

Hydrogen Powered Military Vehicles: A Vision or Reality by 2040?

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EXECUTIVE SUMMARY

Title: Hydrogen Powered Military Vehicles: A Vision or Reality by 2040?

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Thesis: The development of the hydrogen powered military vehicle will be affordable and practical for military application on the battlefield by 2040. However, for the DOD to commit to a hydrogen economy will involve a massive undertaking, requiring large investments and decades to accomplish.

Discussion:

- When hydrogen is used to power the year 2040 generation of the U.S. military vehicles, it will accomplish twice the efficiency of today's gasoline engines, with zero air emissions released into the atmosphere and with ½ the Class III logistics footprint.

- Pure hydrogen is not a viable fuel for the DOD missions, primarily because of the DOD requirement for compact, high volume-energy density power sources.

- With the increased tempo and speed associated with maneuver warfare, when scientists perfect the hydrogen powered vehicle design, storage, and delivery shortcomings, it will positively impact maneuver warfare on the battlefield.

- The volumes required for storage and transportation, and the costs of the fuel storage containers are the big issues and factors in why hydrogen has not emerged as a general purpose fuel to date.

Conclusion:

When hydrogen is used to power the year 2040 generation of the U.S. military vehicles, it will

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accomplish twice the efficiency of today's gasoline engines, with zero air emissions released into the atmosphere. The hydrogen powered military vehicle will become a reality by 2040. The hydrogen powered military vehicle will not be a Revolution in Military Affairs (RMA). Rather it will be evolutionary, and will represent a major technological evolution in military vehicles.

TABLE OF CONTENTS

Chapter	Page
Disclaimer	i
Executive Summary	ii
Table of Contents	iii
List of Figures	v
List of Tables	vi
I Introduction	1
II Background-Context	2
III Body-Hydrogen Powered Cell	12
Alkaline	13
Polymer Electrolyte Membrane	15
Molten Carbonate	17
Solid Oxide	19
Phosphoric Acid	21
Direct Methanol	23
Regenerative (Reversible) Fuel Cells	23
Hydrogen Production Industry	25
Current Steam Reforming of Natural Gas	26
Current Coal-Based Technology	26
Cost	27
Hydrogen from Natural Gas Research	27

Benefits	30
Hydrogen from Coal Research	31
Future Research and Development Requirements	32
<i>FutureGen</i>	34
Hydrogen Distribution	36
Hydrogen Storage	38
Operation Iraqi Freedom Fuel Consumption Rates	38
Conclusion	39
References	42

LIST OF FIGURES

Figures	Page
Figure 1 Alkaline Fuel Cell Diagram	13
Figure 2 Polymer Electrolyte Membrane Fuel Cell Diagram	15
Figure 3 Molten Carbonate Fuel Cell Diagram	18
Figure 4 Solid Oxide Fuel Cell Diagram	20
Figure 5 Phosphoric Acid Fuel Cell Diagram	21
Figure 6 Advanced Ion Transport Membrane Diagram	28

LIST OF TABLES

Tables	Page
Table 1 Energy content of various fuels referenced to gasoline	3

Introduction

What follows is a study on the development of hydrogen power fuel cells, hydrogen production industry, environmental, delivery, and storage considerations, as they relate to developing a hydrogen powered military vehicle by the year 2040. Will the development of the hydrogen powered military vehicle be affordable and practical for military application on the battlefield by 2040? When hydrogen is used to power the year 2040 generation of the U.S. military vehicles, it will accomplish twice the efficiency of today's gasoline engines, with zero air emissions released into the atmosphere and still be affordable. This paper will examine the hydrogen powered vehicle concept by analyzing data from the U.S. Department of Energy, Department of Defense publications, hydrogen industry and academia, while comparing it against U.S. Marine Corps Class III (Fuel) consumption rates for ground and air vehicles during Operation Iraqi Freedom in 2003.

Many military planners, logisticians, and military contractors who support the U. S. Military are studying ways to reduce the massive logistics footprint on the battlefield. Class III (Fuel) is the largest consumed

class of supply for the military on the battlefield. This researcher, who is a U.S. Army logistician, has notable interest in reducing the Class III consumption rates on the battlefield, because Class III requires enormous assets (i.e: transportation, personnel, and time), known as combat enablers to sustain the Class III requirement on the battlefield.

Context-Background

On January 12, 2003, during the State of the Union Address, the President of the United States conveyed to the nation that the hydrogen powered car will allow the United States to become "much less dependent on foreign sources of energy," and requested a \$1.2 billion dollar research effort, "so that America can lead the world in developing clean, hydrogen powered automobiles."¹ The Bush Administration has designated the hydrogen car program as "FreedomCAR."² The FreedomCAR program will focus on the advancement of the fuel cell technology for automobiles to efficiently and effectively convert hydrogen's electrochemical energy into electric power. From a strategic perspective, the hydrogen powered vehicle will benefit our economy by reducing the financial strain caused

¹ President George W. Bush, State of the Union Address. January 12, 2003

² Kolbert, Elizabeth, The Car of Tomorrow. The New Yorker, August 11, 2003, pp. 36

by the purchase of foreign oil, and sustaining a strong international competitiveness.

The hydrogen fuel cell vehicle consumes one-third the energy of the current gas combustion engine per mile driven, while sustaining zero emissions.³ The fuel efficiency and zero emissions are the most attractive characteristics in pursuing the hydrogen powered vehicle. Given the high-energy content of hydrogen and its non-pollutant properties, it is reasonable to ask: why has it not been widely used as a fuel? Table 1 indicates some of the reasons. The volumes required for storage and transportation, and the costs of the fuels storage containers are the main reasons why hydrogen has not emerged as a general purpose fuel to date.

FUEL	ENERGY (MASS)	ENERGY (VOLUME)	TEMP (°C)	MASS (VOL)
GASOLINE	1.0	1.0	25	1.0
JP-5	.97	1.1	25	1.0
METHANOL	.44	.51	25	1.1
ETHANOL	.61	.69	25	1.1
LIQUID HYDROGEN	2.6	.27	-253	.1
METAL HYDRIDE	.046	.36	25	2.5
METHANE (3,000	1.1	.29	25	.25
HYDROGEN GAS	2.6	.06	25	.02
LIQUID PROPANE	1.0	.86	25	.73
METHANE (10,000	1.1	.97	25	.81
HYDROGEN GAS	2.6	.2	25	.08
LITHIUM ION	.019	.035	25	2.02

Table 1. Energy content of various fuels referenced to gas.

