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Hydrogen as a Fuel for DOD

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Overview

Energy issues have been at the center of the national security debate for some time, and the current situation in the Persian Gulf underscores the strategic importance of sound energy policy. Activities or developments—geopolitical, environmental, technological, or regulatory—that materially change the energy security equation are, naturally, of great interest to the Department of Defense (DOD). The announcement by President George Bush in his State of the Union address that he intends to accelerate research and development (R&D) for hydrogen-powered vehicles toward the objective of total U.S. energy independence has great potential impact on DOD. This paper examines a number of technical issues connected with energy independence through hydrogen and how they might affect DOD. We conclude that the move to a hydrogen economy will be a massive undertaking, requiring large investments and decades to accomplish. We will show that, with few exceptions, pure hydrogen is not a viable fuel for DOD missions, primarily because of the DOD requirement for compact, high-volumetric energy density power sources. As a result, to meet its unique needs, DOD likely will have to increase its dependence on nuclear power and support R&D that investigates ways to use hydrogen to synthesize hydrocarbon fuels in an environmentally compliant fashion. Several suggestions and recommendations will be made in this regard.

Hydrogen as a Fuel

Hydrogen is a much-studied element, large quantities of which are produced today for industrial applications. Most of this hydrogen is a chemical commodity rather than an energy commodity. There are, of course, some specialized uses of hydrogen as a fuel, such as in rocket propulsion. Given the high-energy content of hydrogen and its intrinsic non-pollutant properties, it is reasonable to ask: why has it not been used widely as a fuel? Table 1 indicates some of the reasons.

In this table, various fuels have been normalized to a typical gasoline. The comparison is done on a mass and volume basis. The second column of table 1 shows that, on a pound-for-pound basis,

Table 1. Energy content (versus mass and volume) of various fuels referenced to gasoline

Fuel	Energy (per unit mass)	Energy (per unit volume)	Temperature (°C)	Mass (per unit volume)
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 psi)	1.1	.29	25	.25
Hydrogen gas (@ 3,000 psi)	2.6	.06	25	.02
Liquid propane (@ 125 psi)	1.0	.86	25	.73
Methane (@ 10,000 psi)	1.1	.97	25	.81
Hydrogen gas (@ 10,000 psi)	2.6	.2	25	.08
Lithium ion battery	.019	.035	25	2.03

Sources: <http://www.methanol.org/methanol/fact/sumprop.cfm>; <http://www.airliquide.com/en/business/products/gases/gasdata>; <http://webbook.nist.gov/cgi/cbook.cgi?ID=C64175&Units=SI&Mask=2#Thermo-Condensed>; <http://www.cea.fr/gb/publications/Clefs44/an-clefs44/clefs4470a.html>; L. 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>.

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hydrogen has a higher heating value than the other fuels shown. This well-known fact is often touted as one of the great advantages of hydrogen. However, the volume comparison (third column) shows that hydrogen has the lowest heating value per unit volume among the fuels listed (excluding the lithium ion battery). Even liquid hydrogen at -253 °C has only one-fourth the volumetric energy content of gasoline. Furthermore, liquid hydrogen requires complex cryogenics, while gasoline is liquid at room temperature and can be stored and transported easily in inexpensive containers.

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

There are important fuel properties other than energy density. Among these are the limits of flammability, flame speed, minimum ignition energy, auto ignition temperature, ignition properties in the presence of catalysts, and environmental impact. Hydrogen has very wide limits of flammability (4–75 percent hydrogen concentration) and a very high flame speed. It also has a low spark ignition energy (0.0182 millijoules [mJ]) and an auto-ignition temperature somewhat higher than hydrocarbon fuels. However, unlike hydrocarbon fuels, hydrogen can ignite at low temperatures in the presence of catalysts such as rust, and the ensuing flame is nearly impossible to detect with the naked eye. On the positive side, hydrogen is an environmentally benign fuel, producing mainly water when combusted or used in fuel cells. All of the fuel properties of hydrogen impact both positively and negatively on its viability as a fuel.

Another important consideration in evaluating a fuel is the ease of storage and distribution. Because of its low volumetric energy density, hydrogen can be viable as a fuel only in a liquid state or at very high pressures. Yet using liquid hydrogen as a fuel has disadvantages from purely energetic considerations. About 30 percent of the energy content of hydrogen is required just to liquefy it. This energy is not recoverable in a practical sense. For special applications where costs are not a consideration, liquid hydrogen indeed may be viable as a fuel. However, for large-scale energy applications, a requirement for liquefaction would seem to put hydrogen at a great disadvantage.

Compressing hydrogen gas also requires energy, but only a fraction of that required for liquefaction. For example, table 1 shows that hydrogen at 10,000 pounds per square inch (psi) has a volumetric energy density approaching that of liquid hydrogen. Compressing hydrogen from atmospheric pressure to 10,000 psi requires about 11 percent of the hydrogen energy content. This is a more reasonable energy penalty but does involve dealing with fuel at very high pressures. Progress is being made in producing relatively light-weight composite containers for this purpose. Containers are now available to store hydrogen compressed to 5000 psi at about 11 percent hydrogen by weight.[1] The total container volume, however, is about twice the hydrogen storage volume. This exacerbates the hydrogen storage problem and presents DOD with some unique safety problems, especially in combat situations.

