HYDROGEN PRODUCTION AS A MAJOR NUCLEAR ENERGY APPLICATION

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File Name: GenIV.hydrogen.future
Manuscript Date: June 16, 2001

Discussion Paper Prepared for
Non-Classical Technical Working Group
Generation IV Roadmap
U.S. Department of Energy

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*Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

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ABSTRACT

The industrial demand for hydrogen (H_2) is growing very rapidly. Most of the growth in H_2 demand is used to convert heavy, high-sulfur crude oil into transportation (gasoline, diesel, and jet) fuels. Sources of high-grade low-sulfur crude oil are being exhausted. Thus, to produce transport fuels, it is necessary to refine heavy crude oils that require more H_2 for conversion. The demand for cleaner fuels is also increasing the demand for H_2. The H_2 is made from refinery still bottoms (components of crude oil) and natural gas. If an economic external source of H_2 were available, (1) significantly more transportation fuels could be produced per barrel of crude oil, which, in turn, would reduce dependence on foreign oil; (2) the increased coupling of transport fuel prices to rising natural gas prices would be stopped; (3) the chemical and refinery industries would become more competitive; and (4) release of greenhouse gases would be reduced.

Assuming 50% efficiency in conversion of thermal energy to H_2, the energy required to manufacture H_2 for refineries and chemical plants by 2010 will exceed the current energy production of all nuclear reactors in the United States. This industrial demand creates a natural pathway to a future H_2 economy by providing initial large markets for H_2. An H_2 economy may use H_2 as a transport fuel or for dispersed fuel-cell and heat-generation applications. If a H_2 economy developed, the energy needed for H_2 production could exceed that to produce electricity.

Hydrogen can be produced from nuclear power by thermochemical water splitting. (Heat plus water yields H_2 and oxygen.) Thermochemical processes have potentially higher efficiencies and lower costs than the electrolysis of water with electricity. A typical existing refinery would require a 600-MW(t) nuclear power plant to produce sufficient H_2 (7.5×10^7 ft^3/d). High temperatures (750–1000EC) are required for economically viable methods of H_2 production. There are several potential reactor concepts that could meet this application.

I. INTRODUCTION

The industrial demand for H_2 demand is growing rapidly. The demand for H_2—and the characteristics of this demand—are described herein. The leading methods to produce H_2 by thermochemical methods are also outlined, and the requirements imposed on a nuclear reactor by the production methods are defined.

II. CURRENT AND PROJECTED USES

Refining

The world consumes large quantities of H_2 in the production of liquid fuels (Chang 2000). The H_2 production capacity of world refineries is 1.15×10^{10} std ft^3/d, with a U.S. refinery hydrogen production capacity of 3.56×10^9 std ft^3/d. If that H_2 was burned as it was produced, the rate of energy release for the world's refineries would be 46 GW(t). Hydrogen is added to heavy crude oils to produce gasoline, diesel, jet, and other fuels.

A combination of factors (1) is rapidly increasing refinery H_2 demand, (2) may increase that demand fourfold within a decade in the United States, and (3) is causing a major multi-decade transition within the refinery industry (Fig. 1). The factors include the following. The world is rapidly exhausting supplies of high-quality crude oils and is increasingly using lower-quality crude oils. There is a demand for higher performance, cleaner fuels. Furthermore, the demand for heating oils is decreasing while that for transport fuels is increasing.