³ U.S. Department of Energy, Office of Fossil Energy-Hydrogen Program Plan. June 2003, pp.2

For the Department of Defense (DoD) to commit to a hydrogen economy will be a massive undertaking, requiring large investments and decades to accomplish. How the nation moves in this direction undoubtedly will have a great impact on the ultimate success of the move. DoD should be a dedicated player in this undertaking because it will be greatly impacted by its outcome. Pure hydrogen is not a viable fuel for the DoD missions, primarily because of the DoD requirement for compact, high volume-energy density power sources.⁴ Presently, the total container volume is approximately twice the hydrogen storage volume. This hydrogen storage problem presents DoD with some unique safety problems, especially in combat situations. To take it a step further, it's essential that the hydrogen storage cell is physically reduced in size for safety, weight concerns, and allow DoD the ability to use the precious space saved by the downsized storage cell to equip the vehicle with an up-armored variant, if required. For instance, today in Iraq the United States military vehicles are vulnerable to the insurgents rocket propelled grenades. As up-armored retrofits are being installed to repel rocket propelled grenades, contractors are experiencing

⁴L. Schlapbach and A. Zuttel, "Hydrogen-Storage Materials for Mobile Applications," Nature 414, no. 15 (November 2001); <http://www.atsdr.cdc.gov/toxprofiles/tp121-c3.pdf>.

transmission failures and lack of engine power with the current military vehicle, as a result of the excessive weight.

Currently, the United States imports about nine million barrels of crude oil per day. By 2020, the Energy Information Administration projects that the world oil consumption is projected to rise from 76 to 119 million barrels per day.⁵ Most Americans fail to draw the correlation that crude oil equals a finite resource. In fact, some analysts estimate that the world's recoverable oil resource is 2,700 billion barrels, which implies that the peak world oil production will occur around the year 2015.⁶ The current gap between total U.S. consumption and net production of oil is roughly 11 million barrels per day.⁷ Promoting the most efficient use of oil is necessary during the near term. However, over the long term, a petroleum free economy is paramount.

Hydrogen is considered an alternative fuel for two reasons: 1) it is renewable and, 2) it is the most abundant element on the earth. Hydrogen comprises more than 75 percent of the environment, but to be useful as a fuel, it

⁵U.S. Department of Energy, Office of Fossil Energy-Hydrogen Program Plan. June 2003, pp.10

⁶U.S. Department of Energy, Office of Fossil Energy-Hydrogen Program Plan. June 2003, pp.10

⁷Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

must exist as free hydrogen (H₂).⁸ One very common source of hydrogen is water, which is 11.2 percent hydrogen by weight. Although hydrogen offers many benefits, there are disadvantages to using it as a fuel with current technology. Liquid hydrogen, the preferred form of hydrogen, requires four times the storage space of petroleum-based fuels. The other issue is that hydrogen production relies on the availability of a nonrenewable resource--petroleum. The two issues mentioned above will require a majority of the scientists' time and money in order to overcome these obstacles, in an effort to make hydrogen affordable, efficient and safe.

When hydrogen is used to power fuel cell vehicles, it will accomplish twice the efficiency of today's gasoline engines, with zero air emissions released into the atmosphere. The fuel cells' only byproducts are pure water and some waste heat.⁹

The ultimate goal in mass production of the hydrogen fuel cell vehicles will require a hydrogen-based infrastructure that is as efficient as the petroleum-based infrastructure we have today. As the private sector develops the hydrogen fuel infrastructure, the FreedomCAR

⁸Kushnir, Peter, Hydrogen As An Alternative Fuel. <http://www.almc.army.mil/alog/issues>

⁹Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

Partnership and Hydrogen Fuel Initiative will develop the technologies needed by the vehicles.¹⁰

To achieve the FreedomCAR Partnership and Hydrogen Fuel Initiative Vision will require technological breakthroughs, market acceptance, and large investments in a national hydrogen infrastructure. Success in the hydrogen program will take time, time as in decades, not years. Some of the significant requirements necessary to achieve success include:

- Lower the cost of producing and delivering hydrogen by a factor of four.
- Develop lighter, affordable, safer, and efficient hydrogen storage systems that will allow vehicles to exceed the 300 mile range.
- Reduce the cost of materials for advanced conversion technologies by a factor of ten, especially the fuel cells.
- Produce hydrogen more efficiently and reduce the cost by a factor.
- Designs and materials that maximize the safety of hydrogen use.
- Educate the consumer on the use of a hydrogen powered vehicle.¹¹

The Department of Energy has identified critical areas in the production, delivery, storage, conversion, and end-

¹⁰Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

¹¹Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

use, while identifying milestones and decision points that are essential in the success of the program. For instance, examples of key program milestones that support FreedomCAR and achievement of a hydrogen powered economy include the following:

- On-board hydrogen storage systems with a six percent capacity by weight by 2010, with more aggressive goals established by 2015.
- Hydrogen production at an untaxed price equivalent to \$1.50 per gallon of gasoline at the pump by 2010.
- Polymer automotive fuel cells that cost \$45 per kilowatt by 2010 and \$30 per kilowatt by 2015, meet 100,000 miles of service life.
- Zero emission coal plants that produce hydrogen and power, at \$0.79 per kilogram at the plant gate.¹²

It is critical that advances in other technologies occur for the hydrogen fuel vehicle to realize its full potential. These advances include:

- Improved energy storage, (e.g., batteries that are more durable, cheaper, and better performing).
- More efficient and cost effective electric motors.
- Inexpensive and more effective power electronics.
- Better materials for lighter, but strong, structural members.¹³

These improvements will allow hydrogen-fueled vehicles to be more efficient, and equally important, help lower the

¹²Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

¹³Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

vehicle cost to the consumer. Consumer acceptance is key to the hydrogen powered vehicle replacing the internal gas combustion engine vehicle we drive today. For consumers to accept the hydrogen powered vehicle, the gas efficiency must be equal to or greater, and the vehicles must be affordable and safe.

