed gas to the fuel cell anode is pure hydrogen. For the case of methanol steam reforming, the hydrogen content is about 75% by volume and for gasoline partial oxidation about 35%. The voltage and power output of the fuel cell on different anode feed gases is shown in Figure 2. The peak power output is highest on pure hydrogen. The higher the hydrogen content, the better the fuel cell performance, and the greater its power density.

Model of Peak Power Battery

We have modelled our peak power battery as a thin film, spiral wound, lead-acid technology, based on data from the Bolder Battery company (Juergens 1995, Keating 1996, Plichta 1995). The battery system specific weight is assumed to be 1.0 kg/kW. To ensure a long lifetime, the battery is kept near its initial state of charge of 50% by recharging from the fuel cell during driving. The battery charge and discharge rates depend on the battery power demand, the state of charge and on the battery resistance. The charging current is limited to 30 amps.

It is assumed that energy is recaptured via regenerative braking, up to the battery's maximum charge rate. When the battery state of charge exceeds its nominal value of 50%, the program demands more power from the battery and less from the fuel cell, in order to bring the battery state of charge back down to the nominal 50% level.

Models Of Onboard Fuel Processors

Onboard fuel processors convert a liquid fuel (methanol or gasoline) to a hydrogen rich gas for use in the fuel cell.

Heat integrated methanol steam reformer and gasoline partial oxidation systems have been modelled using ASPEN-plus software (Kreutz, Steinbugler and Ogden 1996, Kartha, Fischer and Kreutz 1996). Configurations for a methanol steam reformer /fuel cell system and a gasoline partial oxidation/fuel cell system are shown in Figures 3 and 4.

For the methanol steam reformer, the fuel cell anode exhaust gas is used as fuel in the reformer burner. The energy is recovered as heat input to the steam reforming reaction. The critical feedback loop, in which the anode exhaust is burned to partially satisfy the heat requirements for the steam reforming reaction, complicates a clear definition of the steam reformer efficiency independent of the fuel cell. As a gauge of system efficiency we employ the product of the steam reformer efficiency (HHV of hydrogen produced/HHV of methanol feed) times the hydrogen utilization in the fuel cell. This yields a system fuel reformer efficiency corresponding to the (HHV of the hydrogen consumed in the fuel cell)/(HHV of the methanol feed) = 62%. However, the expander work significantly exceeds that required for air compression, accounted for by a $V_{comp/exp}=0.067$ or on average an 8% increase in the DC output of the system.

In contrast to methanol steam reforming, which requires heat input, partial oxidation is an exothermic reaction. A well heat integrated POX reformer has no need for the energy contained in the anode exhaust. Some of the energy in the anode exhaust gas can be recovered for uses other than the POX reaction. For example, anode exhaust can be burned to vaporize the incoming gasoline and also to provide expander work to offset the required air compressor work. The expander work exceeds power demands for compression, but the excess power produced (<1 kWe) is not sufficient to warrant a separate generator. The conversion efficiency for the POX reactor is well defined (HHV H2 out/HHV gasoline in) and has been measured as the near-equilibrium value of 86.7% (Mitchell 1996).

For comparison with the steam reformer efficiency note that the product of the POX efficiency times the 80% hydrogen utilization in the fuel cell gives a POX system efficiency = (HHV H2 consumed/HHV gasoline in) of 69.4%.

Plotting the power demand P_D from Eq. 1, we see that the demands on the power system change rapidly over a typical drving cycle. This is shown in Figure 5, where the power required by the Federal Urban Driving Schedule is plotted vs. time. (When P_D is negative, the vehicle is braking.)

In a hydrogen fuel cell vehicle, the fuel cell should be able to follow the rapidly changing demands of the driving schedule. However, onboard fuel processors can have a longer response time, as it can take many seconds or even minutes to change the gas output of the reformer. It may be difficult for the fuel processor/fuel cell system to follow the rapidly changing demands.

For POX reactors this may not be much of an issue, as the response time is expected to be quite fast. For steam reformers, it may be longer, on the order of several seconds or more. To model the effect of response time, we assumed that the fuel processor tries to follow the demands of the driving cycle, reaching the desired level in a characteristic response time. Meanwhile, the peak power battery supplies the power needed by the drive cycle, until the fuel processor can "catch up". The peak power battery is recharged while driving from the fuel cell, when the power is lower, or from regenerative braking.

The drive cycle power demand and the output of the fuel cell system are plotted in Figure 6 for fuel processor cases with 1 and 5 second response times. The fuel cell output matches the power demand well for the 1 second case, but lags the power demand significantly for the 5 second case. The battery state of charge is also shown for each case. For the 5 second response time, the battery is used more often and the battery state of charge has larger excursions away from its target value. The amount of energy routed through the battery is shown in Figure 7 as a function of fuel processor response time for the FUDS and FHDS cycles. The longer the response time, the more the battery must be used. For a 5 second response time 40-50% of the energy reaching the wheels on the FUDS cycle has been routed through the battery.

Model Results: Vehicle Performance, Fuel Economy and Cost for Alternative Fuel Cell Vehicle Designs

We now apply the model to compare alternative designs for fuel cell vehicles. Table 1 summarizes the assumptions used in our calculations. Table 2 shows the results for vehicle mass,the required size for the fuel cell and peaking battery, the fuel economy and range for alternative fuel cell vehicle designs.

Vehicle Weight

The vehicle mass varies with the vehicle type. The various components' contributions to the total vehicle mass are shown for hydrogen, methanol and gasoline fuel cells cars in Figure 8. Vehicles with onboard fuel processors are heavier for several reasons. First, the fuel processor adds weight. Second, the fuel cell/fuel processor system is less energy efficient than a pure hydrogen system, so a larger fuel cell is needed to provide the same power output, if the fuel cell is run on reformate. Third, the mass of the vehicle support structure is increased by 15% of the additional weight it carries. The methanol fuel cell vehicle weighs about 10% more than the hydrogen vehicle, the gasoline POX vehicle about 19% more.

Power Requirements for the Fuel Cell and Peak Power Device

The peak power required is shown in Table 2 for various fuel cell vehicle designs. Roughly, the fuel cell and battery each provide about half the peak power. For hydrogen, a lower peak power output is needed because the vehicle is lighter. In Figure 9, we have plotted a histogram showing the power demands of the FUDS and FHDS cycles (fraction of the time a certain power is demanded vs. power). The power required by the FUDS and FHDS cycles is considerably less than the fuel cell power, when the fuel cell is sized for sustained hill climbing. However, the long fuel processor response time means that the battery is used even during the FUDS cycle.

Table 0. Conversion Factors And Economic Assumptions

1 GJ (Gigajoule) = 10^9 Joules = 0.95 Million BTU
1 EJ (Exajoule) = 10^{18} Joules = 0.95 Quadrillion (10^{15}) BTUs

1 million standard cubic feet (scf) = 28,300 Normal cubic meters (m_N^3) = 362 GJ (HHV)
1 million scf/day = 2.80 tons/day = 4.19 MW H_2 (based on the HHV of hydrogen)

1 scf H_2 = 362 kJ (HHV) = 344 BTU (HHV); 1 lb H_2 = 64.4 MJ (HHV) = 61.4 kBTU (HHV) = 178.5 scf
1 m_N^3 = 12.8 MJ (HHV); 1 kg H_2 =141.9 MJ (HHV) = 393 scf

1 gallon gasoline = 130.8 MJ (HHV); $1/gallon gasoline = $7.67/GJ (HHV)

All costs are given in constant $1993.

Capital recovery factor for hydrogen production systems, distribution systems and refueling stations = 15%

Table 1. Parameters Used in Fuel Cell Vehicle Modelling

Vehicle Parameters	
Glider Weight (= vehicle - power train)[a]	800 kg
Drag Coefficient[a]	0.20
Rolling Resistance[b]	0.007
Frontal Area[a]	2.0 m^2
Accessory Load[c]	0.4 kW
Structural Weight Compounding Factor[d]	15%
Fuel Cell System	
Operating pressure	3 atm
Cathode Stoichiometry	2
System weight (including air handling, thermal and water management)[e]	4.0 kg/kW
Fuel Processor Systems	
Methanol Steam Reformer	
Gross efficiency (HHV H2 consumed in fuel cell/HHV MeOH in)	62%
$V_{comp/exp}$	0.067 Volts
Hydrogen utilization[g]	80%
Voltage Penalty for reformate operation[h]	0.06 x current (amp/cm^2)
Weight of system[i]	32 kg+1.1 kg/kW
Response time	5 sec
Reformate Composition	70% H_2, 24% CO_2, 6% N_2
Gasoline POX	
Efficiency (HHV H2 consumed/HHV gasoline in)[j]	69.4%
Hydrogen utilization[g]	80%
Voltage Penalty for reformate operation[h]	0.128 x current (amp/cm^2)
Weight of system[i]	32 kg+1.1 kg/kW
Response time	1 sec
Reformate Composition	42% N_2, 38% H_2, 18% CO_2, 2% CH_4
Peak Power Battery	
Battery type	Spiral wound, thin film, lead-acid
System weight[k]	1.0 kg/kW
Maximum charge rate	30 amps
Nominal state of charge[k]	50%
Energy stored[k]	15 Wh/kg
Motor and Controller	
Overall efficiency[b]	77%
Overall weight[l]	2.0 kg/kW
Fuel Storage	
Hydrogen[d]	5000 psi compressed gas tank total weight 50 kg, 7.5% H2 by weight
Methanol, Gasoline	12 kg tank, 13 gallon capacity total weight 50 kg
Driving schedules	FUDS, FHDS
Regenerative braking recovered up to battery capabilities	

Notes for Table 1

a. Based on PNGV targets. (Source: CALSTART website. http://www.calstart.org/about/pngv/pngv_ta.html)

b. Energy and Environmental Analysis, "Analysis of Fuel Economy Boundary for 2010 and Comparison to Prototypes," p. 4-11, prepared for Martin Marietta Energy Systems, Contract No. 11X-SB0824, November 1990.

c. Ross, M. and W. Wu, "Fuel Economy Analysis for a Hybrid Concept Car Based on a Buffered Fuel-Engine Operating at a Single Point," SAE Paper No. 950958, presented at the SAE Interantional Exposition, Detroit, MI, Feb 27-March 2, 1995.

d. C.E. Thomas and R. Sims, "Overview of Onboard Liquid Fuel Storage and Reforming Systems," "Fueling Aspects of Hydrogen Fuel Cell Powered Vehicles," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, April 1-2, 1996, Arlington, VA.

e. Based on a Ballard-type PEM fuel cell system with a stack power density of 1 kg/kW. Other weight is due to auxiliaries for heat and water management equipment and air compression.

f.Arthur D. Little 1994. "Multi-Fuel Reformers for Fuel Cells Used in Transportation, Multi-Fuel Reformers, Phase I Final Report," USDOE Office of Transportation Technologies, Contract No. DE-AC02-92-CE50343-2.

g. This estimate was verified with fuel cell developers.

h. The voltage penalty for operation on reformate is based on models by Shimson Gottesfeld at Los Alamos National Laboratory.

i. William Mitchell, Arthur D. Little, private communications, 1997.

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Table 2.
Model Results: Comparison of Alternative Fuel Cell Vehicle Designs

Fuel Storage/ H2 Generation System	Vehicle mass (kg)	Peak Power (kW) (FC/Battery)	FUDS mpeg	FHDS mpeg	Combined 55% FUDS 45% FHDS mpeg	range (mi)
Direct H2	1170	77.5 (34.4/43.1)	100	115	106	425
Methanol Steam Reformer	1287	83.7 (37.0/46.7)	62	79	69	460
Gasoline POX	1395	89.4 (39.4/50.0)	65	80	71	940

For the assumptions in Table 1.

Fuel Economy

The fuel economy is shown for the FUDS. FHDS, and combined driving cycles. The combined driving cycle fuel economy is defined as:

mpg (combined) = 1/(.55/mpg FUDS + .45/mpg FHDS)

The energy efficiency of the methanol and gasoline fuel cell vehicles is about 2/3 that of the hydrogen fuel cell vehicle. The loss of efficiency is due to several effects, as shown in Figure 10. First is the 15-25% energy loss in converting methanol or gasoline to hydrogen. Second, operation on reformate means that the fuel cell has a lower efficiency. Third, the vehicle weighs 10-20% more with an onboard fuel processor. Finally, for the methanol steam reformer, the 5 second response time means that a significant fraction (40-50%) of the energy must be routed through the battery, with attendant losses in charging and discharging.

Range

The vehicle range exceeds the PNGV goal of 380 miles, for all the fuel cell vehicle cases considered in Table 2.

Vehicle Cost

The cost of alternative fuel cell vehicles is shown in Figure 11. Table 3 summarizes our cost assumptions for fuel cell vehicle components in high volume mass production. Two sets of cases are shown, one corresponding to a low range of values for fuel cell, fuel processor, battery and hydrogen storage mass produced costs, the other to a high range of values. We see that the first cost of fuel cell vehicles with onboard methanol steam reformers would be higher than that for hydrogen fuel cell vehicles by about $400-430/car. We estimate gasoline POX fuel cell cars would cost $660-870/car than hydrogen vehicles.

For comparison the manufacturing cost of corresponding parts for a gasoline internal combustion engine vehicle (e.g. the engine, transmission, electrical system, fuel and tank, and emission control systems) might be about $39/kW (Steinbugler 1997). For a gasoline IC engine car with an 94 kW engine (the estimated power for an aluminum intensive Ford Sable), this would be about $3666/car. To achieve a first cost similar to that of today's gasoline ICEVs, fuel cell vehicle components must meet stringent cost goals.

Summary

In summary, for the same performance, hydrogen fuel cell vehicles are likely to be simpler in design, lighter, more energy efficient, and less expensive than methanol or gasoline fuel cell vehicles. And the tailpipe emissions will be strictly zero.

Refueling Infrastructure Requirements for Fuel Cell Vehicles

Developing a Refueling Infrastructure for Hydrogen Vehicles

The relative simplicity of vehicle design for the hydrogen fuel cell vehicle must be weighed against the added complexity and cost of developing a hydrogen refueling infrastructure. Indeed, hydrogen infrastructure is often seen as a "show-stopper" for hydrogen fuel cell vehicles.

Table 3. Cost Estimates for Mass Produced Fuel Cell Vehicle Components

Component	High estimate	Low estimate
Fuel cell system[a]	$100/kW	$50/kW
Fuel processor system [b]	$25/kW	$15/kW
Hydrogen storage cylinder rated at 5000 psia[c]	$1000	$500
Motor and controller[d]	$26/kW	$13/kW
Peak power battery[e]	$20/kW	$10/kW
Extra structural support	$1/kg	$1/kg
Cost of 12 kg gasoline or methanol tank	$100	$100

a. Based on a range of estimates found in the literature. For example, GM/Allison projects a fuel cell "electrochemical engine" cost of $3899 for a 60 kW system including the fuel cell, fuel processor (methanol reformer), heat and water management. This is about $65/kW (at the rated power of 60 kW) or $46/kWpeak. About 45% of the cost per peak kW ($21/kW) is for the fuel cell stack, 28% ($13/kW) for the methanol reformer and the rest for auxiliaries. This cost assumes large scale mass production. (Allison Gas Turbine Division of General Motors December 16, 1992).

Mark Delucchi of Institute of Transportation Studies at UC Davis estimates a retail cost of $2954 for a mass produced 25 kW hydrogen/air PEM fuel cell system or about $120/kW. (The manufacturing cost is $59/kW, with a materials costs for the fuel cell stack plus auxiliaries estimated to be $41/kW, and the labor cost $18/kW.) (J. M. Ogden, E.D. Larson and M.A. Delucchi May 1994).

A study by Directed Technologies for the USDOE estimated a cost in mass production of $2712 for a hydrogen/air fuel cell plus auxiliaries with net output of 85 kW power (about $32/kW). Directed Technologies is now working with Ford Motor Company on fuel cell vehicles as part of the PNGV program. (Ref: B.D. James, G.N. Baum and I.F. Kuhn, Directed Technologies, Inc. "Technology Development Goals for Automotive Fuel Cell Power Systems," prepared for the Electrochemical Technology Division, Argonne National Laboratory, Contract No. W-31-109-Eng-28, February 1994.)

Chrysler estimates that even with current fuel cell manufacturing technology, mass produced costs would be $200/kW (Chris Boroni-Bird, private communications 1997).

b. W. Mitchell, J. Thijssen, J.M. Bentley, "Development of a Catalytic Partial Oxiidation Ethanol Reformer for Fuel Cell Applications," Society of Automotive Engineers, Paper No. 9527611, 1995.

c. C.E. Thomas and R. Sims. "Overview of Onboard Liquid Fuel Storage and Reforming Systems," "Fueling Aspects of Hydrogen Fuel Cell Powered Vehicles," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, April 1-2, 1996, Arlington, VA.

d. Derived from estimates in B. James, G. Baum, I. Kuhn, "Development Goals for Automotive Fuel Cell Power Systems," ANL-94/44, August 1994.

e. Based on PNGV goals

We have assessed the technical feasibility and economics of developing a hydrogen vehicle refueling infrastructure (Ogden, Dennis. Steinbugler and Strohbehn 1995, Ogden, Cox and White 1996, Ogden 1997). A number of near term possibilities for producing and delivering gaseous hydrogen transportation fuel were considered (using commercial or near commercial technologies for hydrogen production, storage and distribution). These include (see Figure 12):

* hydrogen produced from natural gas in a large, centralized steam reforming plant, and truck delivered as a liquid to refueling stations,

* hydrogen produced at the refueling station via small scale steam reforming of natural gas, (in either a conventional steam reformer or an advanced steam reformer of the type developed as part of fuel cell cogeneration systems)

* hydrogen produced in a large, centralized steam reforming plant, and delivered via small scale hydrogen gas pipeline to refueling stations,

* hydrogen produced via small scale electrolysis at the refueling station,

* hydrogen from chemical industry sources (e.g. excess capacity in ammonia plants, refineries which have recently upgraded their hydrogen production capacity, etc.), with pipeline delivery to a refuelingstation.