The above discussion implies that the best distribution of hydrogen from centralized source to user would be through gas pipelines. Liquefying hydrogen and then transporting the liquid would seem to be viable only for special applications such as space launch. Trucking highly compressed gas over long distances would not be economically viable due to the low volumetric energy content of the compressed hydrogen. A key question regarding pipeline distribution of hydrogen will be how much power must be supplied to overcome pressure drops along the pipeline. For fully turbulent flow, the required power can be shown as

$$\mathbf{P} = ((\rho v^2/2)(4L/D)f)(\pi D^2\, v/4)$$

where: ρ is the gas density; v is the gas velocity; L is the pipeline length; D is the pipeline diameter; and f is the friction coefficient.[2]

Since the current pipeline standards have been set by the natural gas distribution system, it is useful to compare the power that must be supplied to hydrogen relative to that which must be supplied to natural gas (mostly methane) for the same energy flux down the pipeline. This ratio is:

$$\mathbf{P}_H/\mathbf{P}_M = (D_H/D_M)(v_H/v_M)^3(\rho_H/\rho_M)(f_H/f_M)$$

where the subscripts $_H$ and $_M$ refer to hydrogen and methane respectively. If one were to use the same pipeline diameter ($D_H = D_M$) and the same pressure and then increase the velocity to obtain the same energy flux through the pipeline, the pipeline energy loss for hydrogen would be about three times that for methane. This is not a very attractive approach, especially for long pipelines. As another option, if one were to pump at the same pressure and velocity but increase the pipeline diameter to obtain the required energy flux, then the hydrogen energy loss would be about 15 percent of the methane energy loss. Changing the parameters yet again, if one used the same diameter pipe and pumped at the same velocity but increased the pressure, the hydrogen loss would be about 30 percent of the methane loss. Another factor to be considered is Graham's Law, which indicates hydrogen will leak at about three times the rate of natural gas, thereby creating potential safety problems unless special attention is paid.

The conclusion here is that the use of the current natural gas pipeline infrastructure (beyond the existing rights of way) is probably not viable in the long term for a move to a hydrogen economy. A pipeline infrastructure specifically designed for hydrogen will be required. This is not a surprising result, but it will require a substantial long-term investment. For example, a 12-inch diameter pipeline designed for hydrogen costs about $1 million per mile.[3]

In light of the above, table 2 provides an examination of hydrogen as a fuel by rating its properties as an energy source, a coolant, and a medium to be stored and distributed. Table 2 illustrates how

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Table 2. Scoring hydrogen versus desirable properties of a fuel

Desirable Property	Hydrogen as an energy source	Hydrogen as a coolant	Storage and distribution
High volume energy density	Poor		Poor
High mass energy density	Good		Good
High exhaust velocity	Good		
Low combustion temperature		Good	Poor
High thermal stability		Good	Good
High specific heat/ conductivity		Good	
Low vapor pressure		Poor	Poor
Low critical temperature		Good	
High reaction rate	Good		Poor
High flame speed	Good		Poor
Low ignition energy	Good		Poor
Wide flammability limits	Good		Poor
Low environmental impact	Good		Good

many of the features that make hydrogen desirable from one perspective make it undesirable from another perspective.

Despite some of the known, unfavorable qualities inherent in hydrogen, it is important to note that hydrogen is produced and distributed safely in large quantities today and that procedures have been developed to overcome many of its negative attributes at these quantities. However, tables 1 and 2 suggest that, all other things being equal, if hydrogen were readily plentiful, combining it with carbon to make hydrocarbon fuels would be the most desired option because of the logistic simplicity and high-volumetric energy density found in hydrocarbon fuels. In light of this, why even consider moving to a hydrogen fuel economy? At least two reasons support such a move: the ultimate depletion of oil and natural-gas reserves, and environmental considerations such as the production of carbon dioxide as a greenhouse gas. While there is considerable disagreement over when fossil fuel resources will be depleted, there is little disagreement that eventually they will run out.

In the case of oil reserves, the expected time frame of depletion ranges from 20 to perhaps 100 years. The American Petroleum Institute suggests a 95 percent probability that the world's remaining oil reserves will last another 56 years and a 5 percent probability that they will last another 88 years.[4] If this is the case and hydrogen is to be the replacement fuel, then making it viable must be an immediate priority. With regard to the issue of greenhouse gases, the timeframe to watch is set by the time at which the CO_2 concentration in the atmosphere reaches a level where it produces irreversible climate effects. The predictions in this regard are based upon complex computer models and have considerable uncertainty associated with them. Most project U.S. temperature increases ranging between 3 and 4 °C over the next 100 years.[5] Such rises in average temperature would have significant climatic impact. Therefore, within the current level of understanding, actions required to address oil reserve depletion and greenhouse gases would need to be effected on a similar timescale—that is, about 50 years.

DOD as a User of Hydrogen

DOD has been involved in examining hydrogen as a fuel since at least 1944, when the Navy Bureau of Aeronautics began serious consideration of orbiting spacecraft.[6] This decision led to the 1940s design of liquid-hydrogen-fueled rockets. Many of these designs and the test data collected later played a significant role in the space program.

In the mid-1950s, the Air Force ran a major classified program called *Suntan,* the objective of which was to eclipse the Central Intelligence Agency-developed U–2 aircraft by means of the development of a hydrogen-powered aircraft. While this airplane never materialized, the facilities constructed during this project were key to the subsequent space program. In about the same timeframe, the National Advisory Committee for Aeronautics undertook unclassified design studies for hydrogen-powered aircraft. One mission involved airplanes using turbojet engines flying at a speed of Mach 4 and an altitude of 30,500 meters (m) while carrying a payload of 4,500 kilograms (kg). When designed for hydrogen, the airplane turned out to be 91 m long with a gross mass of 130,000 kg, of which one-third was hydrogen. The airplane using JP–4 fuel was half as long, but had a mass 40 percent greater than the hydrogen configuration, with the JP–4 making up 60 percent of the mass. The hydrogen-fueled airplane had a range just over 5,000 km compared to 3,000 km for the JP–4 airplane.

Studies also were done on hydrogen-fueled ramjet missiles, which outperformed the turbojets. This work on hydrogen-powered aircraft came to a close with the launch of Sputnik. Attention then turned to rockets, which became the approach to launch spacecraft. The designs the Navy Bureau of Aeronautics had considered 15 years earlier became important during this early phase. After much jockeying the newly created National Aeronautics and Space Administration pursued the use of hydrogen for rocket propulsion, leading to the Saturn rockets for the manned moon missions and eventually the space shuttle program of today. DOD benefited from this for launch of its own satellites, but DOD itself focused on ballistic missiles, where the need for readiness argued for the use of solid propellants.