The Department of Energy views the transition to a hydrogen economy as occurring in four phases. The transition will take several decades to occur, and require strong public and private commitment. Phase I: Government and Private Organizations will research, develop, and demonstrate technologies prior to investing heavily into the infrastructure. This phase is ongoing today, and will assist with making a decision for commercialization by 2015.¹⁴

Phase II: Transition to the marketplace could begin as early as 2010, specifically for portable power and stationary applications. If hydrogen related technologies exceed customer requirements, the industry could make a decision to commercialize hydrogen fuel cell vehicles by 2015, leading to mass production around 2020.¹⁵ Phase III: Expansion of the markets and infrastructure begins once

¹⁴Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

¹⁵Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

markets are established. The beginning of Phase III is consistent with a positive decision to commercialize vehicles in 2015. Once a decision to commercialize is made the goal is to attract investments in infrastructure, to support fuel cell manufacturing and hydrogen production, then delivery.¹⁶

Phase IV, Realization of the Hydrogen Vision should begin in 2025. This phase begins when customer requirements are met, environmental quality has been achieved, and industry receives adequate return on their investment to compete globally. Phase IV will provide the transition to a full hydrogen economy by 2040.¹⁷

The Army's Tank-Automotive Research, Development and Engineering Center (TARDEC), is the nation's laboratory for advanced military automotive technology. The U.S. Army is looking at the idea of developing hydrogen-powered tactical vehicles, but will not impose its own priorities on the design of the early hydrogen vehicles. However, the U.S. Army will let the commercial market dictate what hydrogen vehicle applications emerge first, and then become an early adopter of that technology by employing the hydrogen

¹⁶Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

¹⁷Congressional Testimony of David Garmen, "The Path to a Hydrogen Economy". March 5, 2003

vehicle at domestic military installations.¹⁸ The Army has government mandates to use less petroleum and shift toward alternate fuels. The development of the hydrogen powered vehicles will help the Army in accomplishing those goals. To take it a step further, DoD should adopt a policy and become directly involved in the development of hydrogen powered vehicle applications, hydrogen infrastructure, and hydrogen storage issues, in order to leverage the national hydrogen initiative and to have in place an infrastructure to assure DoD energy needs are satisfied. A bilateral arrangement with the hydrogen commercial market and DOD would benefit all involved as scientists develop the hydrogen powered vehicle, infrastructure, and as storage issues are improved. Also, when DoD purchases a major end item (i.e.: truck, tank, artillery gun), the acquisition process can take up to 20-25 years for research, development, and test and evaluation. With immediate DoD involvement, the research process would be initiated and ultimately accelerate the acquisition process once the decision is made to convert the DoD vehicle fleet to hydrogen power.

¹⁸Mullen, Richard, Army Eyes Hydrogen Vehicles As Efficiency Boosters. New Technology Week

Body - Hydrogen Power Cell

Unless researchers are able to make technological breakthroughs in the economics of producing hydrogen, and in the size and weight of hydrogen storage systems, the practical application of hydrogen as a fuel for transportation vehicles may be solely dependent upon the development of an automotive fuel cell system. To date, Daimler-Chrysler, Ford, and General Motors have spent roughly \$2 billion developing fuel cell cars, buses, and trucks, with the first products due out in 2004.¹⁹ The fuel cell is an electrochemical system in which the chemical energy of a fuel and an oxidizer are directly converted into electrical energy. A fuel cell can continuously produce electricity as long as the supply of fuel and oxidizer are sustained.²⁰ For instance, in the case of the fuel cell vehicle, the electricity, which is very efficiently produced by the fuel cell, is used to power an electric motor, which in turn drives the wheels. When the military adopts the hydrogen powered vehicle, it will not only provide the capability of transporting troops and cargo, but can be used to power cantonment areas, tent cities, or brigade support areas.

¹⁹Schwartz. Peter, How Hydrogen Can Save America. www.wired.com/wired/archive/11.04.html

²⁰H.S. Murray, et al., "DOT Fuel-Cell-Powered Bus Feasibility Study," Final Report, Los Alamos National Laboratory, December, 1986.

There are seven different processes or types of fuel cells, which are: Alkaline, Polymer Electrolyte Membrane, Molten Carbonate, Solid Oxide, Phosphoric Acid, Direct Method, and Regenerative (Reversible).²¹ Let us now discuss each process in detail.

Alkaline

The alkaline fuel cell was one of the first types used by the U.S. space program to produce electrical energy and water onboard the spacecraft.²² This alkaline fuel cell uses potassium hydroxide in water as the electrolyte and various non-precious metals as a reactant (Figure 1).

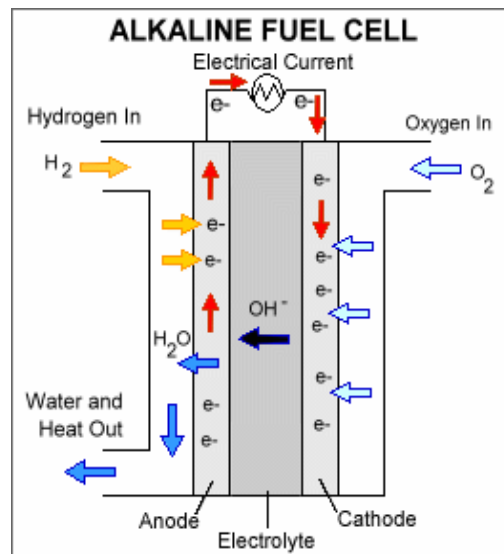


Figure 1

²¹H.S. Murray, et al., "DOT Fuel-Cell-Powered Bus Feasibility Study," Final Report, Los Alamos National Laboratory, December, 1986.

²²U.S Department of Energy, Energy Efficiency and Renewable Energy, <http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

Alkaline fuel cells operate at temperatures between 212°F and 482°F. However, NASA researchers have developed alkaline fuel cell designs that operate between 74°F to 158°F.²³ This is particularly important when discussing delivery and size of fuel cells in military vehicles.