Economics Of Hydrogen Production And Delivery

Delivered cost of hydrogen transportation fuel

The delivered (levelized) cost of hydrogen transportation fuel (to the vehicle) from these sources is estimated in Figure 13. Delivered fuel costs are given in \$/GJ. (On a higher heating value basis, the energy cost of \$1/gallon gasoline is equivalent to \$7.7/GJ -- see Table 0.) In this example, we have used energy prices in the Los Angeles area, where the natural gas cost is low (\$2.8/GJ), and the cost of off-peak power is relatively high (3 cents/kWh). A capital recovery factor of 15% is assumed. (For other assumptions, the delivered costs will vary.) The cost contributions of various factors are shown for each technology over a range of refueling station sizes from 0.1 to 2.0 million scf/day (e.g. stations capable of refueling about 80-1600 fuel cell cars/day or 8-160 fuel cell buses/day). Although all the supply options are roughly competitive, several points are readily apparent.

* Onsite production of hydrogen via small scale steam reforming of natural gas is economically attractive and has the advantage that no hydrogen distribution system is required. Delivered hydrogen costs are shown for onsite reforming of natural gas based on: 1) conventional small steam reformer systems and 2) advanced low cost reformers, which have just been introduced for stationary hydrogen production (Farris 1996, Halvorson et.al 1997). With conventional reformer technology, hydrogen is expensive at small station sizes, but is economically attractive at larger station sizes. As discussed in a recent report (Ogden et.al. 1996), adopting lower cost, advanced steam methane reformer designs based on fuel cell reformers could substantially reduce the delivered cost of hydrogen especially at small station size. With advanced reformers, onsite

reforming is competitive with liquid hydrogen truck delivery and pipeline delivery over the whole range of station sizes considered.

* Truck delivered liquid hydrogen gives a delivered hydrogen cost of $20-30/GJ, depending on the station size. This alternative would be also attractive for early demonstration projects, as the capital requirements for the refueling station would be relatively small (Ogden et.al. 1995, Ogden et.al. 1996), and no pipeline infrastructure development would be required.

* Under certain conditions, a local pipeline bringing centrally produced hydrogen to users could offer low delivered costs. Centrally produced hydrogen ranges in cost from $3/GJ (for refinery excess) to $5-9/GJ for large scale steam reforming to $8-10/GJ for hydrogen from biomass, coal or MSW). If the cost of hydrogen production is low, higher pipeline costs could be tolerated. Still, for pipeline hydrogen to be competitive with truck delivery or onsite reforming, pipeline costs can be no more than a few $/GJ. For a small scale hydrogen pipeline system to be economically competitive a large, fairly localized demand would be required. Alternatively, a small demand might be served by a nearby, low cost supply of hydrogen.

* It appears that onsite electrolysis would be somewhat more expensive than other options, largely because of the relatively high cost of off-peak power (3 cents/kWh) assumed in the study. If the cost of off-peak power were reduced from 3 cents/kWh to 1-1.5 cents/kWh, hydrogen costs would become much more competitive.

Capital cost of building a hydrogen refueling infrastructure

The capital cost of building a hydrogen refueling infrastructure is often cited as a serious impediment to use of hydrogen in vehicles. In Figure 14 and Tables 4a and 4b, we show the capital cost of building a hydrogen refueling infrastructure for the various options discussed in the previous section. We consider two levels of infrastructure development.

* Early development of distribution system and refueling stations to bring excess hydrogen from existing hydrogen capacity to users. We assume that no new centralized hydrogen production capacity is needed. Two refueling stations serve a total fleet of 13,000 cars, each station dispensing 1 million scf H2/day to 800 cars/day. The options for providing hydrogen include: 1) Liquid hydrogen delivery via truck from existing capacity, 2) pipeline hydrogen delivery from a nearby large hydrogen plant or refinery, 3) onsite production from steam reforming of natural gas and 4) onsite production from electrolysis

* Development of new hydrogen production, delivery and refueling capacity to meet growing demands for hydrogen transportation fuel. The system serves a total fleet of 1 million cars, each station dispensing 1 million scf H2/day to 800 cars/day. Options for providing hydrogen are: 1) liquid hydrogen delivery via truck from new centralized steam reformer capacity, 2) pipeline hydrogen delivery from a new centralized hydrogen plant, 3) onsite production from steam reforming of natural gas and 4) onsite production from electrolysis.

The range of infrastructure capital costs for a system serving 13,000 fuel cell cars, is about $1.4-11.4 million or $100-900/car. The range of infrastructure capital costs for a system serving 1 million fuel cell cars. is about $400-900 million or $400-900/car.

Table 4a. Capital Cost for Developing New Hydrogen Delivery and Refueling Station Infrastructure Serving a Total Fleet of 13,000 FCV Cars, Delivering 2 million scf H_2/day (assuming that existing production capacity is used)

	Centralized Production via Steam Reforming of Natural Gas w/LH2 Delivery	Centralized Production via Steam Reforming of Natural Gas w/Pipeline Delivery	Onsite Steam Reforming of Natural Gas: Conventional Steam Methane Reformer	Onsite Steam Reforming of Natural Gas: Fuel Cell Steam Methane Reformer	Onsite Advanced Electrolysis Using Off-Peak Power
Centralized Hydrogen Production	0 (assumed that existing capacity is used)	0 (assumed that existing capacity is used)			
Hydrogen Distribution	0 (assumed that existing trucks are used)	10 km pipeline = $6.2 million (at $1 million per mile)			
2 Refueling Stations each serving 800 cars/day	$1.4 million ($0.7 per station)	$3.4 million ($1.7 million per station)	$10.8 million ($5.4 million per station)	$6.8 million ($3.4 million per station)	$11.4 million ($5.7 million per station)
TOTAL	$1.4 million	$9.6 million	$10.8 million	$6.8 million	$11.4 million
infrastructure cost per car	$105	$740	$830	$520	$880

Adapted from Ogden, Kreutz, Iwan and Kartha 1996.

Table 4b. Capital Cost for Developing New Hydrogen Production, Delivery and Refueling Station Infrastructure Serving a Total Fleet of 1 million Fuel Cell Cars, Delivering 153 million scf H_2/day

	Centralized Production via Steam Reforming of Natural Gas w/LH2 Delivery	Centralized Production via Steam Reforming of Natural Gas w/Pipeline Delivery	Onsite Steam Reforming of Natural Gas: Conventional Steam Methane Reformer	Onsite Steam Reforming of Natural Gas: Fuel Cell Steam Methane Reformer	Onsite Advanced Electrolysis Using Off-Peak Power
Centralized Hydrogen Production	$100 million for reformer + $ 200 million for liquefier + LH2 storage	$170 million for reformer + H_2 compressor			
Hydrogen Distribution	80 LH2 trucks each with a 3 tonne capacity, each making 2 local deliveries/da y = $40 million	600 km pipeline = $380 million (at $1 million per mile)			
153 1 million scf H2/day Refueling Stations each serving 800 cars/day	$104 million ($0.7 million per station)	$260 million ($1.7 million per station)	$830 million ($5.4 million per station)	$516 million ($3.4 million per station)	$870 million $5.7 million per station)
TOTAL	$440 million	$810 million	$830 million	$516 million	$870 million
Infrastructure Cost per Car	$440	$810	$830	$516	$870

Adapted from Ogden, Kreutz, Iwan and Kartha 1996.

It is important to keep in mind the results of Figure 13 for the total delivered cost of hydrogen transportation fuel, as well as the capital cost of infrastructure. Some of the lower capital cost options such as liquid hydrogen delivery, can give a higher delivered fuel cost than pipeline delivery or onsite reforming. Onsite small scale steam reforming is attractive as having both a relatively low capital cost (for fuel cell type reformers), and a low delivered fuel cost.

Developing a Refueling Infrastructure for Methanol Fuel Cell Vehicles

A modest distribution system for chemical methanol exists at present. To service a significant number of fuel cell cars, this network would have to be expanded in some places. To bring methanol to millions of fuel cell cars might involve increases in methanol production capacity as well.

The cost of truck delivery is estimated to be about the same for methanol and gasoline on a volumetric basis. Given the lower energy density of methanol, truck delivery would cost about $1.9/GJ, as compared to $1.0/GJ for gasoline (Ogden, Larson and Delucchi 1994).

The capital cost of retrofitting a refueling station from gasoline to methanol use has been estimated at about $20,000 per station. If a new methanol refueling station were built, the cost should be comparable to that for a new gasoline station, so no incremental cost as compared to gasoline is would be expected.

The costs to develop methanol refueling infrastructure should be relatively small compared to hydrogen infrastructure costs. As a first approximation, we assume additional infrastructure costs for methanol are zero.

Cost of Infrastructure for Gasoline Fuel Cell Vehicles

For this study, we have assumed that there is no extra capital cost for developing gasoline infrastructure for fuel cell vehicles. This may be an oversimplification. For example, if a new type of gasoline (e.g. very low sulfur) is needed for gasoline/POX fuel cell vehicles, this would entail extra costs at the refinery. Environmental effects of gasoline refueling stations are not considered (e.g. remediation of pollution from leaking underground storage tanks). The costs of maintaining the existing gasoline infrastructure are not considered.

Total Infrastructure Costs (On And Off The Vehicle) For Fuel Cell Vehicles: Hydrogen Compared To Methanol And Gasoline

It is often stated that use of methanol or gasoline with onboard reformers would greatly reduce (for methanol) or eliminate (for gasoline) the problem of developing a new fuel infrastructure. How does the capital cost of building a hydrogen refueling infrastructure compare to the capital cost of infrastructure development for methanol or gasoline fuel cell vehicles?

Defining "infrastructure" to mean all the equipment (both on and off the vehicle) required to bring hydrogen to the fuel cell, it is clear that gasoline and methanol fuel cell vehicles also entail extra costs -- largely for onboard fuel processing. In the case of hydrogen, the infrastructure development capital cost is paid by the fuel producer (and passed along to the consumer as a higher fuel cost). In the case of methanol or gasoline fuel cell vehicles, the capital cost is paid by the consumer buying the car.

In Figure 15 we combine our estimates of the cost of alternative fuel cell vehicles (Figure 11) and off-board refueling infrastructure (Figure 14). Our estimates show that gasoline POX fuel cell vehicles are likely to cost S660-870 more than comparable hydrogen fuel cell vehicles. The added cost of off-board refueling infrastructure for hydrogen is in the range $500-900/vehicle. The total cost for infrastructure on and off the vehicle would be comparable for hydrogen and gasoline fuel cell vehicles.

A recent study by Directed Technologies. Inc. also concluded that when the total infrastructure cost (on and off the vehicle) is considered, hydrogen infrastructure capital costs are comparable to those for methanol and gasoline (Thomas 1996).

Discussion: Is Hydrogen Refueling Infrastructure A "Show-Stopper" For Hydrogen Fuel Cell Vehicles

Our study suggests several reasons why hydrogen infrastructure development may not be an insurmountable obstacle to introducing hydrogen fuel cell vehicles.

* The technologies to produce, deliver and dispense hydrogen are well known. There appear to be no major technical hurdles to providing hydrogen transportation fuel.

* The capital cost of building a hydrogen refueling infrastructure off the vehicle appears to be comparable to the added cost of putting individual small hydrogen production systems (fuel processors) onboard each vehicle.

* There are ample resources for making hydrogen. For the next few decades, hydrogen from natural gas appears to be the least expensive option in many locations. In the longer term, gasification of biomass, municipal solid waste or coal (with sequestration of the CO_2) may offer relatively low hydrogen costs. Onsite electrolysis in areas with low cost off-peak power may be attractive as well. (Ogden, Cox and White 1996).

* In a recent case study of potential hydrogen supply and demand in the Los Angeles area (Ogden. Cox and White 1996, Ogden 1997), we found that it would be possible to introduce significant numbers of fuel cell vehicles, even without building any new hydrogen production capacity. The excess hydrogen capacity available from industrial suppliers and refineries in LA today might fuel 700-2000 PEM fuel cell buses or 30,000-100,000 PEM fuel cell cars.

Of course, hydrogen faces the same "chicken and egg" problem as any non-gasoline alternative automotive fuel, in moving beyond centrally refueled niche markets into general public refueling. More than the cost of hydrogen instructure (which appears to be comparable to the added vehicle cost of using onboard fuel processors), the issue may be getting enough hydrogen fuel cell vehicles on the road to reduce the cost of fuel cells via mass production, thereby opening the way to general automotive markets.

Hydrogen in Early Fuel Cell Fleet Demonstrations

Hydrogen is likely to play an important role in early fuel cell vehicle demonstrations. The first fuel cell vehicle fleets may be hydrogen fueled PEM fuel cell buses, for several reasons:

* Ballard will be demonstrating hydrogen fueled PEMFC buses in several cities starting in 1997, with commercialization planned for 1998.

* Refueling with hydrogen or any alternative fuel is easier at centralized fleet locations such as bus garages.

* The daily demand for hydrogen for a bus depot would be large enough to bring the delivered cost of hydrogen down somewhat because of economies of scale, especially for stations based on small scale reformers.

* Fuel cells might be economically competitive first in bus markets, where cost goals are not as stringent as for automobiles.

Early fuel cell fleet demonstrations offer an excellent opportunity to demonstrate hydrogen refueling systems as well. We recommend that hydrogen infrastructure demonstrations be an important part of hydrogen fuel cell bus projects. Demonstrations of small scale methane reformers may be of particular interest. (A fleet of about 8 PEMFC buses could be refueled daily using a small scale reformer producing 100,000 scf H2/day. Rapid developments in small scale reformer technology are making this an increasingly attractive supply option. (Halvorson, Victor and Farris 1997)

Introduction of Fuel Cell Automobiles

Several major automobile manufacturers are conducting R&D on PEM fuel cell cars (including Chrysler, GM, Ford, Daimler-Benz, Mazda, Toyota, and Honda). A PEMFC mini-van using compressed hydrogen gas storage was demonstrated in May 1996 by Daimler-Benz, and it is likely that the first mid-size PEMFC automobiles may be demonstrated before the year 2000. The first mass-produced commercial models might be available a few years later in the 2004-2010 time frame. Chrysler has announced plans to demonstrate a gasoline POX fuel cell vehicle, with commercialization possible around 2005.

If onboard partial oxidation of gasoline is perfected, this might allow a rapid introduction of fuel cell cars to the general public, with attendant lowering of fuel cell costs in mass production. But onboard POX vehicles appear to have penalties in terms of vehicle cost, complexity, efficiency and emissions, which may make hydrogen vehicles an extremely attractive successor or alternative. Given the lower first costs for hydrogen fuel cell vehicles (see Figure 11), there may be a strong incentive to switch to hydrogen fuel, even if large numbers of gasoline/POX fuel cell cars are introduced first, bringing the cost of fuel cells down via mass production. [Recent studies by Directed Technologies, Inc. suggest that the most economically attractive route to fuel cell vehicle commercialization may be starting with hydrogen fuel cell vehicles rather than gasoline (Thomas 1997).]

We recommend that demonstrations of hydrogen refueling systems (especially small scale reformers) be conducted as part of hydrogen vehicle demonstrations (bus and automotive fleets) over the next few years. (In fleet applications hydrogen fuel cell vehicles may be preferred from the beginning for reasons of vehicle simplicity and cost.) As vehicle demonstrations progress, design issues for various types of fuel cell vehicles will be better understood and the path to commercialization should become clearer.

Conclusions

Simulation programs of fuel cell vehicles and onboard fuel processors have been developed. For the same performance, we found that hydrogen fuel cell vehicles are simpler in design, lighter weight, more energy efficient and lower cost than those with onboard fuel processors.

Vehicles with onboard steam reforming of methanol or partial oxidation of gasoline have about two thirds the fuel economy of direct hydrogen vehicles. The efficiency is lower because of the conversion losses in the fuel processor (losses in making hydrogen from another fuel), reduced fuel cell performance on reformate, added weight of fuel processor compents, and effects of fuel processor response time.

For mid-size automobiles with PNGV type characteristics (base vehicle weight of 800 kg -- e.g. weight without the power train and fuel storage, aerodynamic drag of 0.20, and rolling resistance of 0.007), fuel economies (on the combined FUDS/FHDS drving cycle) are projected to be about 106 mpeg for hydrogen fuel cell vehicles, 69 mpeg for fuel cell vehicles with onboard methanol steam reforming, and 71 mpeg for onboard gasoline partial oxidation.

Based on projections for mass produced fuel cell vehicles, methanol fuel cell automobiles are projected to cost about $400-430 more than comparable hydrogen fuel cell vehicles. Gasoline/POX fuel cell automobiles are projected to cost $660-870 more than hydrogen fuel cell vehicles.

The cost of developing hydrogen refueling infrastructure based on near term technologies would be about $500-900/car depending on the type of hydrogen supply. No extra costs are assumed for developing gasoline or methanol infrastructure.

Defining "infrastructure" to mean all the equipment (both on and off the vehicle) required to bring hydrogen to the fuel cell, we find that the cost is comparable for hydrogen, methanol and gasoline POX fuel cell vehicles.

Hydrogen is the prefered fuel for fuel cell vehicles, for reasons of vehicle design, cost and efficiency, as well as potential energy supply and environmental benefits. The cost of developing hydrogen refueling infrastructure is comparable to the total cost (on and off the vehicle) for gasoline fuel cell vehicles. Like CNG or methanol, hydrogen faces the issue of reaching beyond centrally refueled fleet markets. Valuable experience can be gained in the near term by building the refueling systems for centrally refueled hydrogen fuel cell vehicle demonstrations, and investing now in technologies which could play a role in a future hydrogen infrastructure.

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Thomas, C.E. January 19-22, 1997. "Affordable Hydrogen Supply Pathways for Fuel Cell Vehicles," presented at the '97 World Car Conference, Riverside, CA.