Chronologically, the next serious look DOD took at hydrogen seems to have occurred during the 1973 oil crisis. A useful document in this regard was prepared by Carhart et al.,[7] which examined the potential utility of hydrogen for Navy applications. Many of the points made in that study remain valid today.

The 1950s high-altitude hydrogen aircraft designs are informative with respect to DOD missions and the role of hydrogen. For missions with long legs where one can afford large aircraft, hydrogen, because of its energetic combustion properties, can be the best performer. However, for missions constrained by volume—true for most DOD missions—hydrogen, with its low volumetric energy density, is problematic. Also, the cryogenic requirements for liquid hydrogen and the very high-pressure requirements for gaseous hydrogen further complicate design scenarios.

Navy ships powered by fuel oil provide an example of the complications inherent with hydrogen as a fuel source. If liquid or highly compressed hydrogen were substituted for the fuel oil, fuel volume would quadruple to achieve the same number of steaming days between refuelings. This volume simply is not available on present Navy ships. The other option—refueling four times as often—is incompatible with the Navy mission. Therefore, while hydrogen could fuel gas turbines, a direct replacement of fuel oil with hydrogen is very unlikely. This situation could be improved by expected progress in fuel cells. Fuel cells project conversion efficiencies of 80 percent compared to the 35 percent conversion efficiencies of gas turbines. By combining fuel cells with highly efficient (greater than 90 percent) electric motors, hydrogen fuel storage demands could be reduced from four times the current fuel volume requirement to about twice the volume requirement for the same mission. Perhaps with redesigned Navy ships, including substantial manning reduction through automation, mission capability could be maintained with hydrogen fuel. However, even if the volume storage problem could be solved, serious safety problems are involved with storing several hundred thousand cubic feet of liquid hydrogen at -253˚C or similar volumes of hydrogen gas pressurized to 10,000 psi. This is quite evident from table 2. The confined nature of Navy spaces and the low ignition energy for hydrogen could lead to an untenable situation, even in the absence of combat.

The situation is similar for high-performance military aircraft. At present, to accomplish the same mission with hydrogen, fuel storage volumes would have to be increased by a factor of four. Hydrogen fuel stored in the wings would not be practical, because the large surface-to-volume ratio would increase the boil-off of liquid hydrogen and thereby further reduce range. The use of cryogenic or high-pressure storage tanks that also serve structural purposes does not appear to be viable. Wing pods, while addressing the above problems, greatly increase air drag and reduce rapid maneuverability. This leaves the option of storing the hydrogen in the fuselage by increasing its diameter or its length, as was considered in the 1950s. For low altitude aircraft, the drag would be increased, thereby reducing performance. As a result, it does not appear hydrogen would be a viable fuel for the high-performance low altitude aircraft central in DOD present capability.

For long-range missions such as reconnaissance, where high maneuverability is not a requirement, the situation may be different. In this case, expanding the fuselage to accommodate the required extra fuel storage volume may be feasible, and the low fuel weight of hydrogen may be an advantage. Currently, designs are being undertaken to examine this approach for commercial aviation.[8] Here the primary issues likely will be cost of flight and airport safety, rather than engines or fuselage parameters.

The use of hydrogen as a fuel for DOD aircraft missions that operate in the upper atmosphere is also potentially viable. At high altitudes, the atmospheric drag is low and aircraft tend to be large in order to obtain the necessary lift. In this case, hydrogen, with its light weight and high energy per unit mass, is intrinsically attractive.

Hydrogen also could be attractive for DOD missions that are powered by batteries. Table 1 shows the volume energy density of liquid hydrogen to be nearly eight times that of lithium ion batteries while the mass per unit volume of liquid hydrogen is about 5 percent that of lithium batteries. Similar numbers apply for hydrogen compressed to 10,000 psi. If hydrogen were used to power a fuel cell that then provided the electric power in lieu of batteries, considerable mission enhancement might result. For example, the Unitized Regenerative Fuel Cell, coupled with lightweight hydrogen storage, demonstrated about 450-watt hours/kg, which is more than twice the energy available from lithium ion batteries and 10 times that of lead acid batteries.[9] It is quite likely, therefore, that the use of hydrogen powered fuel cells will greatly increase the mission capability of such platforms as electric-powered unmanned vehicles. The importance of extending the battery life for mobile computers, global positioning system tracking devices, and other such devices was noted during Operation *Iraqi Freedom*.[10] Hydrogen-powered fuel cells may prove useful here, particularly when coupled with a lightweight and disposable storage medium, such as glass microshells.[11]

The majority of DOD missions likely cannot be met by the use of pure hydrogen as a fuel, primarily because of its low volumetric energy density. Replacing or replicating the performance of hydrocarbon fuels, especially for high-performance aircraft, will be difficult. Yet, given the eventual depletion of oil reserves and the need to eliminate the addition of carbon dioxide to the atmosphere, DOD will need to make accommodations. In this situation, it is quite likely most Navy platforms would become nuclear powered, since nuclear power demonstrably meets the Navy mission and generates no carbon dioxide. Nuclear power, however, is not a solution for aircraft. Alternative means to fuel aircraft need to be found, and appropriate R&D will need to be done. Potential solutions do exist, such as CO_2-neutral generation of synthetic carbon-based fuels using materials readily available in marine environments. The ocean, for example, has an almost uniform carbon dioxide concentration of about 0.1 gram per liter of water (0.01 percent by weight).[12] The atmosphere is another readily available source of carbon dioxide (0.056 percent by weight).[12] If an efficient process could be found to make hydrogen from seawater, and if the carbon dioxide could be recovered from seawater at sufficiently high rates, it might be possible to synthesize hydrocarbon fuels, with no net production of CO_2 in the atmosphere, through chemistry such as the Fischer-Tropsch process.[13] Should such a scenario prove viable, it would resolve the continuing DOD need for high-performance hydrocarbon fuels in an environmentally compliant fashion.