In space applications, the alkaline fuel cell is 60 percent efficient. The disadvantage of the alkaline fuel cell is that it becomes easily poisoned by carbon dioxide (CO₂), making it necessary to purify both the hydrogen and oxygen. The purification process is costly and susceptible to contamination which affect the cell's lifetime and further adds to the cost.²⁴

To effectively compete in most commercial markets, the alkaline fuel cell must become more cost effective. Presently, the alkaline fuel cell can maintain stable operation for about 8,000 operating hours. To be competitive, economical, and used for large-scale utility applications, the alkaline fuel cell needs to exceed an operating capability of 40,000 hours.²⁵ This will be the most significant obstacle in commercializing the alkaline fuel cell.

²³U.S Department of Energy, Energy Efficiency and Renewable Energy, <http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

²⁴U.S Department of Energy, Energy Efficiency and Renewable Energy,
²⁵U.S Department of Energy, Energy Efficiency and Renewable Energy,
<http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

Polymer Electrolyte Membrane

Polymer electrolyte membrane fuel cells deliver high power and offer the advantages of low weight and volume in comparison to other fuel cells. For a military vehicle fuel cell, this technology is particularly interesting because of the decreased weight and increased volume. The Polymer electrolyte membrane fuel cell uses a solid polymer as an electrolyte, and porous carbon electrodes containing a platinum catalyst (Figure 2).²⁶

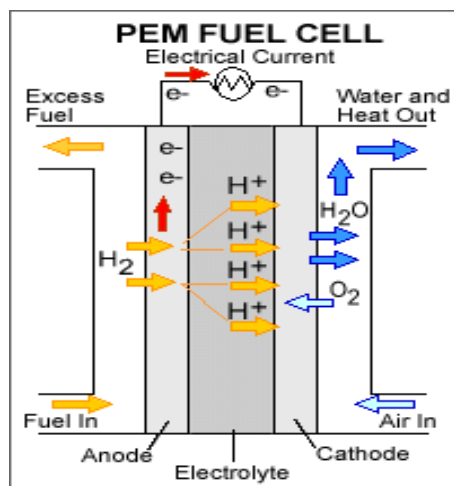


Figure 2

This technology will not require corrosive fluids. Typically it is fueled with pure hydrogen supplied from

²⁶U.S Department of Energy, Energy Efficiency and Renewable Energy.

storage tanks onboard, oxygen from the air, and water to operate.²⁷

Polymer electrolyte membrane fuel cells operate at 80°C (176°F). This low operating temperature allows the fuel cell to start quickly and results in less wear and tear on the fuel cell components, resulting in longer life expectancy. However, the polymer electrolyte membrane fuel cell requires a platinum catalyst used to separate the hydrogen's electrons and protons, which adds to system costs.²⁸ The platinum catalyst is also sensitive to CO₂ contamination. This makes it necessary to employ an additional reactor to reduce the CO₂ in the fuel gas when hydrogen is derived from an alcohol or hydrocarbon fuel. Researchers are presently testing platinum/ruthenium catalysts that are more resistant to CO₂.²⁹

Polymer electrolyte membrane fuel cells are used mainly for transportation and some stationary applications. Due to the quick startup time and favorable power-to-weight ratio, polymer electrolyte membrane fuel cells are suitable in passenger vehicles. As the hydrogen technology exists today, the polymer electrolyte membrane fuel cell is practical for military application due to its quick startup

²⁷U.S Department of Energy, Energy Efficiency and Renewable Energy.

²⁸U.S Department of Energy, Energy Efficiency and Renewable Energy

²⁹U.S Department of Energy, Energy Efficiency and Renewable Energy

time and power-to-weight ratio. A significant drawback to using these fuel cells for passenger and military vehicles is the hydrogen storage issue. Most hydrogen fuel cell vehicles must store the hydrogen onboard in pressurized tanks. Hydrogen has a low energy density, thus making it quite difficult to store enough hydrogen onboard to reach the equivalent travel distances (300-400 miles) of an internal gas combustion engine vehicle.³⁰ Fuels like ethanol, methanol, liquefied petroleum, natural gas, and gasoline can be used for fuel, but the vehicles require a converter to reform the methanol to hydrogen, which increases maintenance requirements and costs. Unfortunately, the reformer releases carbon dioxide, commonly known as a greenhouse gas.

Molten Carbonate

Currently, molten carbonate fuel cells are being developed for industrial, electrical, and military applications. Molten carbonate fuel cells operate at high temperatures of 1,200°F and above (Figure 3).³¹ The improved efficiency of the molten carbonate fuel cells

³⁰U.S Department of Energy, Energy Efficiency and Renewable Energy, <http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

³¹U.S Department of Energy, Energy Efficiency and Renewable Energy, <http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

offer significant cost reductions over phosphoric acid fuel cells. Also, molten carbonate fuel cells have attained a 60 percent efficiency rating, and when the waste heat is recovered and re-used, an 85 percent fuel efficiency rating can be attained.

Unlike phosphoric acid, alkaline, and polymer electrolyte membrane fuel cells, molten carbonate fuel cells do not require a reformer to convert dense fuels into hydrogen. Molten carbonate fuel cells operate at such a high temperature that the hydrogen converts within the fuel cell itself--a cost saving process called internal reforming.

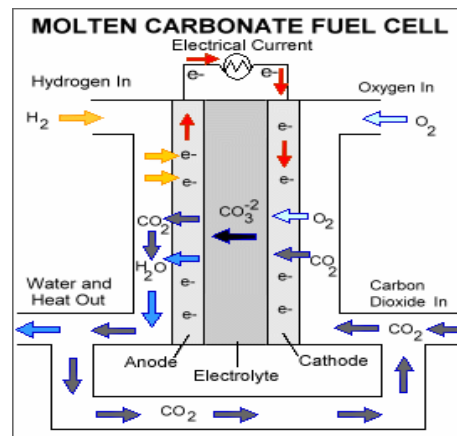


Figure 3

Molten carbonate fuel cells are not prone to carbon dioxide or carbon monoxide contamination, but are more resistant to impurities than other fuel cell types. The

primary disadvantage of molten carbonate fuel cell technology is the durability. This occurs due to the high operating temperatures and the corrosive electrolyte used to accelerate component breakdown and corrosion, which decreases cell life. Scientists are currently researching corrosion-resistant materials for components and fuel cell designs that will increase the cell life without compromising the performance.³² The molten carbonate fuel cell is most appealing for military application today, because it does not require a reformer to convert dense fuels into hydrogen and its high fuel efficiency rating.