Figure 1: Possible Fuel Cell Vehicle Configurations

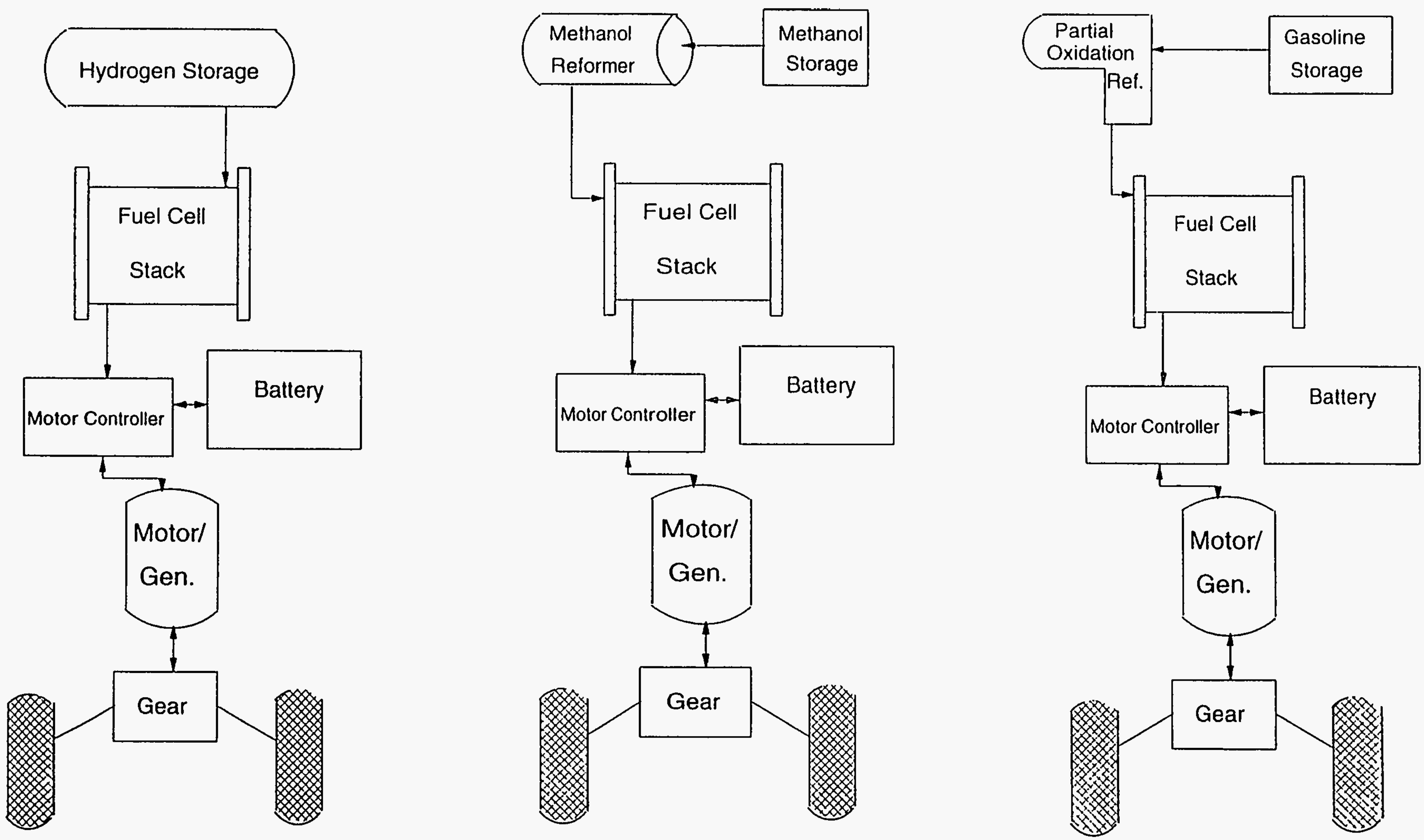
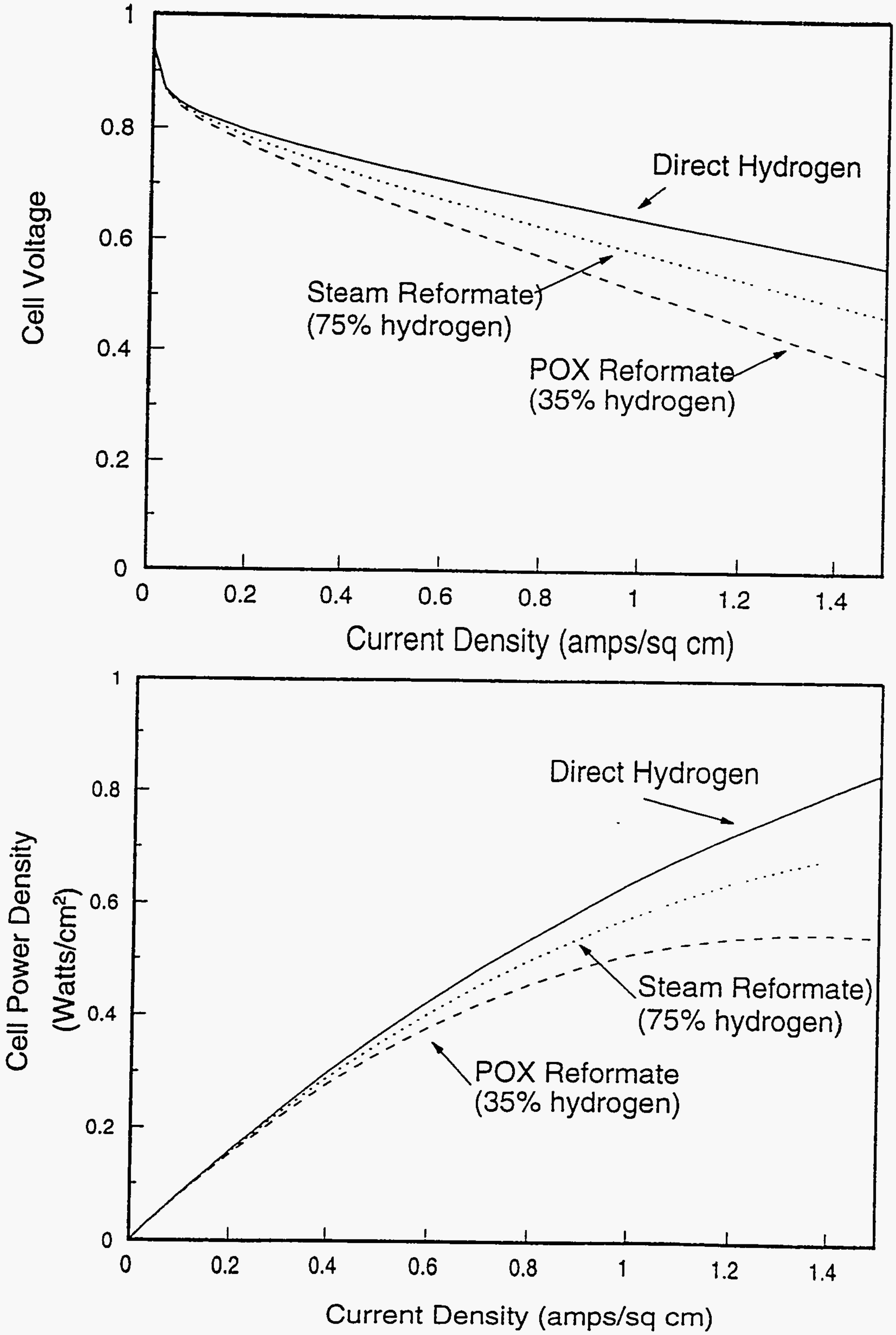


Figure 2: Fuel Cell Model Polarization and Power Curves



Methanol Steam Reformer System

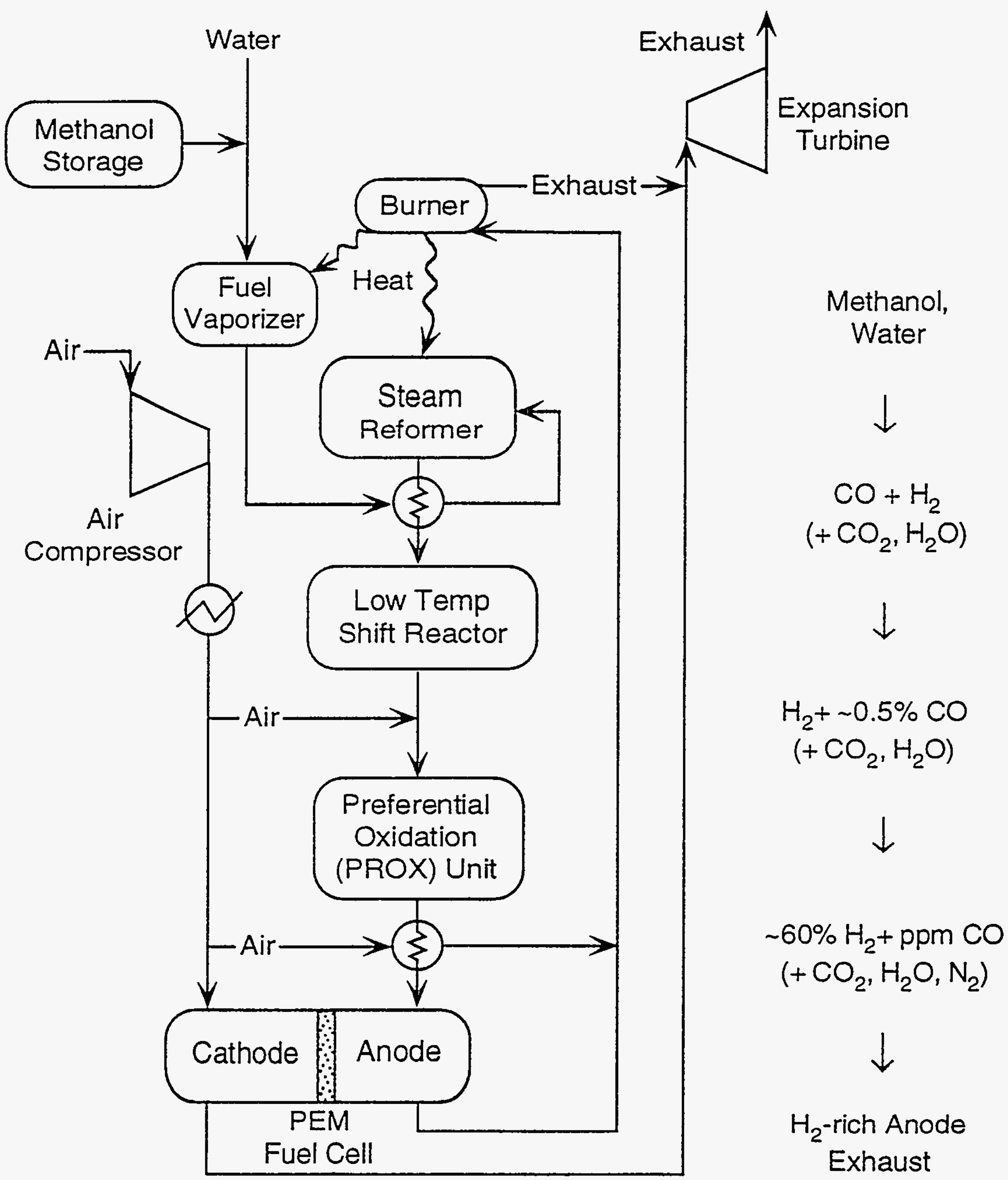


Figure 3. Schematic on-board methanol steam reforming system.

POX Reformer System

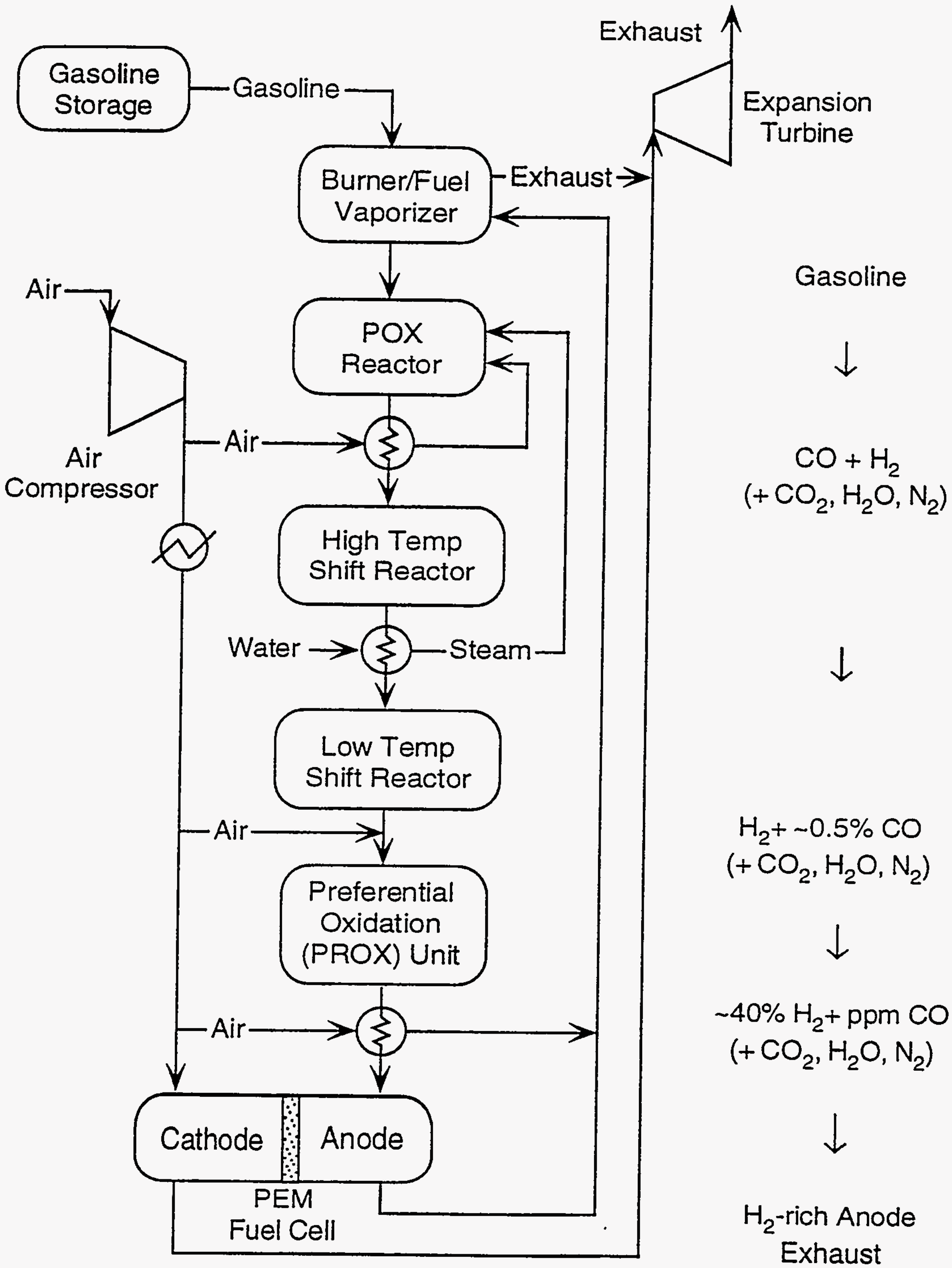


Figure 4. Schematic on-board gasoline partial oxidation (POX) reforming system.

Cycle Power Requirements and System Response

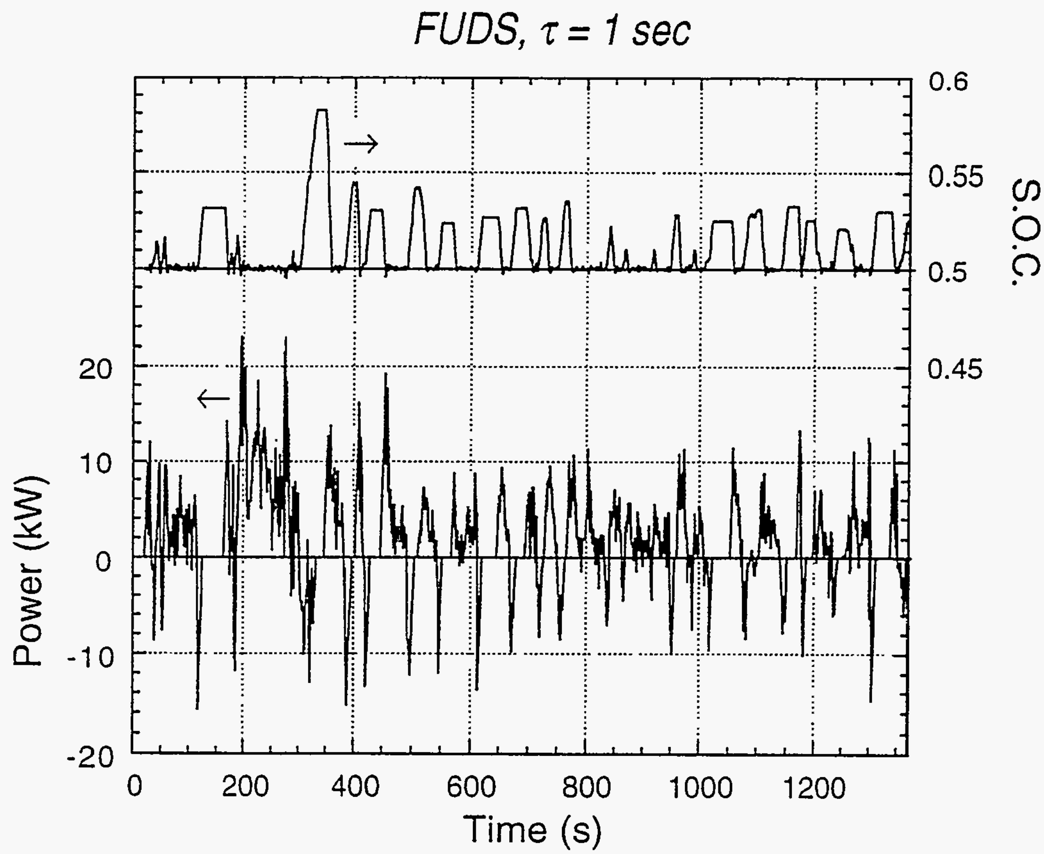


Figure 5. The power required of the fuel processor/fuel cell system during the FUDS cycle, and the resulting fractional battery state-of-charge (SOC). Conditions: 1000 kg vehicle mass, 1 sec fuel processor time constant, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