Scale of Undertaking and Production Issues

To better grasp the issues of moving to a hydrogen economy, the ultimate scale of such a move must be understood. Today, the United States consumes about 4 x 10^{16} British thermal units (BTUs) worth of oil per year.[14] In terms of average power consumption this is about 1,200 gigawatts. To put this in perspective, this is larger than the average total electrical power output of the United States. Using a higher heating value of 142 MJ/kg for hydrogen shows U.S. consumption of oil to be the equivalent of 300 million tons of hydrogen per year. While this production rate can be envisioned (it is within a factor of thirty of the present U.S. hydrogen production rate of 11 million tons per year), one must recognize the implications of the fact that hydrogen does not exist in its elemental form on the earth. It cannot be pumped out of the ground like oil or natural gas. It must be extracted from other materials such as oil, water, natural gas, or biomass. This extraction, in turn, typically requires more energy than is returned when the hydrogen is used as fuel. Therefore, even before getting into a detailed analysis of production, storage, and distribution for a hydrogen economy, it should be obvious that such a move will be a massive undertaking, requiring many decades and huge investments to produce the required infrastructure. How the nation moves in this direction undoubtedly will have a great impact on the ultimate success of the move. DOD should be a serious player in this undertaking because it will be greatly impacted by its outcome.

Today, hydrogen is produced in large quantities as a chemical commodity. It is used principally in fertilizer manufacture and for hydrogenation of hydrocarbon fuels to increase their energy content and to improve their emission properties. It is expected that demand for hydrogen as a chemical commodity will grow for the foreseeable future. However, as long as ample oil and natural gas reserves are present, the volumetric energy comparisons (table 1) will incline the economy heavily in favor of hydrocarbon fuels even as environmental concerns increase. The same argument applies to energy security. Very strong national security arguments have been made in favor of fuels that are not vulnerable to geopolitical instability. Unfortunately, a near-term solution to this problem is unlikely, and an economy that is largely non-fossil-fuel based is decades away. Ultimately, however, a solution must be found. Competition for diminishing oil and natural gas reserves will increase in the coming years. If hydrogen is deemed to be the proper course, then, considering the massive task of moving toward a hydrogen economy, the groundwork to move in this direction needs to begin soon. To do this, many impediments—technical, environmental, economic, social, and political—will need to be resolved in ways that contribute to practical near-term needs while, at the same time, preparing the way for long-term solutions.

Hydrogen is produced, stored, transported, and distributed to end-users in large quantities today, so a great deal already is known in these areas. The areas where efforts should be focused are straightforward to identify, although not as straightforward to resolve. Six of the methods for producing hydrogen, some still in the design phase, are discussed in more detail below.

Steam Reforming of Methane

The vast majority of hydrogen (95 percent) is produced by the process of steam reforming of methane (SMR), which involves the endothermic reaction of methane with high-temperature steam according to the reaction:

$$CH_4 + 2H_2O + \text{energy} = 4H_2 + CO_2$$

According to this reaction, each gram of hydrogen requires 2.4 g of methane and 6.0 g of steam and produces 7.3 g of CO_2. If the energy is provided by burning natural gas, the net result is to produce about 3 moles of H_2 per mole of CH_4 used. This would increase the amount of methane used and the amount of CO_2 released per gram of hydrogen produced by a factor of 4/3. To produce the energy equivalent of the oil consumed by the United States each year would require about 3 x 10^{14} grams of hydrogen (300 million tons), so the SMR process to produce this hydrogen would consume 7.8 x 10^{14} grams of CH_4 and 1.8 x 10^{15} grams of water and produce 2.2 x 10^{15} grams of CO_2. Burning methane to get the equivalent energy would consume about 25 percent less methane and produce about 25 percent less CO_2. Therefore, based purely on energy considerations, using steam reforming of fossil hydrocarbons to make hydrogen from which to produce energy does not make a lot of sense. It does not reduce significantly either the consumption of hydrocarbon fuel or the production of CO_2 (unless one considers sequestration of the CO_2, which process could be equally well coupled to current stationary-site fossil fuel energy production methods), yet it introduces the complexities of a hydrogen fuel.

Use of hydrogen, however, does make possible the use of fuel cells for conversion of the fuel energy to useful work. Fuel cells offer the potential for high efficiency as well as the possibility of sequestration of vehicle propulsion-related CO_2, because the hydrogen for the fuel cells would be produced at stationary sites. The primary current application of steam reforming of fossil hydrocarbons is to produce hydrogen as a chemical commodity. Some of this hydrogen could and should be used as a fuel to test methods for hydrogen storage, transportation, and delivery to the energy end user, but SMR is not the solution to long-term hydrogen production for a hydrogen economy, nor is it an appropriate path to address the unique long-term needs of DOD.

Other approaches must be explored if the long-term issues of oil and natural gas reserve depletion are to be addressed and the greenhouse gas problem that results from CO_2 emission is to be resolved. It is not possible in this paper to examine all possible alternate hydrogen production technologies. However, to gain some perspective, we will discuss briefly several different approaches for the production of hydrogen and comment on the appropriateness of DOD participation in their development. In particular, we will discuss electrolysis; gasification of coal; gasification of biomass; photonic (or comparably, wind) processes; and thermo-chemical processes.

Electrolysis

Electrolysis is a well-known process using electricity to produce hydrogen from water. Electrolysis has the desirable feature of producing no greenhouse gases unless the method of producing electricity for the electrolysis generates them. In addition, modern electrolyzers are highly efficient. They produce about one cubic meter of hydrogen with an energy value of 3.2 kW-hour for an electrical energy investment of 3.9 kW-hour (80 percent efficiency).[15] Since a cubic meter of hydrogen has a higher heating value of 11.7 MJ, about 3.4×10^{12} m^3 of hydrogen would be required to provide for the annual U.S. oil consumption. To produce the required hydrogen by electrolysis would require about 1,500 gigawatts average electrical power, an amount that exceeds the entire electrical generating capacity of the United States. Where will this electricity come from? If electrolysis is a solution attractive to DOD, then electricity from nuclear power also would be of interest to DOD. Additionally, it has been suggested that generation of the electricity from ocean thermal gradients may be of interest to DOD.[16]

Photonic Processes

A number of schemes are available that use photonic processes to create hydrogen directly from sunlight. These include photovoltaic cells coupled to electrolyzers, photo-electrochemical cells, and photo-biological systems using algae.