Solid Oxide

The solid oxide fuel cell is made of a hard ceramic compound like the electrolyte. Thus, it does not have to be constructed in the plate-like configuration typical of other fuel cell types. Solid oxide fuel cells are 50-60 percent efficient at converting fuel to electricity.³³ In applications designed to recover and re-use the solid oxide fuel cell's waste heat (co-generation), the overall fuel use efficiency can reach 85 percent.³⁴

³²U.S Department of Energy, Energy Efficiency and Renewable Energy

³³U.S Department of Energy, Energy Efficiency and Renewable Energy

³⁴U.S Department of Energy, Energy Efficiency and Renewable Energy

The solid oxide fuel cell operates at a very high temperature of 1,830°F, which removes the need for precious-metal catalyst, thereby reducing the cost.³⁵ Solid oxide fuel cells reform fuels internally, which allows the use of a variety of fuels and reduces the cost associated with adding a reformer to the system (Figure 4).

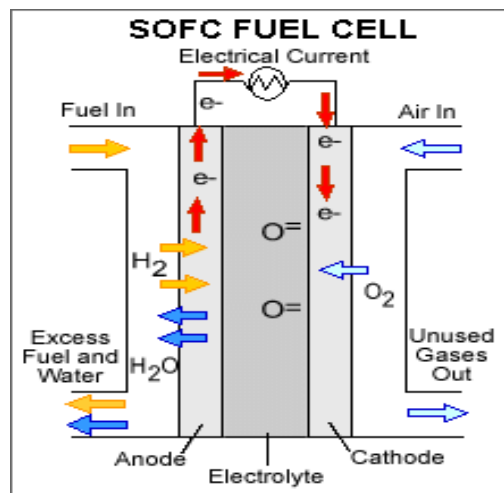


Figure 4

The solid oxide fuel cell is the most sulfur-resistant fuel cell type and cannot be contaminated by carbon monoxide. Solid oxide fuel cells can also use gases made from coal.

The high operating temperatures within the solid oxide fuel cell has disadvantages, which result in slow startup, requires shielding to retain heat and protect personnel,

³⁵U.S Department of Energy, Energy Efficiency and Renewable Energy, <http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

and stress the durability requirements which is unacceptable for military transportation applications. Scientists are researching a low-cost material with a high durability threshold at cell operating temperatures. This is the biggest challenge facing this type of technology.

Researchers are presently developing a solid oxide fuel cell that will operate at a lower temperature, fewer durability problems and cost less. Unfortunately, solid oxide fuel cells produce less electrical power.

Phosphoric Acid

Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte. The electrolyte is contained in a silicon carbide matrix and the carbon electrodes contain a platinum conductor. The chemical reactions that take place in the cell are shown in the diagram (Figure 5).³⁶

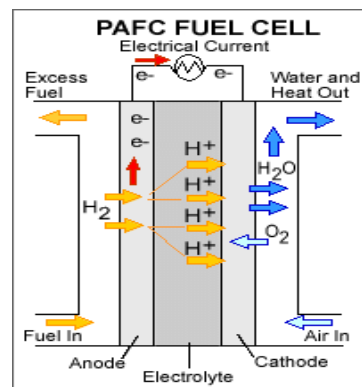


Figure 5

³⁶U.S Department of Energy, Energy Efficiency and Renewable Energy

The phosphoric acid fuel cell is considered the "first generation" of modern fuel cells, the most mature and first to be used commercially with over 200 units currently in use.³⁷ The phosphoric acid fuel cell is normally used in stationary power generation applications, but has been used to power city buses. The phosphoric acid fuel cell is 85 percent efficient when used for the co-generation of electricity and heat, but only 37-42 percent efficient at generating electricity alone.³⁸ This technology is only slightly more efficient than the combustion-based power plant. The phosphoric acid fuel cell is typically large and heavy, and less powerful than other fuel cells given the same weight and volume. A disadvantage with the phosphoric acid fuel cell, is that it is expensive. Like polymer electrolyte membrane fuel cells, the phosphoric acid fuel cell requires a very expensive platinum catalyst, which increases the cost of the fuel cell. A typical phosphoric acid fuel cell costs between \$4,000 and \$4,500 per kilowatt to operate.³⁹ The phosphoric acid fuel cell would not be a wise choice for military vehicle

³⁷U.S Department of Energy, Energy Efficiency and Renewable Energy

³⁸U.S Department of Energy, Energy Efficiency and Renewable Energy

³⁹U.S Department of Energy, Energy Efficiency and Renewable Energy

application, because of the size, weight and lack power compared to other fuel cells.

Direct Methanol

Most fuel cells are powered by hydrogen, which is fed to the fuel cell system directly, or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as methanol, ethanol, and hydrocarbon fuels.⁴⁰ Direct methanol fuel cells are powered by pure methanol, which is mixed with steam and fed directly to the fuel cell anode.

The advantages of the direct methanol fuel cells are: no fuel storage problems, and they are easier to transport and supply using our present infrastructure. Direct methanol fuel cell technology is new, resulting in research and development that is 3-4 years behind other fuel types.