Time Constant Effects

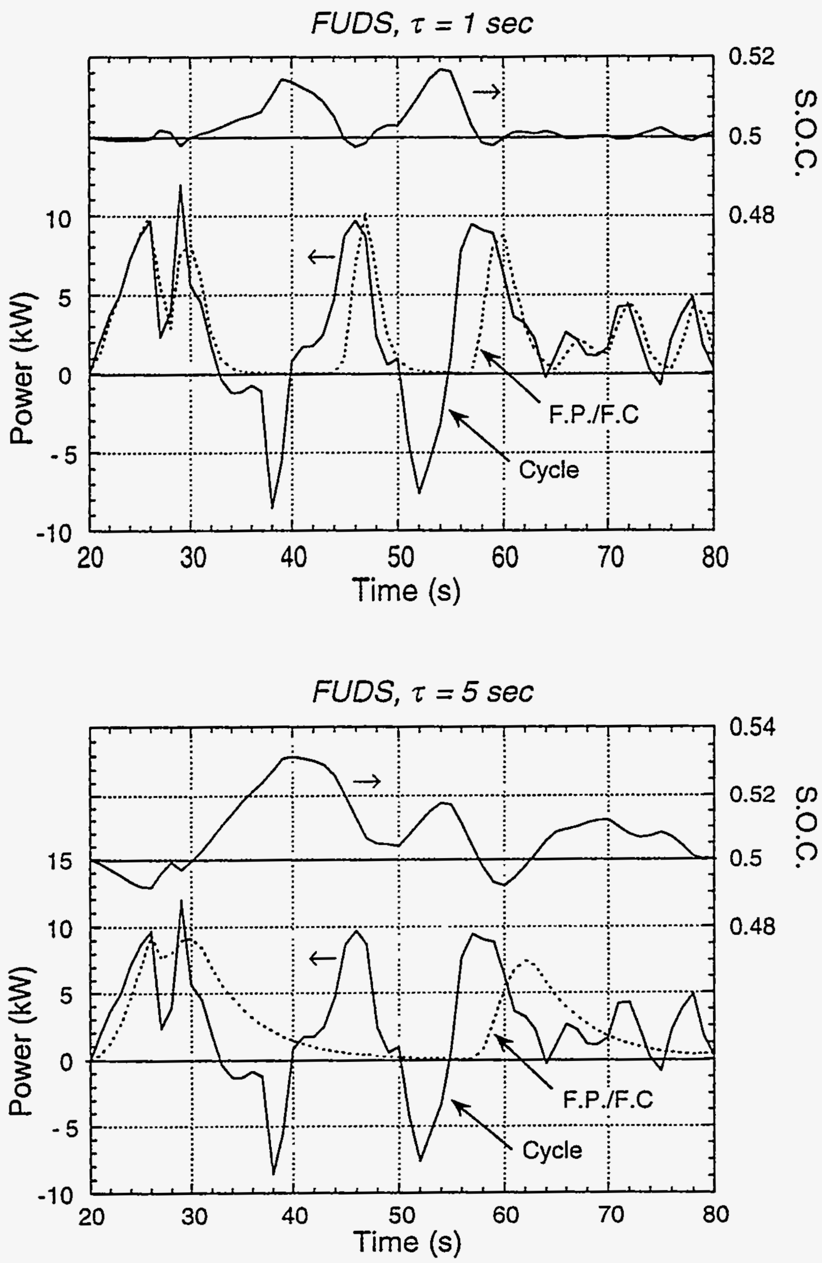


Figure 6. The power provided by the fuel processor/fuel cell - for both 1 and 5 second time constants - as a function of time in response to the power demanded by a portion of the FUDS cycle. The resulting battery fractional state of charge (SOC) is also shown, oscillating about its target value of 50%. Conditions: 1000 kg vehicle mass, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

Time Constant Effects:

Energy Routed Through Battery

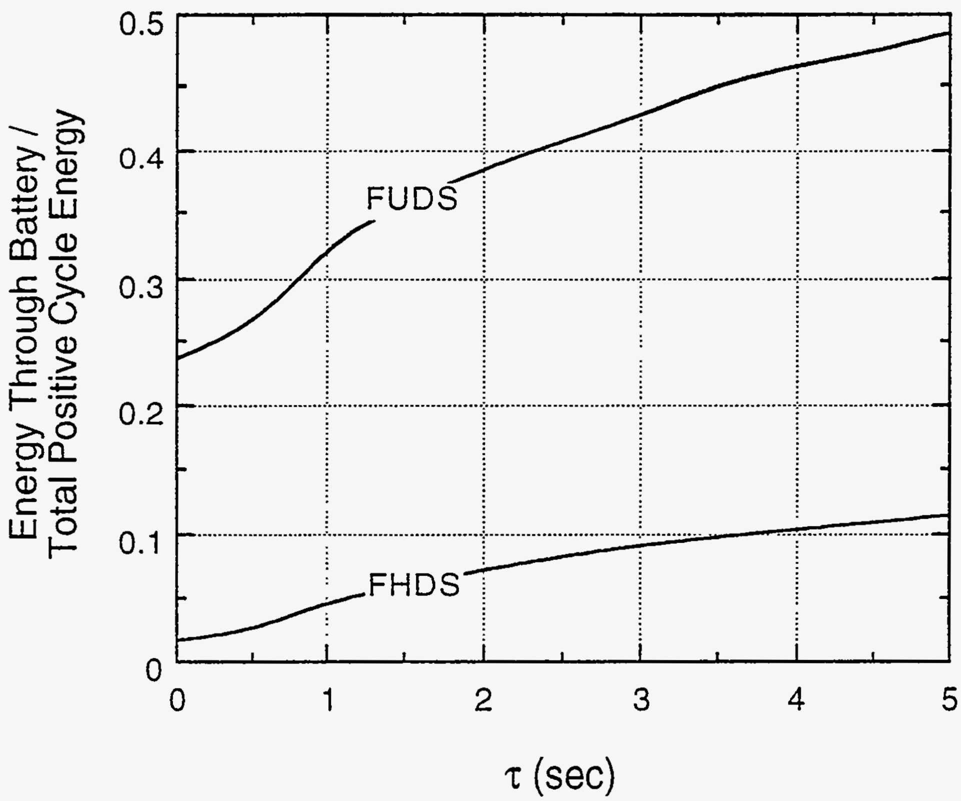
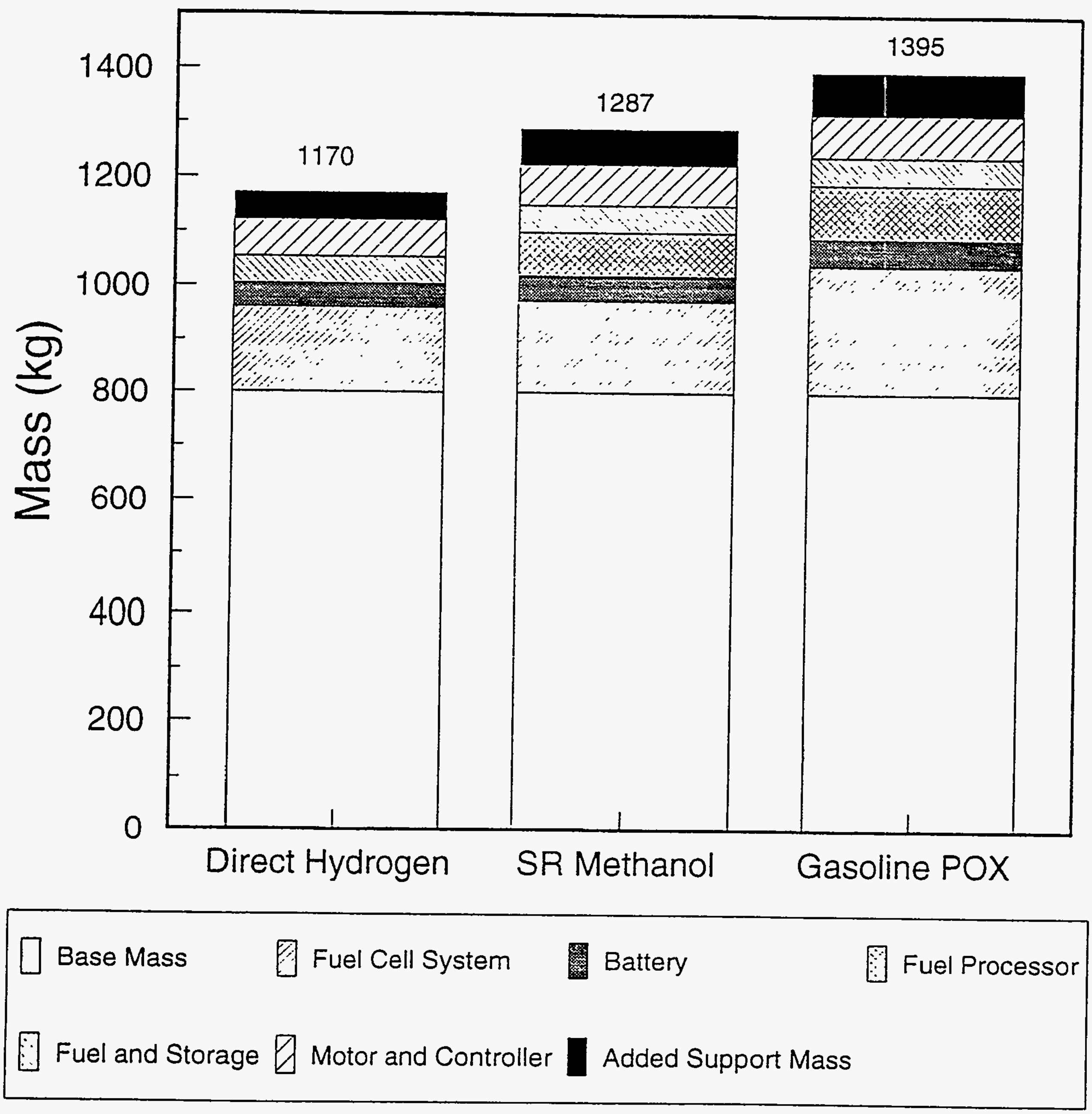


Figure 7. The fraction of the total positive cycle energy, for both the FUDS and FHDS driving cycles, that passes through the peaking device (e.g. battery), which acts as a buffer between the fuel processor/fuel cell system and the rapidly fluctuating demands of the driving cycle. Conditions: 1000 kg vehicle mass, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

Figure 8: Contributions to Vehicle Weight



Required vs. Available Power

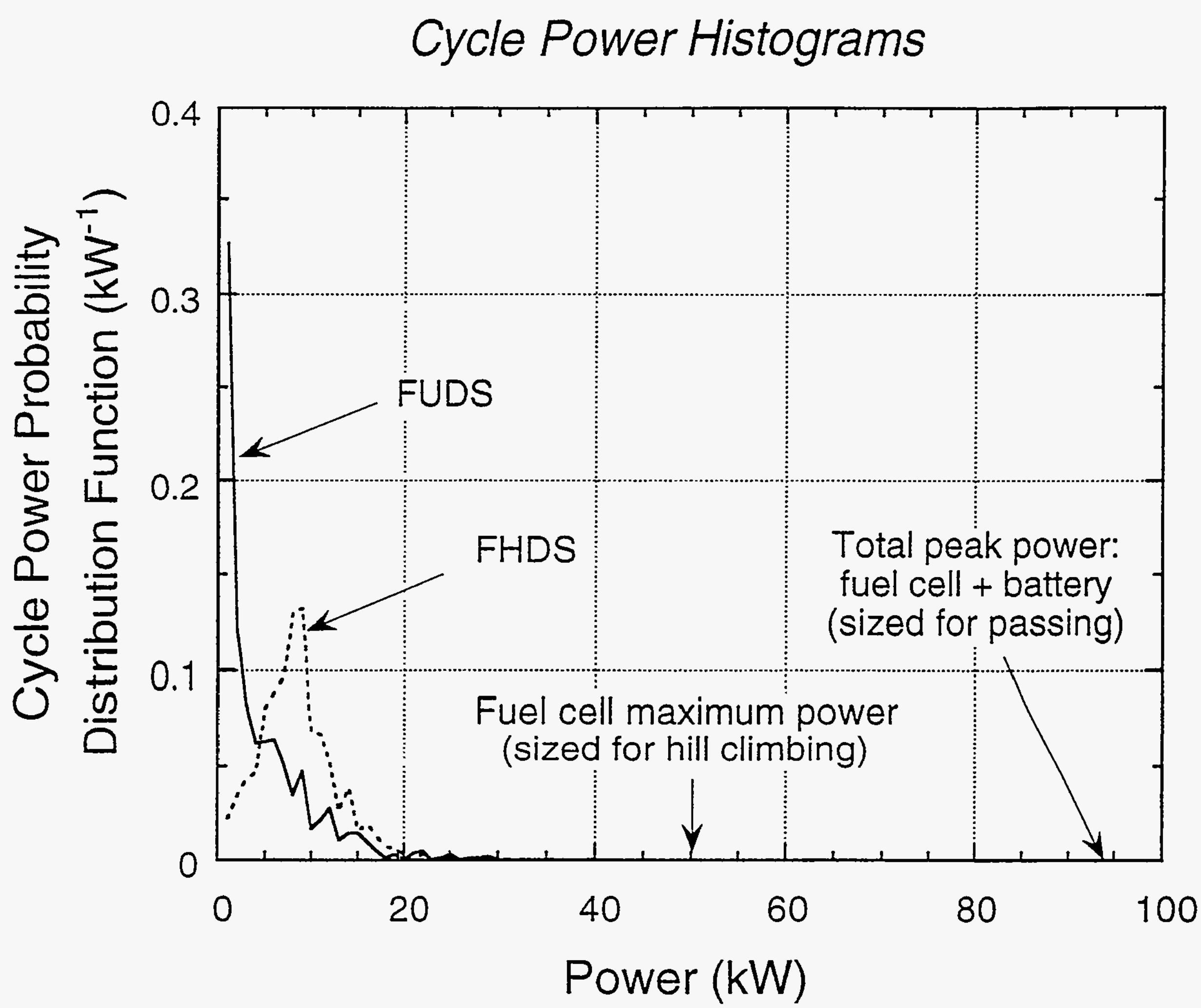


Figure 9. Histograms of the power required by the fuel processor/fuel cell system on the FUDS and FHDS driving cycles. As a result of the stiff performance requirements which govern the size of the fuel cell and the battery, much much more power is available than is usually called for under 'normal' driving conditions. Conditions: 1000 kg vehicle mass, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

Figure 10

Fuel Economy Penalties From On-Board Fuel Processing

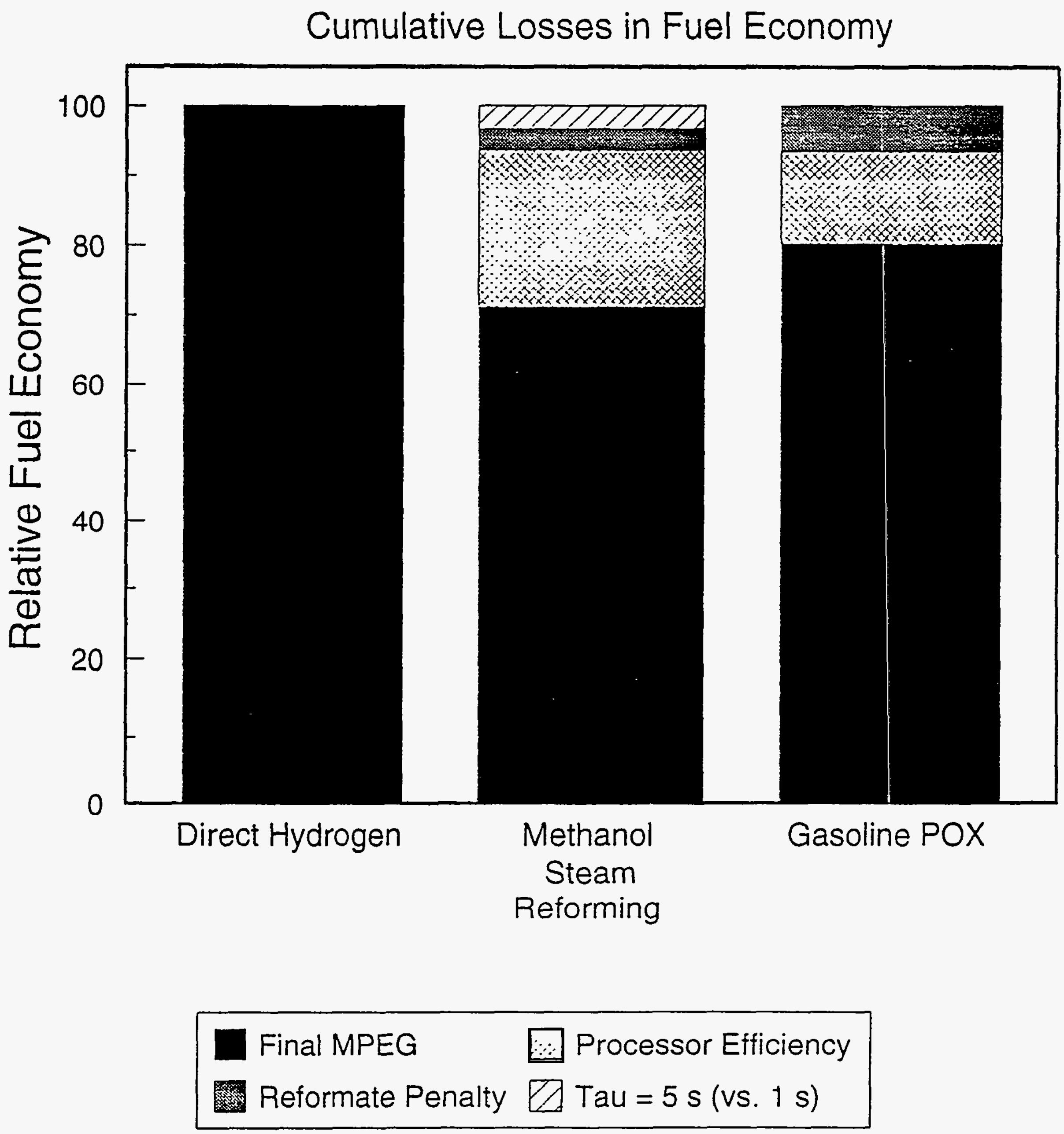
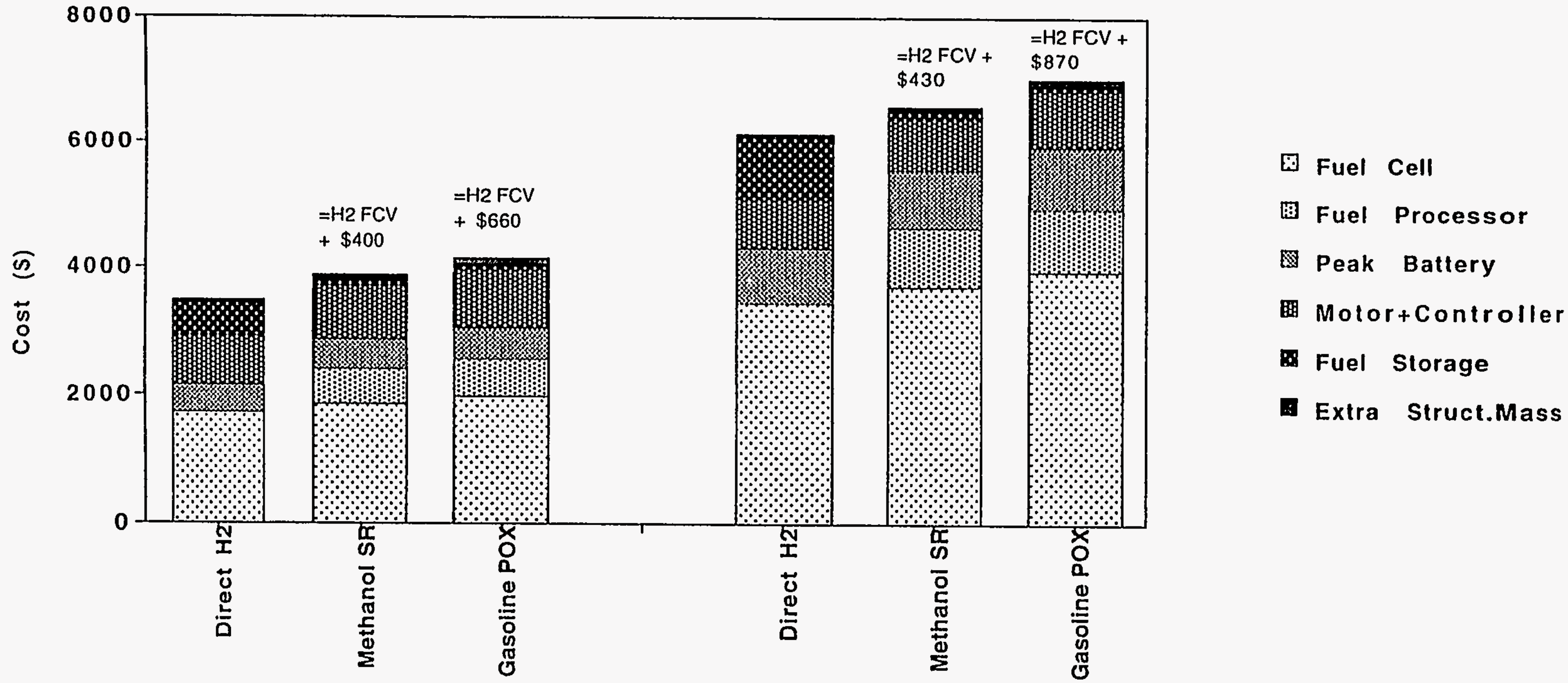