To interpret these photonic systems, one metric that can be applied is to examine the total area of solar collection required. The peak solar flux reaching the earth's surface is about 1,000 W/m^2. This leads to an average flux (averaging over day, night, solar angle, etc.) of about 200 W/m^2. The U.S. oil consumption power equivalent is about 1.2×10^{12} W. Therefore, a collection area of about 6×10^9 m^2 (about 2,400 square miles) would be required in order to provide the solar energy equivalent, neglecting any photovoltaic infrastructural fill factors. Furthermore, this estimate does not include conversion efficiencies for producing hydrogen, which, for example, are presently at about 6 percent using photovoltaic cells plus electrolyzers.[17] This implies a minimum solar collection area of about 10^{11} square meters or 40,000 square miles. Since DOD is responsible for about 2 percent of U.S. oil consumption, a DOD-unique solution would require about 800 square miles or 512,000 acres. While DOD has ample land to house such a facility (for example, China Lake in California is about one million acres), the likelihood of DOD wishing to manage and maintain such a large physical plant is low, especially in view of the fact that other approaches could lead to very compact solutions for DOD requirements. Photoelectrochemical cells claim an efficiency for the production of hydrogen of about 10 percent,[18] which corresponds to a minimum collection area of about 480 square miles for DOD-unique requirements, again probably not a promising area for DOD-unique solutions. Further, since the approximate conversion factor for land mass requirements from photovoltaic to wind power is 4.9,[19] using wind power to generate the energy for DOD-unique requirements is even less promising.

Currently, proposed photo-biological approaches do not seem sufficiently developed to make the simple calculations above. One of the more recent and supposedly promising approaches uses a variant of green pond algae (*C Reinhartii*) to produce 2 milliliters (ml) per hour of hydrogen from a one-liter culture.[20] The optical depth of this system is less than 5 centimeters (cm), implying a surface area of 200 cm^2 to produce 2 ml of hydrogen per hour. The hydrogen equivalent to the United States oil consumption requires about 4×10^{14} ml of hydrogen per hour. This indicates a minimum solar collection area that exceeds the total landmass of the United States. While researchers in this area project a ten-fold increase in production with a mutant strain of the algae presently under development, substantially more work needs to be done on this process for it to be competitive.

The above simple analyses suggest that photonic approaches to the production of hydrogen are probably not well suited for DOD-unique requirements.

Gasification

Another area of potential interest for the production of hydrogen is the gasification of solids such as coal or biomass, a process in which a carbon-based feedstock is reacted with steam and oxygen or air under high temperature and pressure to produce a gaseous mixture that contains H_2, CO, and CO_2.[21] Of the possible hydrocarbon feedstocks, coal is the leading candidate. It is a readily available, long-term, highly concentrated energy source. The cost of producing hydrogen from coal is dominated by the capital and operating costs associated with handling solids. Of greater concern are the environmental issues of mine site restoration, residual ash disposal, and the capture and sequestration of waste CO_2. Biomass may be a partial solution because waste biomass is easily available, but the amount of hydrogen generated from this source will be small compared with the needs of the hydrogen economy. The environmental concerns related to the large land tracts required for biomass energy plantations further make it an unlikely candidate. Ultimately, these processes probably are not well suited for DOD-unique solutions.

Thermochemical Cycles

A final process for consideration involves thermochemical cycles. A number of thermochemical hydrogen-producing cycles have been considered for splitting water to make hydrogen. One of the best developed of these schemes is the sulfur-iodine (S-I) thermochemical cycle.[22] This closed scheme reacts water and sulfur dioxide with iodine to produce sulfuric acid and hydrogen iodide. The sulfuric acid is decomposed to sulfur dioxide, water, and oxygen, with the sulfur dioxide then returned to the process. The hydrogen iodide is decomposed to produce iodine and hydrogen, the hydrogen is collected, and the iodine is recycled. The process requires a high-temperature heat source. Design studies indicate that a continuous thermal source at about 950 ˚C peak temperature, providing heat over the range of 500–950 ˚C would result in a thermal to hydrogen energy efficiency of 50 percent.[23] Under these conditions a 30 megawatt (MW) thermal energy source would provide 10 tons of hydrogen per day. Since the hydrogen is produced from water, such a system would provide hydrogen without producing greenhouse gas. The question here becomes: what provides the thermal energy? It would seem that solar collection or nuclear power would be viable for this. From a DOD viewpoint, the solar (or wind) approach suffers from the same large real estate requirements identified for photonic

Table 3. Annual capital and operating costs associated with adding the ability to produce an additional ton of hydrogen production capability each year for various technologies

Technology	Capital cost ($ per annual ton)	Operating cost ($ per annual ton)	Cost $/kg[†] @20% ROI	Cost $/kg[†] @ 12.7% ROI
Steam Methane Reforming[††]	1,196	500	.93	.81
MHR S-I	4,675	397	1.86	1.43
Coal Gasification	4,348	832	2.26	1.85
Biomass Gasification	5,555	308	3.42	2.58
Electrolysis[†††] + Gas Turbine MHR	6,967	668	2.83	2.21

[†] Assumes 5 percent per year depreciation on capital costs and 20 percent and 12.7 percent return on capital investment (ROI), and full recovery of operating costs. Analysis based upon "Hydrogen Production Costs—A Survey" prepared by SENTECH, Inc., December 1997, and on GA data.

[††] Assuming natural gas cost of 2.167 $/GJ.

[†††] Uses SYNTECH estimates for the electrolysis plant and GA estimates for a gas turbine MHR electric power plant to supply the electricity.

processes. Moreover, researchers still are investigating the efficiency of the S-I cycle in an environment that has diurnal temperature variability. This would seem to leave only the nuclear option for the use of this scheme for DOD-unique requirements.