Regenerative (Reversible) Fuel Cells

Regenerative fuel cells produce electricity from hydrogen and oxygen and generate heat and water as byproducts, like other fuel cells.⁴¹ This fuel cell technology is in its infancy and is being developed by NASA

⁴⁰U.S Department of Energy, Energy Efficiency and Renewable Energy, <http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

⁴¹U.S Department of Energy, Energy Efficiency and Renewable Energy

and others. The regenerative fuel cell systems can use electricity from solar power, to separate excess water into oxygen and hydrogen, a process called "electrolysis."⁴² Although early in the development stage, the regenerative fuel cell technology offers many characteristics that are favorable for military application. For example, the electricity generated from hydrogen and oxygen generate heat and water, a byproduct that may possibly be captured and reused in a Brigade Support Area, Initial Staging Base, or tent city. Also, the regenerative fuel cell systems ability to produce electricity from solar power is an attractive characteristic, considering the abundant sunshine region of Southwest Asia where the United States and coalition partners are presently engaged in Iraq and the Global War on Terrorism. A military vehicle with the capability to regenerate its fuel source would be evolutionary in nature, and significantly reduce Class III (Fuel) on the battlefield. Also, with the regenerative fuel cell vehicles capability to produce electricity, the generator will become obsolete and one less end item that will require Class III on the battlefield.

⁴²U.S Department of Energy, Energy Efficiency and Renewable Energy

Hydrogen Production Industry

It is important now to discuss the hydrogen production industry as seen today, and how the U.S. Department Energy believes it will evolve in the next decade. Today, about half of the world's hydrogen supply and most hydrogen in the United States is produced through the steam reforming of natural gas, or Coal-Based Technology. The U.S. demand for hydrogen currently is about 9 million tons per year, of which, 1.5 million tons is sold to refineries and chemical plants.⁴³

Hydrogen is produced at a refinery as a by-product of naphtha reforming, while any supplemental hydrogen is produced from steam reforming of natural gas.⁴⁴ Naphta reforming is the fraction that boils between gasoline and kerosene. The chemical industry uses hydrogen to manufacture fertilizers and ammonia, and uses steam reforming of natural gas and coal gasification to produce the hydrogen. Approximately 95 percent of the United States hydrogen production for refineries and the chemical industry needs, is produced from natural gas using steam-reforming technology.⁴⁵

⁴³U.S Department of Energy, Energy Efficiency and Renewable Energy

⁴⁴U.S Department of Energy, Energy Efficiency and Renewable Energy

⁴⁵U.S Department of Energy, Energy Efficiency and Renewable Energy

Current Steam Reforming of Natural Gas

Currently, steam reforming is a reaction between natural gas and steam. The result is a mixture of carbon dioxide, water, hydrogen, and carbon monoxide that is produced in a series of three reactions:

- The first step reacts methane to form hydrogen and carbon monoxide in a heat-releasing reaction.
- The carbon monoxide is then mixed with steam to form more hydrogen and carbon dioxide in a heat-absorbing reaction.
- The carbon dioxide and traces of carbon monoxide are removed using several adsorption processes, leaving pure hydrogen for commercial use.⁴⁶

Current Coal-Based Technology

Presently, hydrogen is produced from coal by a process called gasification. This process is currently used primarily to produce ammonia for fertilizer. Coal gasification works by reacting coal with oxygen and steam under high pressures and temperatures to form a synthesis gas consisting of carbon monoxide and hydrogen.⁴⁷ The gas is then cleaned of all of its impurities and shifted to

⁴⁶U.S Department of Energy, Energy Efficiency and Renewable Energy, <http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html>

⁴⁷U.S Department of Energy, Energy Efficiency and Renewable Energy

produce additional hydrogen, the clean gas is sent to a separation system to capture the pure hydrogen.

Cost

Natural gas will likely provide the earliest affordable feeder for hydrogen, because today's costs are too expensive. The cost associated with producing and delivering hydrogen from a small scale reformer of natural gas for use in a fuel cell vehicle could be as high as \$40-\$50 per million BTUs with current technology.⁴⁸ Presently, hydrogen is about four times as expensive as gasoline at the pump.

The Department of Energy's Office of Fossil Energy has begun a new effort to develop technologies that will drastically lower the cost of producing hydrogen from both natural gas and coal. Let us now discuss the new technologies projected for the next decade.

Hydrogen from Natural Gas Research

Currently, a mature technology called steam reforming of natural gas is conducted to produce hydrogen. By the year 2013, the Department of Energy envisions developing natural gas technology modules that reduce the cost of

⁴⁸U.S. Department of Energy, Energy Efficiency and Renewable Energy

hydrogen produced from natural gas by 25 percent.⁴⁹ The development of the advanced ion transport membrane technology may simplify the process of manufacturing hydrogen from natural gas and separate it into oxygen, which in a single step will generate synthesis gas. This technology uses a smooth ceramic membrane fabricated from various metallic components that will conduct both electrons and oxygen ions at temperatures of 700 degrees C.⁵⁰ Figure 6 depicts the advanced ion transport membrane process.⁵¹

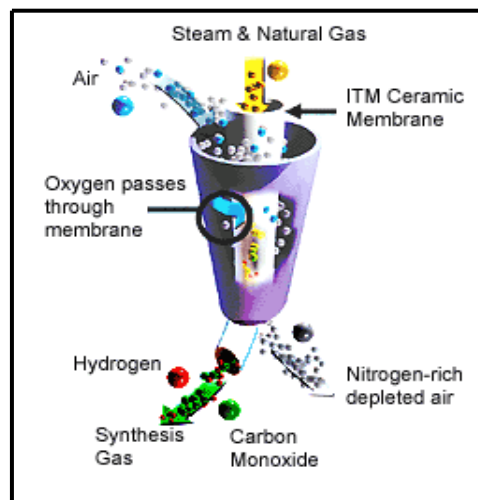


Figure 6

⁴⁹Department of Energy, [Today's Hydrogen Production Industry](http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml), <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁵⁰Department of Energy, [Today's Hydrogen Production Industry](http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml), <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁵¹Department of Energy, [Today's Hydrogen Production Industry](http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml), <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

The process begins with the flow of oxygen from a hot air stream that is forced into an ion transport membrane to create oxygen ions. The oxygen ions flow through the membrane where they partially oxidize to a hot mixture of steam and natural gas to form synthesis gas, a mixture of carbon monoxide and hydrogen.⁵² The ratio of carbon monoxide to hydrogen is mostly dependent on the amount of steam that is used.