Fig. 11 Cost of Components in Alternative Fuel Cell Automobiles



Fuel Cell = $50/kW
Fuel Processor = $15/kW
Peak Battery = $10/kW
H2 cylinder = $500
Motor+Controller=$13/kW
Gasoline or MeOH Tank =$100
Extra Struct. Mass = $1/kg

Fuel Cell = $100/kW
Fuel Processor = $25/kW
Peak Battery = $20/kW
H2 cylinder = $1000
Motor+Controller=$13/kW
Gasoline or MeOH Tank =$100
Extra Struct. Mass = $1/kg

FIG 12. NEAR TERM GASEOUS H2 SUPPLY OPTIONS

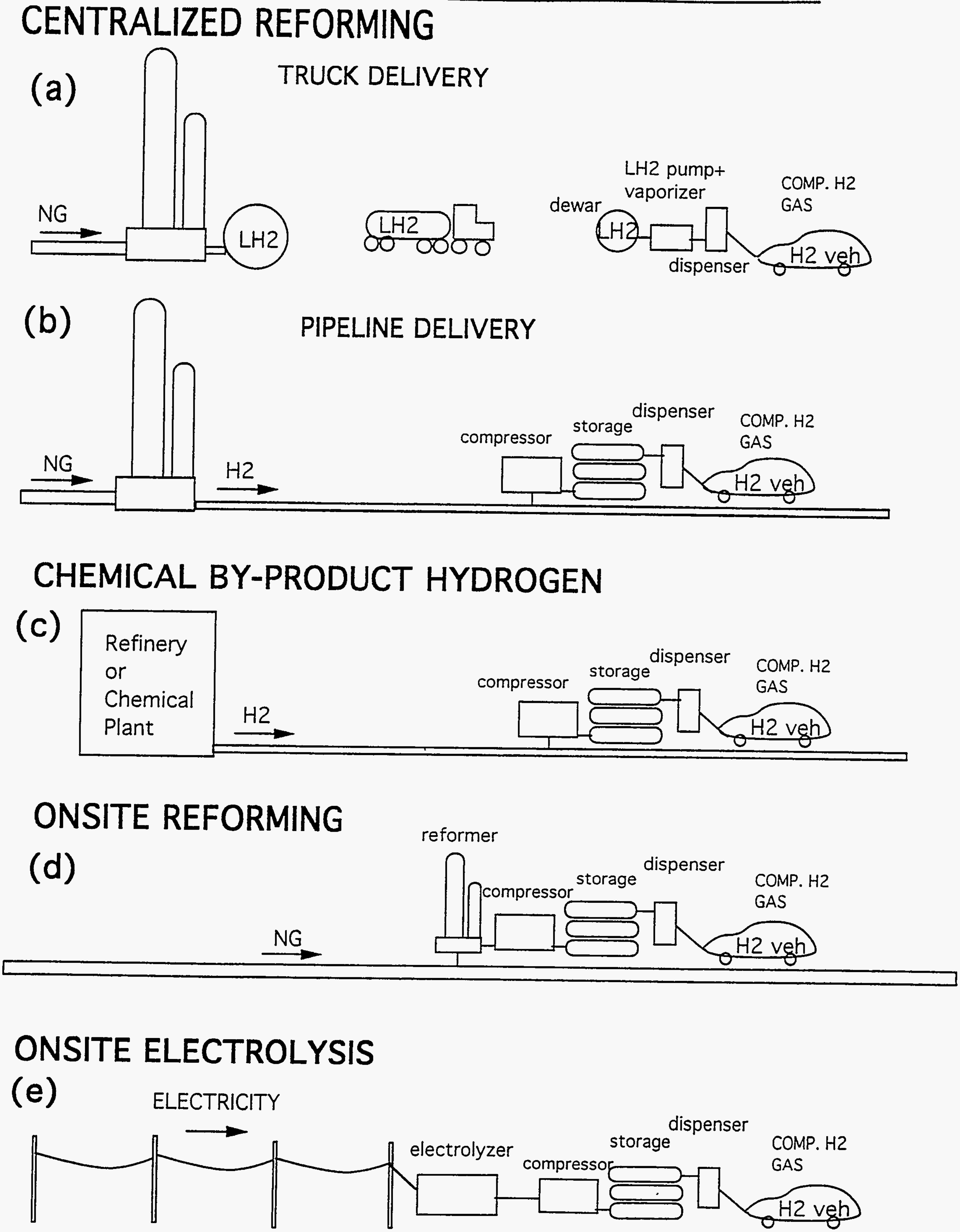


Figure 13. Delivered Cost of Hydrogen Transportation Fuel ($/GJ) vs. Station Size

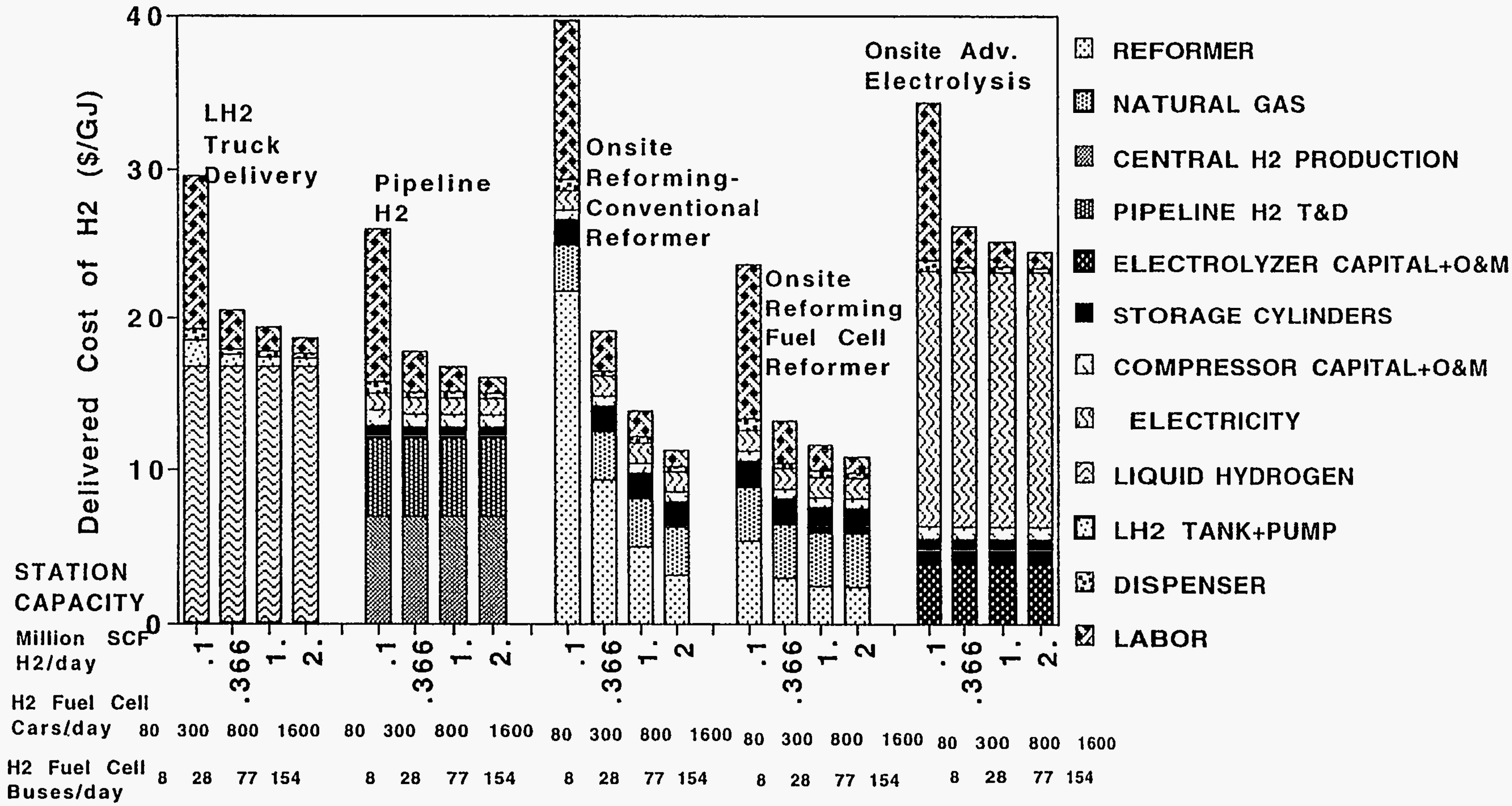
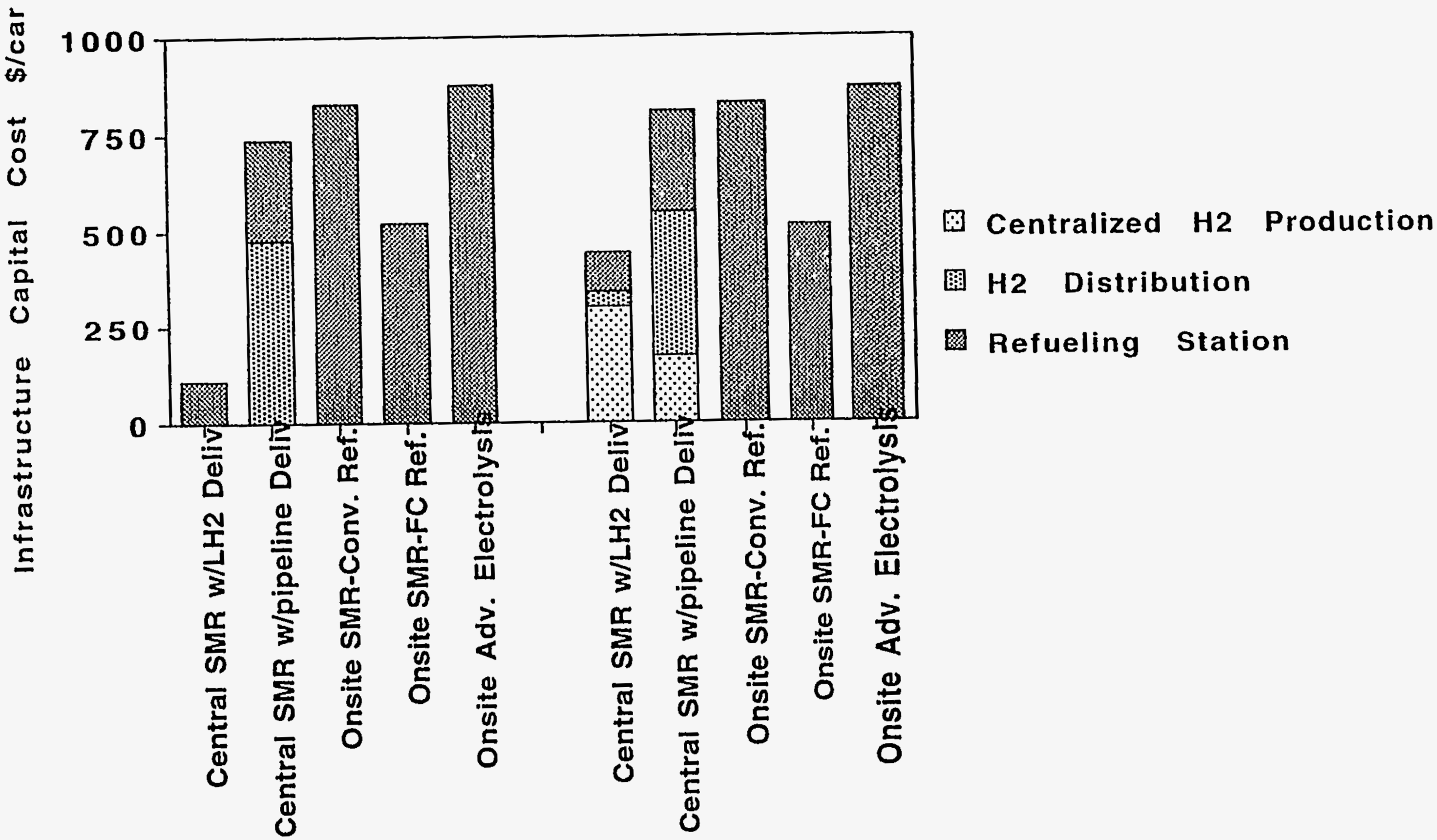


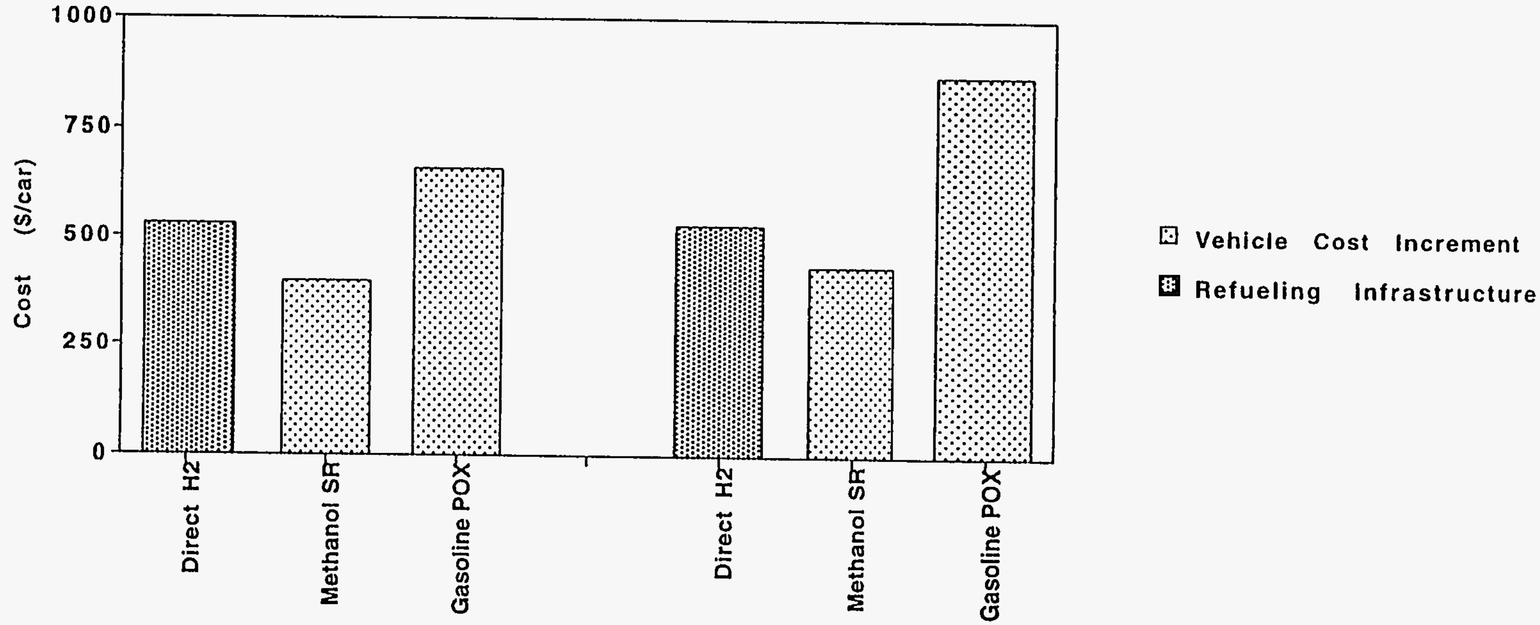
Figure 14. Capital Cost of Hydrogen Infrastructure