In 1997, SYNTECH, Inc., prepared a report that compared hydrogen production costs for a number of the processes discussed above, including SMR, electrolysis, coal gasification, and biomass gasification.[24] Table 3 is derived from this report along with data provided by General Atomics (GA) regarding the thermochemical process mentioned above using a modular helium gas reactor (MHR) to provide heat for the thermochemical processes and/or electricity for the electrolysis process discussed in the SYNTECH study. The table presents capital costs and annual operating costs for each method per annual ton of hydrogen produced. The costs are expressed in 1997 dollars to be consistent with the SYNTECH report.

conversion to a hydrogen economy will take decades to put in place, just as did the oil infrastructure that it would be structured to replace

The highest capital cost results for the electrolysis plus the gas turbine-MHR plant. The gasification of biomass approach led to the second most costly plant and the most costly hydrogen. The thermochemical approach (MHR S-I) and coal gasification had comparable capital costs, with coal gasification leading to somewhat higher priced hydrogen. Yet one must be careful in taking the absolute numbers in such analyses too seriously. The results can be very sensitive to the cost of feedstock, prevailing interest rates, and taxes. One also should expect continued progress in the various approaches to hydrogen production. For example, the intensive research program under way on fuel cells for automotive applications undoubtedly will substantially lower the cost of fuel cells. This will have a direct effect on the cost of electrolysis cells, since they use the inverse of the fuel cell process, thereby making electrolysis more competitive than is indicated in table 3. Nevertheless, the analysis does give a sense of the ranking of the various approaches and of the scale of the move to a hydrogen economy.

The SMR approach listed in table 3 can be ruled out, because it does not resolve the natural gas depletion problem or the CO_2 problem. Among the remaining options, coal gasification and thermochemical approaches each have capital costs of about $4,500 per annual ton of hydrogen produced. About 3 x 10^8 tons of hydrogen per year would be required to provide the energy equivalent of the oil consumed by the United States each year. This results in a capital investment requirement of about $1.5 trillion just for these sorts of hydrogen production facilities, with electrolysis being approximately 1.5 times higher. The remaining required infrastructure is likely to have comparable costs. These are huge costs, but they are not surprising and are representative of the investments that have been made by the oil industry to date.[25] Conversion to a hydrogen economy will take decades to put in place, just as did the oil infrastructure that it would be structured to replace.

In consideration of the above analysis, it seems that DOD should pay particular attention to the nuclear option because of its relatively compact land requirements, high-volumetric energy density, and the inevitable long-term commitment to nuclear power for DOD missions. In the next section we will explore that option in somewhat more detail.

The Nuclear Option

Water-splitting, the separation of water into hydrogen and oxygen, can provide an environmentally clean source of hydrogen if the primary source of energy is not a source of greenhouse gases. Solar or nuclear energy will likely be the most appropriate source, considering the massive energy requirements identified above for the conversion to a hydrogen economy.

As previously noted, two approaches can be used for hydrogen production from water using nuclear energy, electrolysis, and thermochemical cycles. The first is to use electricity generated by nuclear power to separate water into hydrogen and oxygen by electrolysis. For light water reactors (LWRs), this is a low-temperature approach with about 25 percent net efficiency. Essentially, LWRs are a proven technology, with most of the issues being economic. With a high-temperature heat source (600–950 °C), such as produced by an MHR, net hydrogen producing efficiencies as high as 40–50 percent could be obtained by using high-temperature electrolysis, a developing technology that could provide higher efficiency by using both heat and electricity from the reactor.[26]

The second major approach to nuclear production of hydrogen, suited primarily to a high-temperature, gas-cooled reactor system, is to use high-temperature nuclear-generated heat directly to drive a thermochemical water-splitting cycle, a set of chemical reactions that separates water into hydrogen and oxygen at moderate temperatures. A significant research effort worldwide in the 1970s discovered more than 100 different possible thermochemical water-splitting cycles. Researchers at GA invented several of these cycles, among them the sulfur-iodine (S-I) cycle.[27] This cycle also was studied in Japan, where a complete laboratory-scale test loop was operated.[28] A team consisting of GA, Sandia National Laboratories (SNL), and the University of Kentucky, identified S-I from among 115 known thermochemical cycles as the best suited for coupling to nuclear power.[29] SNL also carried out an evaluation and determined that helium gas-cooled reactors, like the MHR, are best for coupling to the S-I thermochemical water-splitting cycle.[30] A complete flow sheet design for the S-I cycle with this reactor predicts good efficiency at reasonable cost.[31] While previous studies provide evidence that the S-I cycle is technically feasible, work is now under way to prove the cycle is also practical.[32]

The Electric Power Research Institute recently has completed a study of various hydrogen production technologies.[33] Their results show that comparison of the economics of alternative means of hydrogen production depends on such factors as capital charge rate, cost of feedstock, value of oxygen sale, and cost or penalty for CO_2 capture and sequestration. That study estimated the cost of hydrogen for a number of possible methods of production, including fossil-fired steam reformation of methane, nuclear-heated steam reformation of methane, and the nuclear-heated S-I cycle. Both of the latter processes made use of the MHR, which has high gas outlet temperatures and can operate safely in the temperature regime needed for efficient S-I cycle hydrogen production.[34] The economic parameters used in the computation were capital rates for a typical public utility, $20/ton oxygen sales credit, and $30/ton CO_2 capture and sequestration cost. The results indicate that, with reasonable credit for oxygen sales and moderate CO_2 cost, S-I water-splitting could be economically competitive with steam reformation of methane at current natural gas costs ($4/million BTU for large-scale, long-term contracts).[35]

> **used in today's LWRs, the known reserves of uranium, could provide our current nuclear electricity needs along with our current hydrogen needs by electrolysis for almost 200 years**

In the general sense, one of the advantages of nuclear energy is the large energy resource that uranium represents.[36] While only 0.7 percent of uranium is fissile U–235 isotope, the other 99.3 percent U–238 is "fertile" and can be converted to fissile Pu–239 by capture of a neutron in the core of a reactor. Similarly, fertile thorium–232 can be converted to fissile U–233. The nuclear energy resources are summarized in table 4.

Used in today's LWRs, the known reserves of uranium, could provide our current nuclear electricity needs along with our current hydrogen needs by electrolysis for almost 200 years. Even our current known reserves of "low-cost" uranium would supply all current nuclear electricity and hydrogen needs for the next 34 years.