The synthesis gas is diverted to a water and gas reactor where additional steam is added to convert the carbon monoxide and steam to more hydrogen and carbon dioxide.⁵³ Now the a mixture of hydrogen, carbon dioxide, and small amounts of carbon monoxide is separated to produce a stream of hydrogen and a stream of carbon dioxide that can be captured and eventually sequestered.

The present technology used to separate hydrogen from the synthesis gas is called pressure swing adsorption. Researchers believe that further development of the advanced membrane technology has great potential to reduce the cost of this process.

⁵²Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁵³Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

Benefits

The introduction of a lower cost, small-scale hydrogen plant will allow earlier production of low cost hydrogen. Due to the small footprint, hydrogen plant construction time is decreased. Further, the smaller facilities reduce the need for a significant transportation and delivery infrastructure. The large hydrogen plants that use the ion transport membrane reactor systems will have even lower costs to produce hydrogen because of the economy of scale benefits, and will become a great source of hydrogen in the near to mid term.⁵⁴

Researchers believe the low-cost technology for hydrogen production from natural gas will bridge technology and allow earlier transition to the hydrogen economy. Also, this technology will provide a platform for more hydrogen production facilities that support technologies such as fuel cell vehicles in a shorter period of time.

The large and smaller scale plants that produce hydrogen from natural gas will provide the earliest, low-cost transitional source of hydrogen for the FreedomCAR

⁵⁴Department of Energy, Today's Hydrogen Production Industry,
<http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

program which will reduce our Nation's energy consumption and pollution.⁵⁵

Hydrogen from Coal Research

The Department of Energy's goal by the year 2015 is to operate a zero emissions, high-efficiency power plant that will produce hydrogen and electricity from coal.⁵⁶

The partial oxidation of coal is a very promising technology for the production of electric power and hydrogen that will use the technology called integrated gasification combined-cycle technology.⁵⁷ Presently, there are no commercial power and hydrogen plants of this kind. However, with a combined effort by academia, private industry and the Department of Energy, this goal may soon come to fruition.

In producing hydrogen, the synthesis gas is processed further using a mature water and gas reactor technology to increase hydrogen and convert carbon monoxide to carbon dioxide. Hydrogen is then separated using pressure swing adsorption technology. Hydrogen produced from coal-derived synthesis gas is essentially the same process currently

⁵⁵ Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁵⁶ Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁵⁷ Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

being developed in the Department of Energy's coal-based clean electric power generation program.⁵⁸

To reduce the cost, a new and advanced technology must be developed in all phases of the gasification through all hydrogen separation phases. The carbon dioxide produced in the hydrogen production process would be removed utilizing capture and storage technology, which is presently being developed in Department of Energy's carbon sequestration research program.⁵⁹

Future Research and Development Requirements

Currently in the Department of Energy, the Hydrogen from Coal Program is developing new processes that include:

- An advanced water and gas reactor that uses sulfur catalysts to produce more hydrogen from synthesis gas at lower cost,
- membranes that allow a more advanced, lower cost separation process of hydrogen from carbon dioxide and other contaminants,
- technology concepts that will combine the hydrogen separation and the water and gas reaction,
- a technology that utilizes fewer steps to separate carbon dioxide, hydrogen sulfide, and other impurities from hydrogen.⁶⁰

⁵⁸Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁵⁹Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁶⁰Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

This researcher has learned that newer catalysts and materials must be developed for these technologies to succeed. Further, technology and engineering studies are also needed for co-production and integration of coal gasification for power production with hydrogen production and separation.⁶¹

In an effort to reduce costs to produce a coal-derived hydrogen, it is imperative that improvements are made in the coal gasification technologies. These improvements include:

- Advanced ion transport membrane technology for oxygen separation from air,
- advanced cleaning of raw synthesis gas,
- improvements in gasifier design, materials and systems,
- advanced carbon dioxide capture and sequestration technology.⁶²

A collaborative effort is required by the government, industry and academic institutions in conducting the necessary research needed to identify, design and demonstrate the most advanced technologies that will significantly reduce the cost to produce hydrogen and

⁶¹Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

⁶²Department of Energy, Today's Hydrogen Production Industry, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

provide a feasible alternative to current, mature technology.

FutureGen - Tomorrow's Pollution-Free Power Plant

"Today I am pleased to announce that the United States will sponsor a \$1 billion, 10-year demonstration project to create the world's first coal-based, zero-emissions electricity and hydrogen power plant..."

President George W. Bush
February 27, 2003



FutureGen is an initiative to build the world's first integrated sequestration and hydrogen production research power plant. The \$1 billion dollar project is intended to create the world's first zero-emissions fossil fuel plant.⁶³

This initiative is a response to President Bush's directive to tap into the best scientific research available to address the issue of global climate change. The President's intent is to create a hydrogen economy and fuel pollution free vehicles. Also, other countries will

⁶³U.S. Department of Energy, FutureGen - A Sequestration and Hydrogen Research Initiative.
<http://www.fossil.energy.gov/programs/fuels/hydrogen-from-gas.shtml>

be invited to participate in the demonstration project through the Carbon Sequestration Leadership Forum.⁶⁴

The FutureGen plant will produce electricity and hydrogen from coal (the lowest cost and most abundant domestic energy resource), while capturing and sequestering the CO₂ generated in the process.⁶⁵ The government and industry will partner to pursue a project focused on the design, construction and operation of a state of the art power plant that is intended to eliminate environmental concerns associated with coal utilization. The FutureGen project will receive support by the ongoing coal research program, and be the main source of technology for the prototype. The FutureGen project will require 10 years to complete, and will be led by an industrial consortium represented by the coal and power industries. The project results will be shared among all participants and industry.

During the operational phase of the FutureGen project, the revenues generated from the sales of electricity, hydrogen and CO₂ will be shared among the project

⁶⁴U.S. Department of Energy, [FutureGen - A Sequestration and Hydrogen Research Initiative.](http://www.fossil.energy.gov/programs/fuels/hydrogen-from-gas.shtml)
<http://www.fossil.energy.gov/programs/fuels/hydrogen-from-gas.shtml>

⁶⁵U.S. Department of Energy, [FutureGen - A Sequestration and Hydrogen Research Initiative.](http://www.fossil.energy.gov/programs/fuels/hydrogen-from-gas.shtml)
<http://www.fossil.energy.gov/programs/fuels/hydrogen-from-gas.shtml>

participants in proportion to their respective cost-sharing percentage.⁶⁶

Hydrogen Distribution

The Department of Energy's goal by 2011 is to make several hydrogen delivery systems available that will provide an affordable and competitive-priced hydrogen to consumers.