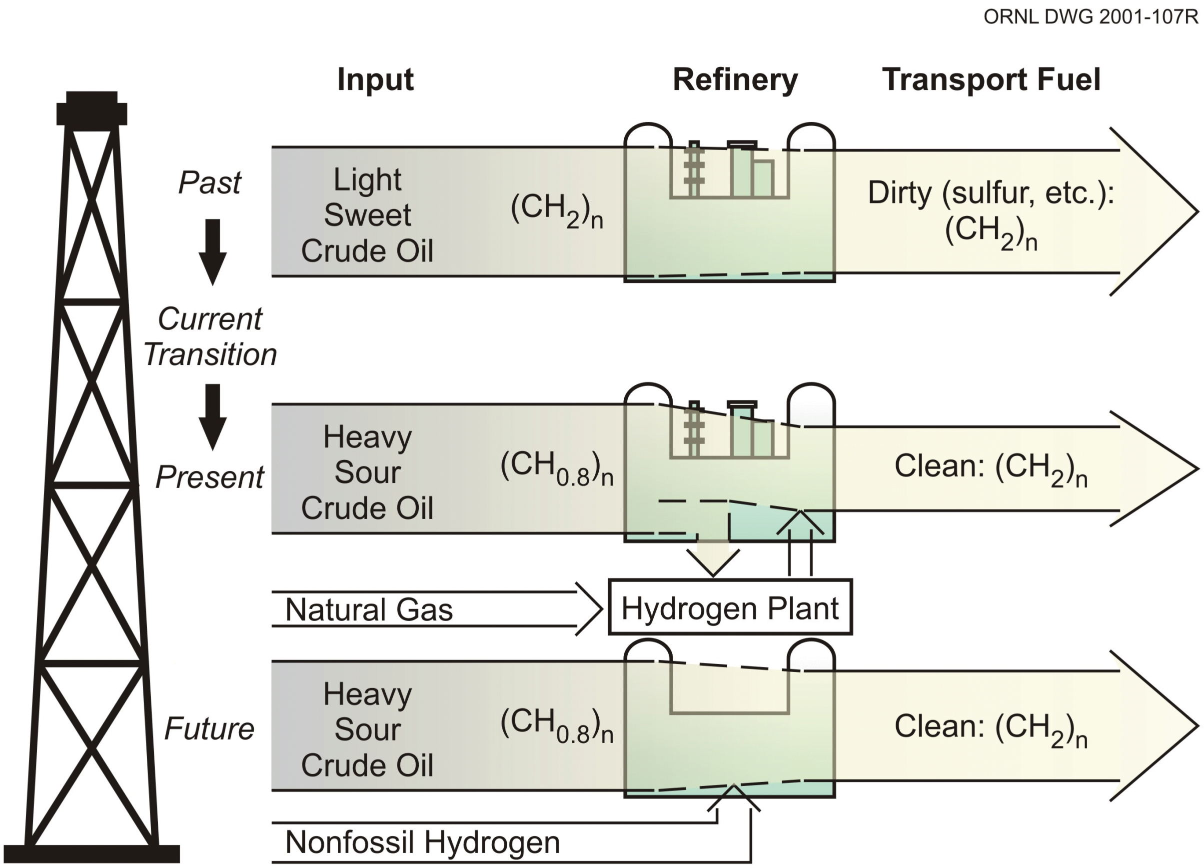

Fig. 1. The changing characteristics of available crude oil supplies are increasing the refinery demand for H_2.

An example of these changes can be seen by comparing a refinery that processes a sweet (low-sulfur), light, West Texas crude oil with one that processes a sour (high-sulfur), heavy, Venezuelan crude oil. For the high-quality crude oils, the energy value of the products (jet fuel, gasoline, etc.) exiting the refinery is -95% of that of the crude oil entering the refinery. Some of these crude oils would operate, with some difficulty, in a car engine without refining. In contrast, for low-grade, heavy, more-plentiful, and cheaper crude oils, the energy value of the products exiting the refinery is -80% of that of the crude oil entering the refinery. For coal liquefaction, the energy efficiency is -60%. Much of the energy consumed within the refinery is used for converting lower-value hydrocarbon streams and natural gas into H_2. This H_2 is used for several purposes.

- *Production of light oil*. Heavy crude oils are removed from the ground at high temperatures and become highly viscous as they cool. In fact, such oils are so viscous that they do not flow unless heated or dissolved in a lighter oil. The very heavy oils have an H_2-to-carbon ratio of -0.8. Cracking and other operations add H_2 to increase this ratio to between 1.5 and 2, thereby yielding a light refinery oil product that can be separated into various transport fuels. The lighter the fuel (such as gasoline), the more H_2 that is required for this conversion. The market is growing for light transport fuels vs heavy fuels (bunker C, etc.) and heating oils.

- *Reduction of toxicity*. Oils contain a variety of carcinogenic compounds such as benzene (C_6H_6). These substances are converted to non-carcinogenic fuels through the addition of more H_2.

- *Sulfur removal*. A sour crude oil may be 6% sulfur by weight. Heavy oils tend to have much higher sulfur content. The sulfur is removed by using H_2 to convert it to hydrogen sulfide (H_2S), which is then oxidized to sulfur and sold as a by-product. Sulfur is removed to (1) avoid catalyst poisoning within the refinery, that interferes with refinery operations; (2) minimize corrosion in fuel transport and engines; (3) produce clean fuels; and (4) improve engine efficiency.