Early Development : Total fleet of 13,000 fuel cell cars. Centralized Options use Existing H2 Production Capacity

Extensive infrastructure development: Total fleet of 1 million fuel cell cars. Centralized options use new H2 Production Capacity

Fig. 15. Comparison of Incremental Costs for Vehicles (Compared to H2 Fuel Cell Vehicle) and Infrastructure (Compared to Gasoline)



Fuel Cell = \$50/kW
Fuel Processor = \$15/kW
Peak Battery = \$10/kW
H2 cylinder = \$500
Motor+Controller=\$13/kW
Gasoline or MeOH Tank =\$100
Extra Struct. Mass = \$1/kg

Fuel Cell = \$100/kW
Fuel Processor = \$25/kW
Peak Battery = \$20/kW
H2 cylinder = \$1000
Motor+Controller=\$13/kW
Gasoline or MeOH Tank =\$100
Extra Struct. Mass = \$1/kg

H2 Refueling Infrastructure = \$530/car (onsite reforming)
No extra infrastructure cost for gasoline

8TH ANNUAL U.S. HYDROGEN MEETING

THE CURRENT STATUS OF THE WE-NET PROGRAM

(WORLD ENERGY NETWORK)

PRESENTED BY

KAZUKIYO OKANO

WE-NET OFFICE
ENGINEERING ADVANCEMENT ASSOCIATION OF JAPAN (ENAA)

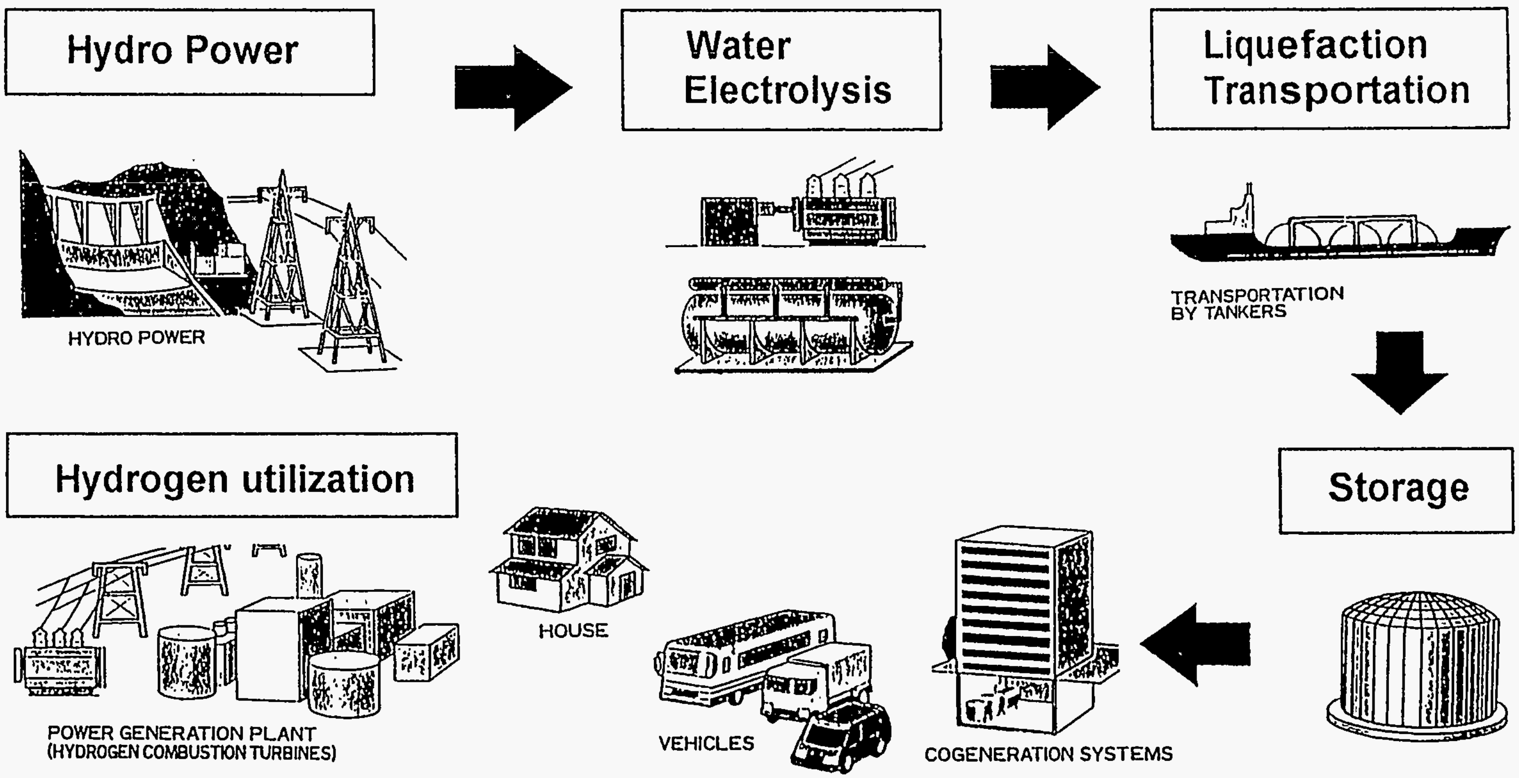
ENAA

GOALS AND CONCEPT OF THE WE- NET PROGRAM

Goals

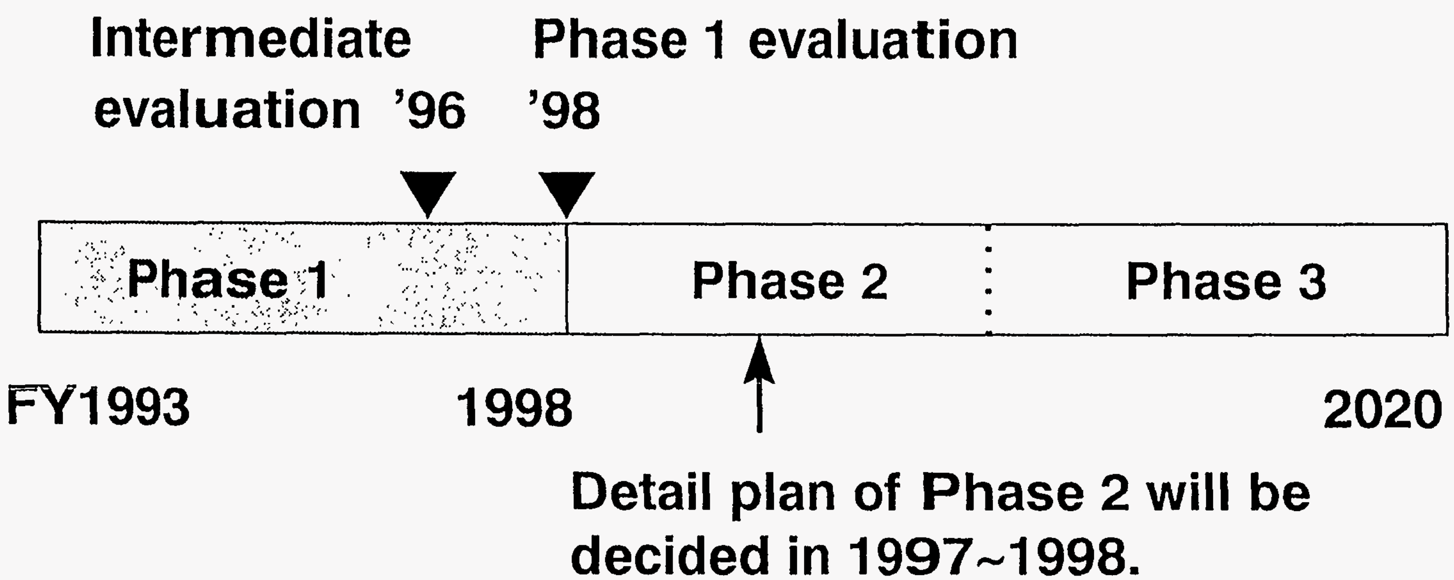
- To establish clean energy network using hydrogen
- To improve air quality and reduce CO_2 emission
- To assure adequate future energy and fuel sources

Hydrogen energy system flow



WE-NET PROGRAM STRUCTURE

Phase 1 : Basic research and system studies
Phase 2 : Technology development and validation
(Prototype systems)
Phase 3 : Full system demonstrations



THE WE-NET PROGRAM ORGANIZATION

MITI
AIST

NEDO

Steering comm.

Subtask leaders meeting

Subtask of R&D	Manager
1. Coordination & evaluation	IAE
2. International cooperation	ENAA
3. System design and analysis	EPDC CRIEPI L.R/I.C
Safety analysis	IAE
4. Hydrogen production	ENAA
5. Transportation & storage	ENAA
6. Cryogenic materials	JRCM
7. Hydrogen utilization	ENAA
8. Hydrogen combustion turbine	CRIEPI JAPIC
9. Innovative technologies	IAE

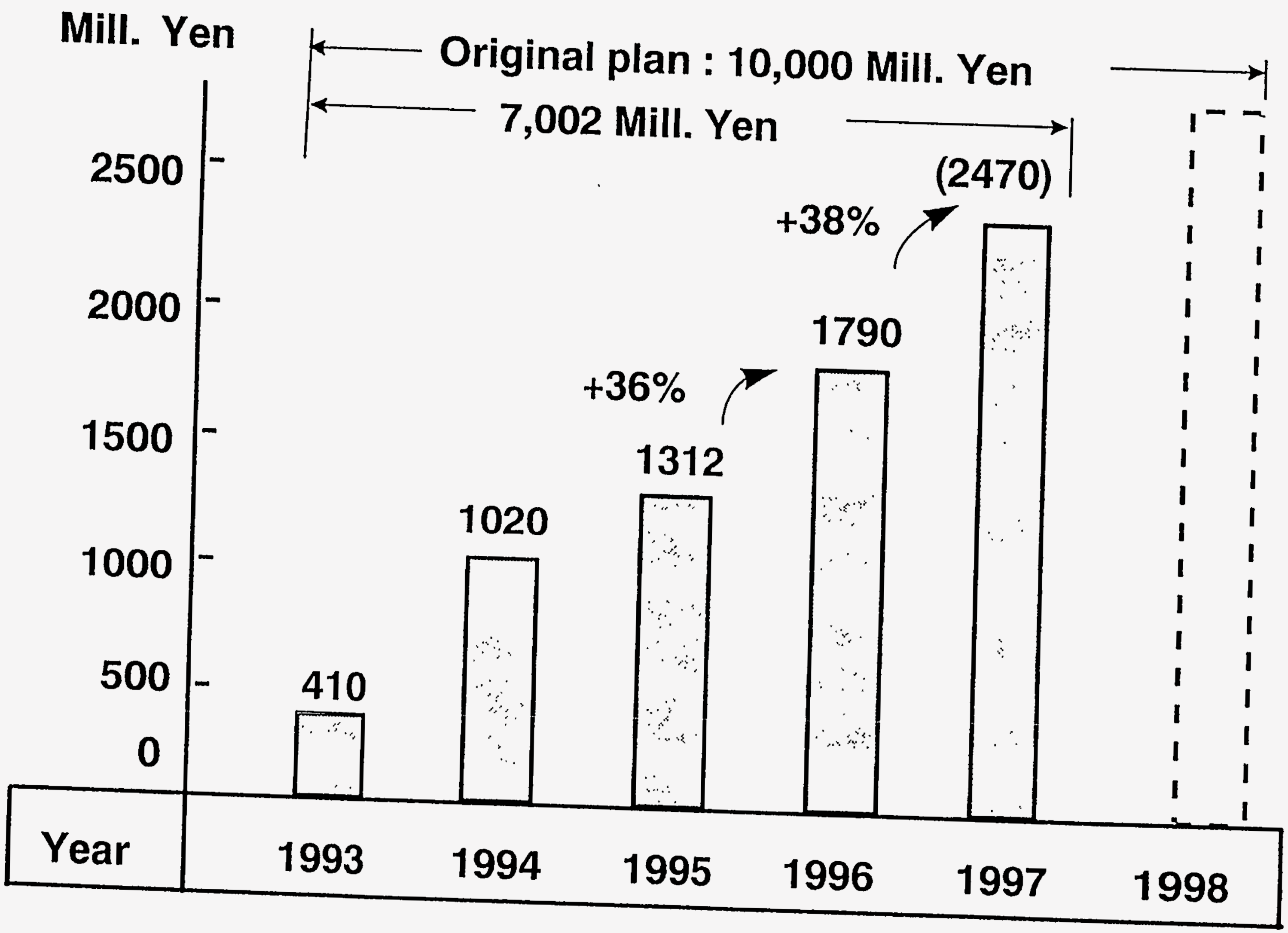
Subtask 1~9 Committee

Participants

University : 30
Natio. Labo : 11
Foundation : 17
Corporation : 55
Foreign part : 10
(Canada, USA, UK, Germany)

IAE: The Institute of Applied Energy
ENAA: Engineering Advancement Association of Japan
EPDC: Elec.Power Development Co.
CRIEPI: Central Res.Institute of Electric Power Industry
L.R/I.C:London Research and Imperial College
JRCM:The Japan Research and Dev. Center of Materials
JAPIC: Japan Power Engineering & Inspection Corporation

WE-NET PROGRAM FUNDING (Phase 1)



TARGET OF TECHNOLOGY DEVELOPMENT

Hydrogen production
Eff.>90%, 1~3A/cm^2

Liquefaction plant *
300t/day

LH_2 tanker
200,000m^3

LH_2 Storage tank
50,000m^3

LH_2 pump
60kg/cm^2, 90m^3/h

Metal hydride
3wt% at 100℃. 5000cycle

Hydrogen comb. turbine
500MW, Eff.>60%, at 1700℃

Hydrogen utilization system
Diesel cogeneration systems
(600kW, 1000kW)
Hydrogen vehicles *
(Engine, PEM-FC)
PEM fuel cell power plants *
(200kW, 5000kW)

* : Conceptual design only in Phase 1

TECHNOLOGY DEVELOPMENT FROM FY1997

1993	1994	1995	1996	1997	1998	Phase 2

1. PEM water electrolysis
2. Cryogenic materials
3. Hydrogen combustion turbine

—— Study and design ——→|←Development→

4. Testing of insulation structure for storage tanks and tankers
5. Liquid hydrogen pumps
6. Metal hydrides
7. Diesel engine

SYSTEMS ANALYSIS

Goal : To identify and define research opportunities for hydrogen as an energy carrier via system evaluation and analysis.

Current status and plan :

FY1994~96

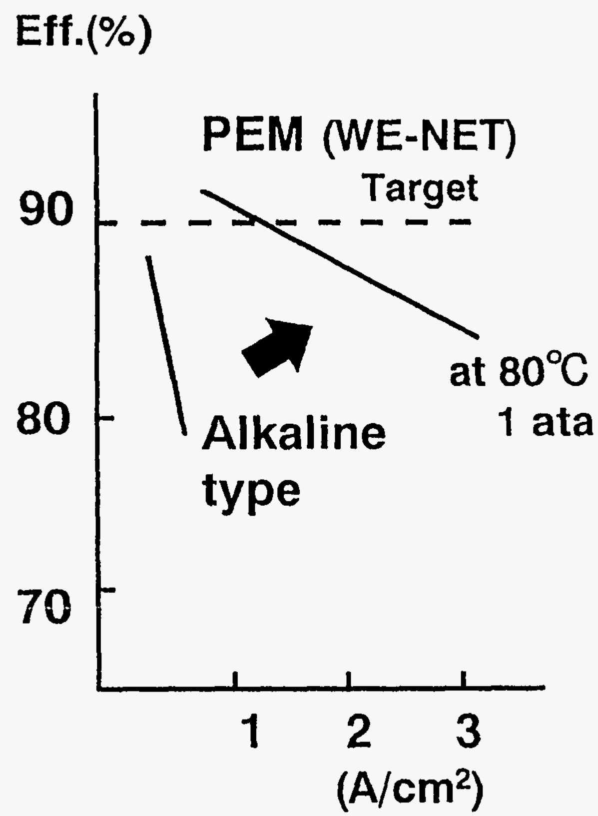
- Conceptual design of the whole hydrogen energy syste
- Cost analysis
- System comparison of hydrogen with other enrgy carrier
- Study on a global network
- National level and city level energy estimation and assessmet
- Safety analysis

FY1997~

- Continue further studies

HYDROGEN PRODUCTION (Phase 1)

Goal : To develop high performance cells
of PEM electrolyte water electrolysis.
Efficiency : ≧90% at 1~3A/cm^2
Cell size : 2,500cm^2
(Final size : ≧10,000cm^2)



Current status and plan :

- FY1994~96
  Achieved 90~95% efficiency
  at 1A/cm^2 by 50 and 200 cm^2 cells.

- FY1997~98
  Development of 2,500cm^2 cell stacks.

TRANSPORTATION AND STORAGE (Phase 1)

Goal :
- Conceptual design of 200,000m^3 liquid hydrogen tankers and 50,000m^3 storage tanks
- Evaluation of thermal insulation structures

Current status and plan :

FY1994~96

- Conceptual design of tankers with spherical tanks and prismatic tanks were completed.
- Conceptual design of spherical, cylindrical and in-ground storage tanks were completed.

FY1997~98

Testing and evaluation of thermal insulation structures of tanks for tankers and storage tanks will be carried out.

HYDROGEN UTILIZATION (Phase 1)

Goal : System study and conceptual design of the following items.