LWR nuclear reactors burn U–235 and convert some U–238 to Pu–239 with a conversion ratio (CR) of about 0.5 atoms produced per atom consumed. This means that they can extend the reserves of U–235 by up to about a factor of 2. (Fuel consumption scales as 1/(1–CR).) To extend the life of our nuclear fuel resources, reactors with higher conversion ratio are needed. The helium gas-cooled reactor, which has higher neutronic efficiency than LWRs and, thus, the potential to operate with a CR of about 0.75, would extend the U–235 reserves by another factor of 2.

To extend nuclear fuel resources even further and ultimately make all the resources of both U–238 and Th–232 accessible will require breeder reactors or reactors with a CR greater than unity. (That is, they produce more than one atom of fissile fuel from fertile materials in the core for every fissile atom they consume.) Experimental breeder reactors successfully have operated on both the U–238/Pu–239 and the Th–232/U–233 cycles. An important feature of these reactors is that they could be used to fuel other reactors. For example, a breeder reactor with a CR of 1.25 could produce enough excess fuel to support a burner reactor of the same thermal power with a CR of 0.75. In this way, breeder reactors that might not be well suited for the high temperatures needed for thermochemical water-splitting could provide the fuel for high-temperature reactors that could produce hydrogen efficiently.

In order to take advantage of the fuel resource extension obtained by high conversion ratio burner reactors and breeder reactors, reprocessing and recycling of nuclear fuel will be required. Currently, the United States has a policy not to reprocess and recycle fuel but, instead, to dispose of the leftover fuel, both fissile and fertile, as waste. This policy is contrary to what other countries with significant nuclear energy programs (France, Britain, Japan, China and others) are doing and is expected to change.

Fissioning one atom of uranium or plutonium produces two fission product atoms. These are almost always radioactive, with a high initial level of radioactivity that will, for the most part, decay to harmless levels in about 300 years. Since the fission process produces thermal energy, the efficiency with which it is transformed into electricity or hydrogen impacts the total amount of waste produced. For example, it is estimated that an MHR making hydrogen at 50 percent efficiency by thermochemical water-splitting will produce one-half the fission product waste as an LWR making hydrogen

Table 4. Nuclear fuel resources

Technology	Conventional nuclear fuel resources (TW-hr)	Years at current world nuclear electricity generation rate (*i.e., at 355 GWe, 2,540 TWe-hr*)	Years at current world nuclear generation rate, plus current total world hydrogen production rate†
Current LWR, no recycle	827,000	326	189
Gas-cooled reactor, no recycle	1,240,000	489	317
LWR with recycle	930,000	366	212
Advanced gas-cooled reactors with recycle	1,860,000	1,098	713
Fast breeders + advanced gas-cooled reactors	26,000,000	10,000	6,500

Sources: R. Price and J.R. Blaise, "Nuclear Fuel Resources: Enough to Last?" Nuclear Energy Agency Updates, NEA News 2002 no. 20.2, accessed at <http://www.nea.fr/html/pub/newsletter/2002/ 20-2-Nuclear_fuel_resources.pdf>. Also see "Supply of Uranium" and "Supply of Thorium," World Nuclear Association, accessed at <http://www.world–nuclear.org/info/inf75print.htm> and <http://www.world–nuclear.org/info/inf62print.htm>.

† LWR (Light Water Reactor) is assumed to use electrolysis, advanced gas reactor is assumed to use thermochemical water-splitting.

by electrolysis at 25 percent net efficiency. A more detailed analysis show that in the absence of any reprocessing, an MHR producing hydrogen by means of the S-I cycle would produce a factor of 6 less spent fuel waste and actinides than a LWR producing the same quantity of hydrogen by electrolysis. With reprocessing and recycling, the total quantity of waste would be reduced still further.

While LWRs could meet all current U.S. energy needs in terms of nuclear electricity and hydrogen production for about 190 years, and the use of advanced reactors could extend this period or expand this use considerably, longer-term options are still needed.

The ultimate form of nuclear energy is fusion energy. If fusion energy is eventually developed, it can be used to produce hydrogen by either electrolysis or thermochemical processes. It is expected that fusion will be well suited for production of hydrogen by thermochemical water-splitting. In the D–T fusion reaction, 80 percent of the energy produced is carried by 14 MeV neutrons. These neutrons can penetrate a cooled, low-temperature structural boundary and deposit the energy in the hot, non-structural interior. In principle, very high temperatures are then possible and would yield high thermochemical cycle efficiency. Fusion does have some constraints with regard to hydrogen production. Some of the fusion neutrons must be used to breed tritium—one atom of tritium for each fusion event—to continue the fusion process. In addition, tritium must be kept out of the product hydrogen. The tolerance for radioactive tritium in the product hydrogen is very low, and removal of tritium from the hydrogen would be impractical.

Serious design studies were performed using fusion energy for the production of hydrogen in the early 1980s.[37] Helium gas temperatures as high as 1,250 °C were obtained using a portion of the fusion energy. Lower temperatures were required for the tritium production portion of the energy. Coupled to the S-I thermochemical water-splitting cycle, these thermal energy streams allowed production of hydrogen at a net fusion energy-to-hydrogen energy efficiency approaching 50 percent, similar to that obtained with the nuclear-matched S-I cycle described above. By use of ceramic heat exchangers—required by the high temperatures in any case—tritium contamination of the product hydrogen was projected to be kept to very low allowable levels. Fusion energy, therefore, does appear to be promising as a very long-term source of hydrogen.

Hydrocarbon Fuel Synthesis

It seems unlikely that DOD missions that require high-performance fuels can be met by pure hydrogen fuels. However, the emergence of a hydrogen economy will require the development of efficient methods for the production of large quantities of hydrogen. The existence of this hydrogen raises the possibility of a direct hydrogenation of gases such as CO or CO_2 to produce hydrocarbon fuels. If CO_2 could be provided from the atmosphere or the ocean as a feedstock for this process, then it might be possible to produce high-performance hydrocarbon fuels (for example, jet fuel) in a fashion that adds no additional CO_2 to the atmosphere. If this could be accomplished on a sufficiently large scale, it would provide a means for DOD to participate in the hydrogen economy and still meet its high-performance fuel requirements.