Presently, hydrogen delivery systems exist only for the small merchant hydrogen market in the chemical and refining industries. The bottom line is, customers expect the same convenience, cost and safety when dispensing hydrogen fuel as when dispensing gasoline or diesel fuel. The present hydrogen delivery infrastructure lacks the scope or scale to deliver hydrogen, and is insufficient to supply the hydrogen fuel needs of the FreedomCar program announced in 2003 by President Bush.

Hydrogen has physical properties that may cause some high-strength steel piping materials to become brittle. Therefore, today's natural gas pipelines may not be

⁶⁶U.S. Department of Energy, FutureGen - A Sequestration and Hydrogen Research Initiative.
<http://www.fossil.energy.gov/programs/fuels/hydrogen-from-gas.shtml>

available or capable of handling the additional volumes of hydrogen projected.⁶⁷

It is quite unlikely that industry or government will dedicate any significant capital into a hydrogen delivery infrastructure prior to determining if a hydrogen economy is practicable and feasible. In studying other hydrogen delivery alternatives, the Department of Energy will use computer analyses to determine the best hydrogen delivery system. At which time the trade-offs between the capital investments in new delivery systems, and the use of today's liquid and natural gas transportation systems will be studied. Also, further development of a small-scale on-site reformer will be evaluated against the large capital costs of a dedicated hydrogen infrastructure.⁶⁸ The high cost of hydrogen delivery methods may lead us to initially use conventional fuels and infrastructure up to a point, while small-scale conversion systems make hydrogen onsite. However, small-scale conversion systems to make hydrogen onsite are currently not cost effective.

⁶⁷U.S. Department of Energy, FutureGen - A Sequestration and Hydrogen Research Initiative, <http://www.fossil.energy.gov/programs/fuels/hydrogen-from-gas.shtml>

⁶⁸Department of Energy, Hydrogen Delivery Research, <http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml>

Hydrogen Storage

Hydrogen storage technology must be transparent to the consumer, similar to today's experience with gasoline powered vehicles. The hydrogen storage is a critical enabler in the hydrogen cycle. The ultimate hydrogen storage system must be low cost, energy efficient, provide fast fill capability and be safe. Hydrogen storage systems need to enable a vehicle to travel 300 to 400 miles, and fit in an envelope that will not compromise either passenger space or storage space.⁶⁹ A substantial research and development investment in hydrogen storage technologies is necessary to achieve the performance and cost goals for an acceptable storage solution.

Operation Iraqi Freedom Fuel Consumption Rates

From March 1, 2003 to May 24, 2003, the 1st Marine Expeditionary Force, U.S. Marine Corps, consumed 28,670,751 gallons of fuel during Operation Iraqi Freedom.⁷⁰ Is it relevant to discuss fuel consumption rates during Operation Iraqi Freedom? Yes, it is very necessary to discuss fuel consumption rates. As the DOD transforms, specifically the Army and Marine Corps, into a lighter,

⁶⁹Fuel Cell Report to Congress, February 2003, p.p. 43

⁷⁰1st Marine Expeditionary Force, U.S. Marine Corps, Operation Iraqi Freedom Fuel Consumption Rates, March 1, 2003 thru May 24, 2003.

more lethal, and more deployable fighting force, it is paramount that the next generation of military vehicles consumes less energy or fuel, in order to reduce the Class III (Fuel) logistics footprint, and less dependent on Host Nation Support. How will this impact maneuver warfare? When scientists perfect the hydrogen powered vehicle design, storage, and delivery shortcomings, it will have a positive impact on the battlefield with increased tempo and speed associated with maneuver warfare.

Conclusion

While there is no short-term fuel crisis facing the Department of Defense (DoD), this situation is likely to change over the coming decades as fossil fuel reserves become depleted and demand grows. DOD will be confronted with some serious challenges, such as protecting U.S National interests and resolving defense fuel requirements as the nation moves to alternate fuels. Will the development of the hydrogen powered military vehicle be affordable and practical for military application on the battlefield by 2040? Yes; however, for the DoD to commit to a hydrogen economy, will involve a massive undertaking, requiring large investments and decades to accomplish. How

the nation moves in this direction, undoubtedly will have a great impact on the ultimate success of the move. DoD should be a dedicated player in this undertaking because it will be greatly impacted by its outcome. Pure hydrogen is not a viable fuel for the DOD missions, primarily because of the DOD requirement for compact, high volume-energy density power sources. Presently, the total container volume is about twice the hydrogen storage volume. This hydrogen storage problem presents DOD with some unique safety problems, especially in combat situations. Promoting the most efficient use of oil is necessary during the near term. However, over the long term, a petroleum free economy is paramount.

Hydrogen is considered an alternative fuel for two reasons: 1) it is renewable and, 2) it is the most abundant element on the earth. Hydrogen comprises more than 75 percent of the environment, but to be useful as a fuel, it must exist as free hydrogen (H_2). One very common source of hydrogen is water, which is 11.2 percent hydrogen by weight. Although hydrogen offers many benefits, there are disadvantages to using it as a fuel with current technology. Liquid hydrogen, the preferred form of hydrogen, requires four times the storage space of

petroleum-based fuels. The other issue is that hydrogen production relies on the availability of a nonrenewable resource--petroleum. The two issues mentioned above will require a majority of the scientist's time and money in order to overcome these obstacles, in an effort to make hydrogen affordable, efficient, and safe. When hydrogen is used to power the year 2040 generation of the U.S. military vehicles, it will accomplish twice the efficiency of today's gasoline engines, with zero air emissions released into the atmosphere. The hydrogen powered military vehicle will become a reality by 2040. The hydrogen powered military vehicle will not be a Revolution in Military Affairs (RMA). Rather, it will be evolutionary, and will represent a major technological evolution in the military vehicle.

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