- Diesel cogeneration systems
- 200kW, 5000kW PEM-FC plants
- Hydrogen vehicles（Engine、PEM-FC）
- Oxygen production plants
- Hydrogen fuel distribution systems

Current status and plan :

FY1994～96 System studies were carried out .

FY1997～98 ・Conceptual design of each systems.

・R&D of diesel engine systems.

POWER GENERATING PLANTS

Results of System Studies

System	Capacity	Fuel / Oxidant	Efficiency (HHV)
Hydrogen combustion turbine	500MW	H_2/O_2	61%
PEM-FC power plants	200kW 5MW	H_2/Air H_2/O_2	43% 56%
Diesel Engine cogeneration plants	600kW 1MW	H_2/O_2 H_2/O_2	41% 43%

HYDROGEN COMBUSTION TURBINES

Goal : To develop 500 MW turbines of over 60 % efficiency at 1700℃ gas inlet temperature

Current status and plan :

FY1994~1996

- Evaluation of optimum turbine cycle
- H_2/O_2 combustion tests
- Design of turbine blades and aux. equipments
- Eevaluation of ultra high temperature materials

FY1997~1998

- Conseptual design of the whole plant
- Testing of a combuster
- Design of model blades for cooling test
- Tesing of a roter cooling model
- Development of ultra high temp. materials

5MW PEM FUEL CELL POWER PLANT

High Efficiency and Large Power Plant

Aplication	Power plant for electric utilities and industries
Output power	5000 kW
Fuel / oxidant	Hydrogen / oxygen (hydrogen: 2,520 Nm^3/h)
Op.condition	8 ata, 80℃
Fuel cell stack	660 cells x 6 stacks (cell size: 5000cm^2)
Elec. efficiency	56.4 % (HHV)

HYDROGEN VEHICLES (Phase 1)

Goal : To complete conceptual designs of hydrogen vehicles (Engine type and fuel cell type).

Current status and plan :

FY1994~98 Conceptual design of two vehicles

- Hydrogen Engine Vehicles

  Type : 6-passenger wagon
  Power system : Engine / battery hybrid system
  Fuel storage : Metal hydride tank

- Fuel cell vehicles

  Type : 26- passenger bus
  Power system : PEM-FC / battery hybrid system
  Fuel storage : Liquid hydrogen tank

JAPAN'S KEY R&D PROJECTS FOR GLOBAL WARMING PREVENTION

Midterm projects :

- Market introduction of photovoltaic systems
- Development & market introduction of fuel cells

Long-term projects :

- R&D of energy and environmental technologies
  - Hydrogen energy technologies
  - Nuclear fusion technologies
  - Biomass, gasification proccess technologies
  - CO_2 fixiation and storage

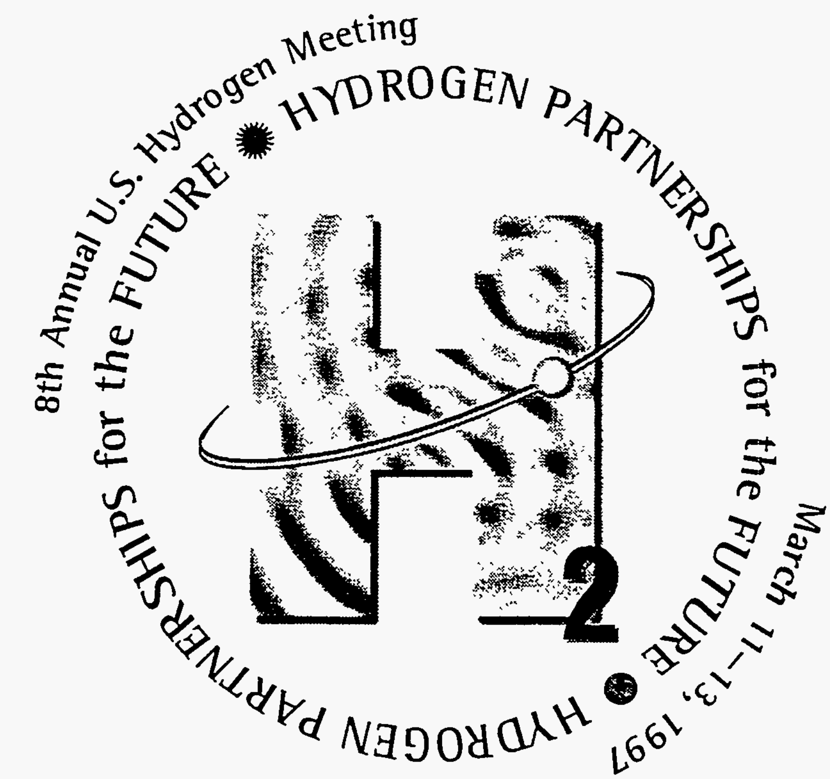
Appendix A

Final Program

The National Hydrogen Association's

Final Program

8th Annual U.S. Hydrogen Meeting



11-13 March 1997
Radisson Plaza Hotel at Mark Center
Alexandria, Virginia, U.S.A.

Sponsored by:

Office of Utility Technologies, U.S. Department of Energy
National Aeronautics and Space Administration
South Coast Air Quality Management District
Office of Transportation Technologies, U.S. Department of Energy

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8:00 am — Registration
Foyer

9:00 am — Keynote Address
Plaza Ballroom *(Via Satellite)*
Utility Restructuring and the Implication for Renewables
S. David Freeman, Trustee, California Restructuring Trust, and Chairman of the Board, SunLight Power International, Inc., San Francisco, California, USA

9:45 am - 11:05 am — **GENERAL SESSION IV**
Opportunities for Partnerships in the Utility Market
Plaza Ballroom
Session Chair: *Bud Beebe*, Licensing and Regulatory Affairs Coordinator, Sacramento, Municipal Utility District, Sacramento, California, USA

Electric Industry Restructuring Impacts on Utility RD&D
Bud Beebe

DOE Hydrogen Program Strategy
Dr. Sig Gronich, Hydrogen Program Team Leader, Office of Utility Technologies, U.S. Department of Energy, Washington, D.C., USA

Commercializing Proton Exchange Membrane Technology
Walter W. Schroeder, President, Proton Energy Systems, Inc., Rocky Hill, Connecticut, USA

APS Activities in Solar Energy Services, Regional Air Quality, and Local Transportation Issues
Herb Hayden, Renewables Resources Program Coordinator, Arizona Public Service Company, Phoenix, Arizona, USA

11:05 am - 11:20 am — Break

11:20 am - 12:25 pm — **GENERAL SESSION V**
Advanced Technologies
Plaza Ballroom
Session Chair: *Matthew Fairlie*

HOGEN Proton Exchange Membrane Hydrogen Generators: Commercialization of PEM Electrolyzers
William F. Smith, Vice President, Business Development, Proton Energy Systems, Inc., Rocky Hill, Connecticut, USA

Making the Case for Compressed Hydrogen Onboard Storage
Brian D. James, Project Engineer, Directed Technologies, Inc., Arlington, Virginia, USA

PEM Fuel Cell Cost Minimization Using "Design for Manufacture and Assembly" Techniques
Franklin D. Lomax, Jr., Staff Engineer, Directed Technologies, Inc., Arlington, Virginia, USA

Hydrogen as a Fuel for Fuel Cell Vehicles: A Technical and Economic Comparison
Dr. Joan Ogden, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey, USA

12:30 pm - 1:15 pm — Awards Luncheon/Keynote
Terrace Room

1:15 pm - 1:45 pm — Keynote Address
The Current Status of the WE-NET Program
Kazukiyo Okano, Director of Research, World Energy Network Center, Engineering Advancement Association of Japan, Tokyo, Japan

1:45 pm - 3:15 pm — **GENERAL SESSION VI**
Panel Discussion: Financial Partners
Plaza Ballroom
Moderator: *Dr. Venki Raman*, Manager, Hydrogen Applications, Air Products and Chemicals, Inc., Allentown, Pennsylvania, USA

Panelists:
Dr. Barry Stevens, President, National Hydrogen Fund, Ltd., Arlington, Texas, USA
Dominique Kluyskens, Project Manager, Hydro-Québec, Montréal, Québec, Canada
Robert F. Weir, Director/Consultant, Commercial Loss Control, Hartford Steam Boiler Inspection & Insurance Company, Hartford, Connecticut, USA
Dr. Robert W. Shaw, Jr., President, Aretê Ventures, Inc., Rockville, Maryland, USA
Dr. Carl-Jochen Winter

3:15 pm - 3:30 pm — 8th Annual U.S. Hydrogen Meeting Summary
Dr. Venki Raman

FRIDAY, 14 MARCH 1997

9:00 am - 2:00 pm — Hydrogen Implementation Workshop
Attendance By Invitation Only

- Hydrogen Infrastructure Work Group Meeting
Beech A Room

- Transitioning from Demonstration to Commercialization Work Group Meeting
Beech B Room

TUESDAY, 11 MARCH 1997

1:00 pm - 6:00 pm — NHA Board of Directors Meeting
Beech Room
NHA Members 2:30pm-5:00pm Only

4:00 pm - 8:30 pm — Registration
Foyer

5:00 pm - 8:30 pm — Exhibition Open
Foyer

6:30 pm - 8:30 pm — Opening Reception
Foyer

WEDNESDAY, 12 MARCH 1997

7:30 am — Continental Breakfast
Foyer

7:30 am - 5:00 pm — Registration
Foyer

7:30 am - 9:00 pm — Exhibition Open
Foyer

8:30 am — Welcome
Plaza Ballroom
Dr. Keith Prater, Vice President, Power Systems, Ballard Power Systems, Burnaby, B.C., Canada, and Chairman of the Board, National Hydrogen Association

8:40 am — Keynote Address
Plaza Ballroom
The Honorable Harry Reid, U.S. Senator for the State of Nevada, USA

9:15 am - 10:30 am — **GENERAL SESSION I**
Government's Partnership Role for Hydrogen Technology Development
Plaza Ballroom
Session Chair: *Dr. Alan Lloyd*, Chairman, Hydrogen Technical Advisory Panel, U.S. Department of Energy, and Executive Director, Energy & Environmental Center, Desert Research Institute, Reno, Nevada, USA

Support of a Pathway to a Hydrogen Future
Dr. Allan R. Hoffman, Deputy Assistant Secretary, Office of Utility Technologies, U.S. Department of Energy, Washington, D.C., USA

The Hydrogen Commercialization Plan
Dr. Keith Prater

Fuel Cells for Future Transportation: The OTT/OUT Partnership
Dr. Pandit G. Patil, Director, Office of Advanced Automotive Technologies, Office of Transportation Technologies, U.S. Department of Energy, Washington, D.C., USA

Hydrogen Technical Advisory Panel Update
Dr. Alan Lloyd

10:15 am - 2:15 pm — Secondary School Invitational
Dogwood Room

10:30 am - 10:45 am — Break

10:45 am - 12:00 pm — **GENERAL SESSION II**
Government/Industry Partnerships: Demonstrations
Plaza Ballroom
Session Chair: *Jay Laskin*, Manager, Marketing and Sales, Teledyne Brown Engineering/Energy Systems, Hunt Valley, Maryland, USA

Hydrogen Technology Testing and Demonstration Facility at the Nevada Test Site
Terry Vaeth, Acting Manager, Nevada Operations Office, U.S. Department of Energy, Las Vegas, Nevada, USA

Safety Evaluation of a Hydrogen-Fueled Transit Bus
Dr. Allan Coutts, Principal Engineer, Westinghouse Savannah River Company, Aiken, South Carolina, USA

Hydrogen Generation, Storage, and Dispensing System Safety Assessment: A Case Study
Kevin Knudsen, Energy Technology Engineering Center, Rocketdyne Division, Boeing North American, Inc., Canoga Park, California, USA

The Palm Desert Demonstration
Dr. Peter Lehman, Director, Schatz Energy Research Center, Humboldt State University, Arcata, California, USA

12:00 pm - 2:00 pm — Luncheon/Keynotes
Terrace Room

1:00 pm - 1:30 pm — Keynote Address
The Hindenburg Incident: Cause and Effect
Addison Bain, National Aeronautics and Space Administration (NASA), Satellite Beach, Florida, USA

1:30 pm - 2:00 pm — Keynote Address
Hydrogen Safety
Heidi L. Barnes, Electrical Engineer, John C. Stennis Space Center, NASA, Bay St. Louis, Mississippi, USA

12:15 pm - 1:00 pm — Press Interviews
Foyer

2:15 pm - 3:30 pm — **GENERAL SESSION III**
Entering the Market: Partnerships in Transportation
Plaza Ballroom
Session Chair: *Frank E. Lynch*, President, Hydrogen Components, Inc., Littleton, Colorado, USA

Market Penetration Scenarios for Fuel Cell Vehicles
Dr. C.E. (Sandy) Thomas, Research Director, Directed Technologies, Inc., Arlington, Virginia, USA

Speeding the Transition to Fuel Cells: Designing a Fuel Cell Hypercar
Brett D. Williams, Research Associate, The Hypercar Center, Rocky Mountain Institute, Snowmass, Colorado, USA

Solar Hydrogen for Urban Trucks
Paul Scott, Project Engineer, Clean Air Now!, Santa Monica, California, USA

The Chicago Bus Project
Craig Greenhill, Manager, Fuel Cell Bus Programs, Ballard Power Systems, Burnaby, B.C., Canada

3:30 pm - 3:45 pm Break

3:45 pm - 5:00 pm

CONCURRENT TECHNICAL SESSIONS

• TECHNICAL SESSION I: Hydrogen: The Aerospace Fuel
Plaza Ballroom
Session Chair: Herman T. Everett, Jr., Propellants Manager, Kennedy Space Center, NASA, Cape Canaveral, Florida, USA

Hydrogen: Key to Aerospace Motive Power, Today and Tomorrow
William J. D. Escher, Director, Aeropropulsion Business, Kaiser Marquardt, Van Nuys, California, USA

Hydrogen and the Greenhouse
Dr. Carl-Jochen Winter, Director, ENERGON Carl-Jochen Winter, GmbH, Überlingen, Germany

Fuel Cells for Aerospace and Terrestrial Applications
Paul J. Farris, Manager, Hydrogen Business Development, International Fuel Cells Corporation, South Windsor, Connecticut, USA

The X-33 Experimental Aerospace Vehicle: Mach 3 in 1999
David Stone, Manager, Space Transportation Vehicle Systems Technology, NASA, Washington, D.C., USA

Geothermal Resource Requirements for an Energy Self-Sufficient Spaceport
Dr. Paul Kruger, Department of Civil Engineering, Stanford University, Stanford, California, USA

• TECHNICAL SESSION II: Codes and Standards
Terrace Room
Session Chair: *David B. Sonnemann*, Manager, Regulatory Affairs, Praxair, Inc., Danbury, Connecticut, USA

Development of a Manual of Recommended Practices for Hydrogen Energy Systems
William Hoagland, President, W. Hoagland & Associates, Boulder, Colorado, USA

NHA Work Group Updates:

• Report from WG 1: Connectors
Matthew Fairlie, Director of Technology, Electrolyser Corporation, Ltd., Toronto, Ontario, Canada, and WG 1 Chairman

• Report from WG 2: Containers
Dr. James G. Hansel, Senior Engineering Associate, Engineering Safety, Air Products & Chemicals, Inc., Allentown, Pennsylvania, USA, and WG 2 Chairman

• Report from WG 3: Service Stations
Dr. Allan Coutts, WG 3 Chairman

The Value of Odorants in Detecting Hydrogen Diffusion in a Garage
Dr. Michael Swain, Associate Professor, University of Miami, Florida, USA

An Interdisciplinary Analysis of Odorants for Hydrogen Safety
David Haberman, President, DCH Technology, Inc., Sherman Oaks, California, USA

• TECHNICAL SESSION III: Advanced Technologies
Beech Room
Session Chair: *Steven G. Chalk*, Fuel Cells, Office of Advanced Automotive Technologies, Office of Transportation Technologies, U.S. Department of Energy, Washington, D.C., USA

A Portable Power System Using PEM Fuel Cells
Eugene Long, Program Manager, Aerospace Systems Division, Ball Aerospace and Technologies Corporation, Boulder, Colorado, USA

Magnic Hydrogen Production: Current Status of RTI Feasibility Study and Demonstration
John Cleland, Program Director, Research Triangle Institute, Research Triangle Park, North Carolina, USA

Composite Metal Membranes for Hydrogen Systems Applications
Dr. Thomas S. Moss, III, Materials Science and Technology Division, Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Hydrogen Production from Water: Recent Advances in Photosynthesis Research
Dr. Elias Greenbaum, Group Leader, Biotechnology Research, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

5:00 pm - 9:00 pm Poster Session
Dogwood Room

5:15 pm - 6:45 pm NHA Business Meeting/Elections
Terrace Room
NHA Members Only

7:00 pm - 9:00 pm INDUSTRY-SPONSORED RECEPTION
Foyer

INDUSTRY-SPONSORED RECEPTION

Featuring Live Jazz by Musical Four
Wednesday, 12 March
7:00 pm – 9:00 pm, Foyer

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Air Liquide America Corporation • Air Products and Chemicals, Inc.
BOC Gases • Ford Motor Company • Iwatani International Corporation • Praxair, Inc. • Nippon Sanso Corporation
Southern California Gas Company

THURSDAY, 13 MARCH 1997

7:30 am - 8:30 am NHA Board Meeting
Beech Room
Members of New Board Only

8:00 am Continental Breakfast
Foyer

Appendix B

List of Participants

8th Annual U.S. Hydrogen Meeting

Attendee List (239)

Mr. Andris Abele
South Coast Air Quality Management District

Sakae Aouagi
Washington International Energy Group

Mr. P. Chungmoo Auh
Science and Technology Policy Institute

Mr. Addison Bain

Dr. U. Balachandran
Argonne National Laboratory

Dr. John A. Barclay
University of Victoria

Ms. Heidi L. Barnes
National Aeronautics & Space Administration (NASA)

Mr. Robert Bartocci
Teledyne Wah Chang

Mr. Bradford Bates
Ford Motor Company

Mr. Frederick Becket
Thermo Power Corporation

Mr. Bud Beebe
Sacramento Municipal Utility District

Mr. Michael Belanger
Northeastern University

Mr. Lawrence C. Belnoski
Air Products and Chemicals, Inc.