Several processes for direct hydrogenation are well established. One of the most successful was developed in Germany in the 1920s by Franz Fischer and Hans Tropsch.[38] In 1938, early German plants produced 591,000 metric tons per year of oil and gasoline using the Fischer-Tropsch process. Recent work by the University of Kentucky has demonstrated the important role played by CO_2 in this process when an iron catalyst is employed.[39]

In order to scope out the required capabilities for DOD, consider the case of an aircraft carrier, which uses about 100,000 gallons of jet fuel a day. The hydrogen contained in this fuel is about 47 tons. Producing this much hydrogen in a 24-hour period using the nuclear S-I process discussed above would require about a 150 MW_{th}, 900 °C reactor. This is modest by nuclear reactor standards. The hydrogen also could be produced by electrolysis, which might be better suited for shipboard production. In the case of electrolysis, the reactor would need to be approximately twice the capacity.

Nuclear production of the required hydrogen looks to be relatively straightforward. However, the carbon required for the fuel synthesis would be about 250 tons per day and would need to be obtained such that the process would be CO_2-neutral when the synthesized fuel is burned. Several options are possible for obtaining this carbon. One would be to obtain it from biomass where the carbon comes from atmospheric CO_2. This approach may involve the burning of environmentally neutral biomass and capturing the CO and CO_2 released. Another approach might be to obtain the carbon from the CO_2 dissolved in the air or the ocean.

Near the ocean's surface, CO_2 is distributed uniformly, with a concentration of about 0.1 g per liter of seawater.[40] Carbon constitutes 27 percent of the mass of CO_2. Therefore, it would take about 8 x 10^9 liters of seawater to supply the carbon if the CO_2 could be removed efficiently. This volume of water corresponds to a cube 200 m on a side. To access this volume of water over a 24-hour period by pumping would require a pump rate of 3,500 ft^3/second. Pumps that operate at these rates have been designed as a part of the Ocean Thermal Energy Conversion (OTEC) program.[41] For a pipe with a 10-meter diameter and 100-meter length, the pumps would consume about 1 MW of power. Further, the CO_2 would have to be extracted from the seawater at sufficient rates. This might be accomplished by applying a modest vacuum to the water as it is pumped. OTEC noted the presence of copious amounts of CO_2 in the vacuum manifolds during relevant seawater pumping experiments they conducted.[42] The CO_2 also could be obtained from seawater by means of chemistry, for example, reacting seawater with calcium oxide to produce calcium carbonate, followed by roasting the calcium carbonate to produce concentrated CO_2 and regenerated calcium oxide.

DOD should consider establishing an R&D program to assess and resolve defense-unique issues connected with hydrogen generation, carbon-based fuel synthesis, and the development of a CO_2-neutral feedstock

An outstanding question with the approach described above is whether the CO_2 released by burning the synthesized fuel would return to the ocean rapidly enough to prevent a CO_2 buildup in the atmosphere. It may be possible in such a case to get the CO_2 from the air instead of from seawater. Seawater is 0.01 percent CO_2 by weight, whereas air is 0.056 percent by weight (0.037 percent by volume) and rising. There is, of course, a trade-off. One would need to handle one-fifth the mass of air but 140 times the volume. Recovery of CO_2 from gases is very highly developed compared with recovery from water, with a caveat that the CO_2 concentrations for many present commercial applications, such as stack scrubbing, are much higher than for CO_2 recovery from the atmosphere.

If an approach like that described above proved viable, a one gigawatt thermal H-2 MHR nuclear plant would be able to supply the aviation fuel for all U.S. aircraft carriers in the context of a hydrogen economy, in an environmentally acceptable fashion, and with total independence from imported oil. Of course, this approach will require a significant R&D program to resolve some key issues. Among these are complete testing of the S-I process, demonstration of the H-2 MHR, efficient extraction of CO_2 from seawater or air, and identification and development of an efficient fuel synthesis process.

Conclusion

While there is no near-term fuel crisis facing DOD, this situation is likely to change over the coming decades as fossil fuel reserves deplete and world demand for them grows. DOD will be confronted with some significant challenges, ranging from protecting U.S. interests as supply and demand come into increasing conflict, to resolving defense-unique fuel requirements as the Nation moves to alternate fuels. The current trend toward a hydrogen economy presents DOD with some special challenges, because a pure hydrogen fuel likely will not satisfy many DOD requirements. The resolution of this problem will take decades. DOD should engage on this issue in the near term in order to influence and leverage the national hydrogen initiative and to have in place an infrastructure to assure that DOD energy needs are met, in particular those related to fuel requirements for low-altitude, high-performance aircraft missions.

The wider DOD requirement for compact, high-volumetric energy density power sources will likely increase DOD dependence on nuclear power and require the development of technology for the CO_2-neutral synthesis of high-performance hydrocarbon fuels. DOD should consider establishing an R&D program to assess and resolve defense-unique issues connected with hydrogen generation, carbon-based fuel synthesis, and the development of a CO_2-neutral feedstock. For the limited and unique needs of DOD, serious consideration should be given to the use of nuclear power to drive the electrolytic or thermochemical generation of hydrogen. The extraction of CO_2 from the atmosphere or from the upper ocean should be examined as a possible CO_2-neutral means of supplying the necessary feedstock of carbon for synthesis of fuel for high-performance jet aircraft. Studies of various fuel synthesis methods capable of meeting the unique DOD needs should be undertaken. The elementary analysis presented here suggests that a system based upon pressurized water reactors might be compatible with aircraft carrier-based synthesis of jet fuel or that a single shore-based system using high-temperature nuclear reactors might be capable of producing the jet fuel for all U.S. carriers. If this turns out to be correct, then the extension to meet all DOD-unique, high-performance fuel requirements would be in sight and would be compatible with and contribute to the larger hydrogen economy initiative.

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