Ms. Kim Bergland
3M Company

Mr. Larry S. Blair
Los Alamos National Laboratory

Mr. Christopher Blazek
Institute of Gas Technology

Dr. David L. Block
Florida Solar Energy Center

Mr. Gus Block
Arthur D. Little, Inc.

Dr. Tapan K. Bose
Université du Québec a Trois-Rivières

Mr. Robert Bowman
Jet Propulsion Laboratory

Mr. John Brogan

Mr. Randal Brown
Southern California Gas Company

Mr. David E. Bruderly
Cross Creek Initiative

Mr. Matt Bruustar
Stirling Thermal Motors, Inc.

Mr. Stan Bull
National Renewable Energy Laboratory (NREL)

Mr. Gary D. Burch
U.S. Department of Energy

Mr. Hazen Burford
Hydrogen Burner Technology

Mr. Tim Carlson
NTS Development Corporation

Dr. Steven G. Chalk
U.S. Department of Energy

Mr. Anthony Chargin
Lawrence Livermore National Laboratory

Dr. Earl J. Claire
Southeastern Technology Center

Mr. James Cockrell
National Aeronautics & Space Administration (NASA)

Mr. Kirk Collier
NRG Technologies, Inc.

Mr. Allan Coutts
Westinghouse Savannah River Company

Mr. James Cross, III
Arthur D. Little, Inc.

Mr. Russ Derickson
South Dakota School of Mines and Technology

Dr. Russell Eaton, III
U.S. Department of Energy

Mr. Eric Esselstyn
Cross Creek Initiative

Mr. Rick Fadeley
Teledyne Brown Engineering - Energy Systems

Mr. Paul J. Farris
International Fuel Cells Corporation

Mr. William Firestone
DCH Technology, Inc.

Mr. Hans Friedericy
AlliedSignal, Inc.

Dr. Susan Fuhs
AlliedSignal, Inc.

Mr. Robert F. Goff
3M Company

Dr. Elias Greenbaum
Oak Ridge National Laboratory

Mr. John Cleland
Research Triangle Institute

Mr. Steven J. Cohen
Teledyne Brown Engineering - Energy Systems

Mr. Serre Combe
C.E.A.

Mr. Marshall Crew
Bend Research, Inc.

Mr. Edward Danieli
Praxair, Inc.

Ms. Dana Doherty
Hydrogen Burner Technology

Mr. William J.D. Escher
Kaiser Marquardt

Mr. Herman T. Everett, Jr.
National Aeronautics & Space Administration (NASA)

Mr. Matthew Fairlie
Electrolyser Corporation, Ltd.

Mr. Ron Fawcett
Ronald P. Fawcett & Associates

Mr. Allan L. Frank
Allan L. Frank Associates

Mr. Robert Friedland
Proton Energy Systems, Inc.

Mr. Jose A. Garcia
University of Toronto

Dr. Shimshon Gottesfeld
Los Alamos National Laboratory

Mr. Craig Greenhill
Ballard Power Systems

Ms. Catherine Gregoire-Padro
National Renewable Energy Laboratory (NREL)

Mr. James A. Grimm
Duquesne Enterprises

Dr. Michael A. Gurevich
U.S. Department of Energy

Mr. Saul Haberman
DCH Technology, Inc.

Mr. Tom Halvorson
Praxair, Inc.

Mr. S. Yousef Hashimi
National Science Foundation

Mr. Michael Heben
National Renewable Energy Laboratory (NREL)

Mr. Kit Heung
Westinghouse Savannah River Company

Mr. John H. Hirschenhofer
Parsons Power Group

Mr. William Hoagland
Hydrogen 2000, Inc.

Ms. Barbara Hoffheins
Lockheed Martin Energy Research

Mr. Peter Hoffmann
The Hydrogen and Fuel Cell Letter

Ms. Kimberly Holland
National Hydrogen Association

Mr. Carl Hunter
Questor Industries, Inc.

Dr. Gerhard Isenberg
Daimler-Benz AG

Mr. Patrick Grimes
Grimes Associates

Mr. Sig Gronich
U.S. Department of Energy

Mr. David Haberman
DCH Technology, Inc.

Mr. Mike Hainsselin
Praxair, Inc.

Dr. James G. Hansel
Air Products and Chemicals, Inc.

Mr. Herb Hayden
Arizona Public Service Company

Mr. James Heffel
University of California, Riverside

Ms. Barbara Heydorn
SRI International

Dr. Gaines Ho
CECOM

Mr. Earl W. Hodge
U.S. Department of Energy

Dr. Allan R. Hoffman
U.S. Department of Energy

Ms. Diane Holden
National Aeronautics & Space Administration (NASA)

Mr. Greg Hummel
Phoenix Gas Systems

Mr. Koji Ikoma
Nippon Sanso Corporation

Mr. Brian D. James
Directed Technologies, Inc.

Mr. Thomas Janossy
Remedial Ecotoxicological Expeditions Fund

Dr. Jay O. Keller
Sandia National Laboratories

Mr. Krissanapong Kirtikara
Kmit Thonburi

Mr. Dominique Kluyskens
Hydro-Quebec

Mr. Richard Knight
Institute of Gas Technology

Mr. Abraham Kogan
Weizmann Institute of Science

Mr. Jay Laskin
Teledyne Brown Engineering - Energy Systems

Mr. Peter LeFort
DCH Technology, Inc.

Ms. Susan Leach

Dr. Peter Lehman
Schatz Energy Research Center

Mr. Richard Lemak
Air Products and Chemicals, Inc.

Mr. Michael Levine
BOC Gases

Dr. Alan Lloyd
Desert Research Institute

Mr. Eugene Long
Ball Aerospace

Dr. Amory B. Lovins
Rocky Mountain Institute

Mr. Don Jorgensen
Prime Gas, Inc.

Mr. George Kervitsky
Energetics, Inc.

Ms. Faith Klareich
Sentech, Inc.

Dr. J. R. Knight
Westinghouse Savannah River Company

Mr. Kevin Knudsen
Rockwell International Corporation

Mr. Uwe Kueter
H-Tec

Mr. Robert Lauf
Oak Ridge National Laboratory

Mr. Steven LeLewer
Bechtel Nevada Corporation

Ms. Donna Lee
U.S. Department of Energy

Mr. Robert Lein
Air Liquide America Corp./L'Air Liquide Eng.

Mr. Mark Lersch
Solar Energy Industries Association

Dr. Clovis Linkous
Florida Solar Energy Center

Mr. Franklin D. Lomax, Jr.
Directed Technologies, Inc.

Mr. Francois P. Louis

Mr. David Lowe

Mr. Jim Lowell
Bend Research, Inc.

Mr. Steve Mathison
Honda R&D

Mr. Steve Matthews
Stirling Thermal Motors, Inc.

Mr. Paul Mazzuca

Mr. James McElroy
Hamilton Standard

Mr. Steve Mehta
University of Toronto

Ms. Karen Miller
National Hydrogen Association

Ms. JoAnn Milliken
U.S. Department of Energy

Mr. Trent Molter
Proton Energy Systems, Inc.

Terry J. Montgomery
U.S. Department of Energy

Dr. Renaut Mosdale
P.S.A. Peugeot-Citroen

Dr. Ted Motyka
Westinghouse Savannah River Company

Mr. Harold Muller
Arizona Microteck

Mr. David Nahmias
David Nahmias & Associates

Mr. Johnny Ng
DCH Technology, Inc.

Mr. Frank E. Lynch
Hydrogen Components, Inc.

Mr. Ashok Mathur
Air Products and Chemicals, Inc.

Mr. Robert L. Mauro
National Hydrogen Association

Mr. Robert McClain
Nazco/Exxon Energy Chemicals

Mr. Iain McPhie
New Energy Development Organization (NEDO)

Dr. George Miley
University of Illinois

Mr. Robert N. Miller
Air Products and Chemicals, Inc.

Mr. Fred Mitlitsky
Lawrence Livermore National Laboratory

Dr. Michael J. Monsler
W. J. Schafer Associates, Inc.

Mr. Robert Moore
Air Products and Chemicals, Inc.

Dr. Thomas S. Moss, III
Los Alamos National Laboratory

Mr. Larry Moulthrop
Proton Energy Systems, Inc.

Mr. Dwight Nafziger
Superior Valve Corporation

Mrs. Susan Naughton
Bechtel Nevada Corporation

Mr. Len Nicholson
National Aeronautics & Space Administration (NASA)

Mr. Chris Nimptsch
Profamo, Inc.

Ms. Erin O'Donnell
National Hydrogen Association

Dr. Joan Ogden
Princeton University

Mr. Kazukiyo Okano
Engineering Advancement Association of Japan

Mr. Chris Palasinski
Gardner Cryogenics

Mr. Robin Z. Parker
Solar Reactor Technologies, Inc. (SRT)

Dr. Pandit G. Patil
U.S. Department of Energy

Dr. Keith Prater
Ballard Power Systems

Ms. Georgianna H. Purnell
Ford Motor Company

Mr. Bugga V. Ratnakumar
Jet Propulsion Laboratory

Mr. Chet A. Roberts
Compressed Gas Association, Inc.

Dr. Marian H. Rose
Sierra Club

Mr. Boonrod Sajjakulnukit
Department of Energy Development and Promotion

Dr. Krishna Sapru
Energy Conversion Devices, Inc.

The Honorable Dan Schaefer
U.S. House of Representatives

Mr. Gary Noland
W. J. Schafer Associates, Inc.

Dr. Takashi Ogawa
Toshiba Corporation

Dr. James Ohi
National Renewable Energy Laboratory (NREL)

Mr. David H. Otto
Energy Conservation Equipment Corp.

Mr. Marcel Paquette
Sofinov

Mr. Kenneth Partain
Center for Sustainable Technology

Mr. Roger Peterson
Teledyne Wah Chang

Mr. James J. Provenzano
Clean Air Now!

Dr. Venki Raman
Air Products and Chemicals, Inc.

The Honorable Harry M. Reid
U.S. Senate

Mr. Richard E. Rocheleau
University of Hawaii at Manoa

Mr. Neil Rossmeissl
U.S. Department of Energy

Mr. Gary Sandrock
SunaTech, Inc.

Mr. James K. Scarsdale
The Solar Flair Corporation

Mr. Thomas Schmidt
Oak Ridge National Laboratory

Mr. Walter W. Schroeder
Proton Energy Systems, Inc.

Mr. Paul B. Scott
Clean Air Now!

Dr. Robert W. Shaw, Jr.
Arete Corporation

Mr. Paul Shillock
City of Palm Desert

Mr. Ronald I. Sims
Ford Motor Company

Dr. Edward G. Skolnik
Energetics, Inc.

Mr. Richard Smith
The Hydrogen Center

Mr. William F. Smith
Proton Energy Systems, Inc.

Ms. Pamela Spath
National Renewable Energy Laboratory (NREL)

Mr. David Stone
National Aeronautics & Space Administration (NASA)

Dr. William A. Summers
Westinghouse Savannah River Company

Dr. Michael R. Swain
University of Miami

Ms. Mary-Rose Szoka
MRS Enterprises

Mr. Tim Tangredi
DAIS Corporation

Dr. C. E. (Sandy) Thomas
Directed Technologies, Inc.

Mr. Steve Scoles
Babcock & Wilcox

Mr. Jeffrey A. Serfass
National Hydrogen Association

Mr. Kenneth G. Sheinkopf
Florida Solar Energy Center

Mr. Bill Simpkins
TASC-GM

Dr. Jerry E. Sinor
Clean Fuels Report

Mrs. Debbi L. Smith
National Hydrogen Association

Mr. Roger Smith
Compressed Gas Association, Inc.

Mr. David B. Sonnemann
Praxair, Inc.

Dr. Barry Stevens
National Hydrogen Fund, Ltd.

Mr. Mark Stroze
Safetyscan, LLC

Mr. Matthew Swain
University of Miami

Mr. William Swift
Argonne National Laboratory

Mr. Toshiichi Takematsu
Iwatani International Corporation

Mr. Apichai Therdthianwong
Khon Kaen University

Mr. George J. Thomas
Sandia National Laboratories

Dr. John A. Turner
National Renewable Energy Laboratory (NREL)

Mr. Itsuki Uehara
Osaka National Research Institute (AIST)

Dr. Nicholas Vanderborgh
Los Alamos National Laboratory

Mr. Charles A. Veley

Mr. David Walker
DCH Technology, Inc.

Mr. Henry W. Wedaa
Hydrogen 2000, Inc.

Mr. Robert Weir
Hartford Steam Boiler Inspection & Insurance Co.

Mr. Brett D. Williams
Rocky Mountain Institute

Mr. Raymond Winkel
DCH Technology, Inc.

Dr. Michael Winter
United Technologies Corporation

Ms. Rachelle Wood
Ball Aerospace

Mr. Akira Yoshizawa
Nissho Iwai American Corporation

Ms. Marcia Zalbowitz
Los Alamos National Laboratory

Mr. Fred H. Zerkel
Institute of Gas Technology

Dr. Robert M. Zweig
Clean Air Now!

Mr. Akiyoshi Tomio Ueda

Mr. Terry Vaeth
U.S. Department of Energy

Mr. Alexander P. Varghese
Gardner Cryogenics

Dr. Steven Vosen
Sandia National Laboratories

Ms. Vicki Walker
DCH Technology, Inc.

Dr. James Wegrzyn
Brookhaven National Laboratory

Mr. George White
BOC Gases

Mr. Gregory B. Williams
AMERISEN

Dr. Carl-Jochen Winter
Energon, GmbH

Mr. Charles Wolf
Teledyne Brown Engineering - Energy Systems

Mr. Hiroshi Yamamoto
Yamaha Motor Company, Ltd.

Mr Jim Yuen
Rockwell International Corporation

Dr. Leszek Zaluska
McGill University

Mr. Paul E. Zollman
Mayo Clinic

Appendix C

List of Exhibitors

EXHIBITOR LIST

Air Products and Chemicals, Inc.
Ball Aerospace & Technologies Corporation
DCH Technology
Hydrogen Burner Technology
National Aeronautics and Space Administration (SSC)
Praxair, Inc.
Teledyne Brown Engineering

Appendix D

Evaluation Results

Results of the National Hydrogen Association's Seventh Annual U.S. Hydrogen Meeting Evaluation

Meeting evaluation forms were distributed with registration materials. 61 forms were returned. Attendees were asked to rate their level of interest for the various sessions using the following scale:

5 = very interesting   1 = not interesting

General Session I - Government's Partnership Role for Hydrogen Technology Development

5	👍👍👍👍👍👍👍	(7)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(31)
3	👍👍👍👍👍👍👍👍👍👍👍👍	(12)
2	👎👎👎👎	(4)
1	👎	(1)
Blank		(4)

General Session II - Government/Industry Partnerships: Demonstrations

5	👍👍👍👍👍👍👍	(7)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(30)
3	👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(14)
2	👎👎👎	(3)
1	👎	(1)
Blank		(4)

Luncheon Keynotes - Addison Bain, The Hindenburg Incident: Cause and Effect & Heidi Barnes, Hydrogen Safety

5	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(17)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(27)
3	👍👍👍👍👍	(5)
2	👎👎👎👎	(4)
1	👎	(1)
Blank		(4)

General Session III - Entering the Market: Partnerships in Transportation

5	👍👍👍👍👍👍👍	(7)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(30)
3	👍👍👍👍👍👍👍👍👍	(9)
2	👎👎👎	(3)
1	👎	(1)
Blank		(8)

Technical Session I - Hydrogen: The Aerospace Fuel

5		(0)
4	👍👍👍	(3)
3	👍👍👍	(3)
2	👎	(1)
1	👎	(1)
Blank		(5)

Technical Session II - Codes and Standards

5	👍👍	(2)
4	👍👍👍👍	(4)
3	👍👍👍👍👍👍👍	(7)
2	👎👎👎👎	(4)
1		(0)
Blank		(5)

Technical Session III - Advanced Technologies

5	👍👍👍👍	(4)
4	👍👍👍👍👍👍👍👍👍👍👍👍	(12)
3	👍👍👍👍	(4)
2	👎👎👎👎	(4)
1	👎👎	(2)
Blank		(5)

Keynote Address - S. David Freeman, Utility Restructuring and the Implication for Renewables

5	👍👍👍👍👍👍👍👍👍👍	(10)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(20)
3	👍👍👍👍👍👍👍👍👍	(9)
2	👎👎👎👎👎	(5)
1	👎👎👎	(3)
Blank		(11)

General Session IV - Opportunities for Partnerships in the Utility Market.

5	👍👍👍👍👍👍👍👍👍👍👍👍	(12)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(20)
3	👍👍👍👍👍👍👍👍👍👍👍👍	(12)
2	👎👎👎👎👎👎	(6)
1	👎👎	(2)
Blank		(6)

General Session V - Advanced Technologies

5	👍👍👍👍👍👍👍👍👍👍👍👍👍	(13)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(25)
3	👍👍👍👍👍👍👍👍👍	(9)
2	👎👎	(2)
1	👎	(1)
Blank		(7)

General Session VI - Panel Discussion: Financial Partners

5	👍👍👍👍👍👍👍👍👍👍👍👍	(12)
4	👍👍👍👍👍👍👍👍👍👍👍👍👍👍👍	(15)
3	👍👍👍👍👍👍	(6)
2	👎👎👎👎	(4)
1	👎👎	(2)
	Blank	(20)

Hotel Location

Liked the location	(26)
Would perfer meeting in D.C.	(4)

How did you hear about this meeting?

Meeting announcement in the mail	(17)
Colleague	(33)
Industry magazine calendar	(10)
NHA world wide web home page	(9)
Other	(7)

Topics for next year:

- Oil Industry People
- CO_2 sequestration
- How to expand hydrogen fromexisting market to other uses
- Venture Capital
- Renewables for the future
- Fleet users/markets
- Heavy vehicles/rails
- Stationary fuel cells
- PEM Membrane Improvements
- Portable H_2-O_2/PEM fuel cells
- More varying fuels cells other than PEM
- R&D Pipeline