The H_2 is currently produced from lower-value refinery streams and from natural gas. If an alternative source of H_2 were available, the quantity of transport fuels produced per barrel of heavy crude oil could be significantly increased because these lower-value refinery streams could then be converted to transport fuels.

Chemical H_2 Use

Hydrogen is the primary feed input to manufacture ammonia (the principal fertilizer used worldwide). Fertilizer production facilities are a major consumer of H_2 today; however, the market is not expected to grow significantly. Most of this H_2 is manufactured from natural gas. Hydrogen is also used in the production of many other chemicals, such as methanol.

Hydrogen Economy

There have been many proposals for an H_2 economy (Ogden 1999). Hydrogen would be used as a transport fuel or in a dispersed mode to generate electricity and heat using fuel cells and other technologies. Major incentives for such an approach are to (1) minimize environmental impact at the point of use, (2) develop a dispersed energy system, and (3) create a storable energy source. These scenarios imply energy use to make H_2 that is similar to that now applied in the production of electricity.

In one context, the H_2 economy already exists here. Massive quantities of H_2 are used at refineries, and in many H_2 futures, most of the demand would remain at the refineries. For example, major research programs are underway to develop fuel cells as replacements for gasoline engines in automobiles. Hydrogen is the preferred fuel. Many of these proposed fuel-cell systems include an onboard system to convert a liquid fuel to H_2. This type of system takes advantage of the ease of transport and storage of liquid fuels while using more-efficient fuel cells. In such a future, a demand would exist for very-clean liquid fuels with high H_2 contents to minimize onboard processing of the liquid fuel to H_2. Such options imply very large H_2 demands by the refineries to produce such fuels.

It is difficult, expensive, and time-consuming to create a large energy infrastructure of any type without a smaller market to develop the technical, economic, financial, and regulatory structure. In the context of an H_2 economy, the growing industrial demand for H_2 provides a bridge to such an economy.

III. PROJECTED H_2 DEMAND

In 1999, Ogden estimated that the energy value of the H_2 consumed in the United States was about 1.5×10^{18} J/year [-50 GW(t)]. Hydrogen is produced primarily from lower-value refinery streams and natural gas. Although some H_2 is produced from coal, the conversion efficiency is lower and the plant costs are significantly higher. More than 1% of U.S. primary energy use (~5% of the natural gas) is directed to H_2 production. Almost all of this is used for chemical and refinery purposes. Hydrogen production is expected to grow by a factor of four to 6×10^{18} J/year by the year 2010, primarily because of the higher H_2 demand as refineries are expected to (1) process lower-grade crude oils and (2) produce less polluting (clean-burn) liquid fuels.

If all the H_2 in the United States in 2010 were produced using nuclear power and the thermal-to-H_2 conversion efficiency were 50%, the thermal energy required would be about the same as the current energy output of all the nuclear reactors that exist in the United States today. A 600-MW(t) reactor with 50% efficiency would produce -75 million std ft^3/d—enough at present for a moderately large refinery processing an average crude oil.

Hydrogen has also been proposed as a future transport and distributed-power fuel as part of an H_2 economy. Such applications would increase the H_2 demand by one to two orders of magnitude. In such scenarios, the demand for H_2 would exceed the demand for electricity. The estimates here assume no H_2 economy (as generally considered). The growth in H_2 demand detailed herein applies to industrial customers only.

IV. HYDROGEN ECONOMICS

In the United States, pipelines are located along the Gulf Coast for transport of H_2 between refineries, chemical plants, and merchant-H_2 generation plants. Large facilities generally produce the H_2 they consume internally, while smaller facilities may purchase H_2. The pipelines also provide a method to import purchased H_2 when internal production facilities are down for maintenance or to export H_2 for sale when internal consumption is low. Consequently, with expansion the existing systems could accept large merchant-H_2 generating plants. Production economics, not the H_2 demand of a single chemical plant or refinery, would thus determine plant size.

Because most H_2 is made from natural gas, their costs are closely related. Large increases in natural gas prices have occurred in the last year (Fig. 2). If these prices remain high for an extended period of time, the chemical industries that consume large quantities of H_2 will move offshore to locations with lower-cost natural gas. A significant fraction of the refinery industry may also move offshore, particularly that part of the industry that uses imported—rather than domestic—crude oil. The competition is primarily from the Caribbean, where lower-cost natural gas is available. The above H_2 projections assume that U.S. natural gas prices will decrease. If this is not the case, the demand for H_2 to produce chemicals and fuels for the United States will grow; however, the facilities that use the H_2 will be built offshore.

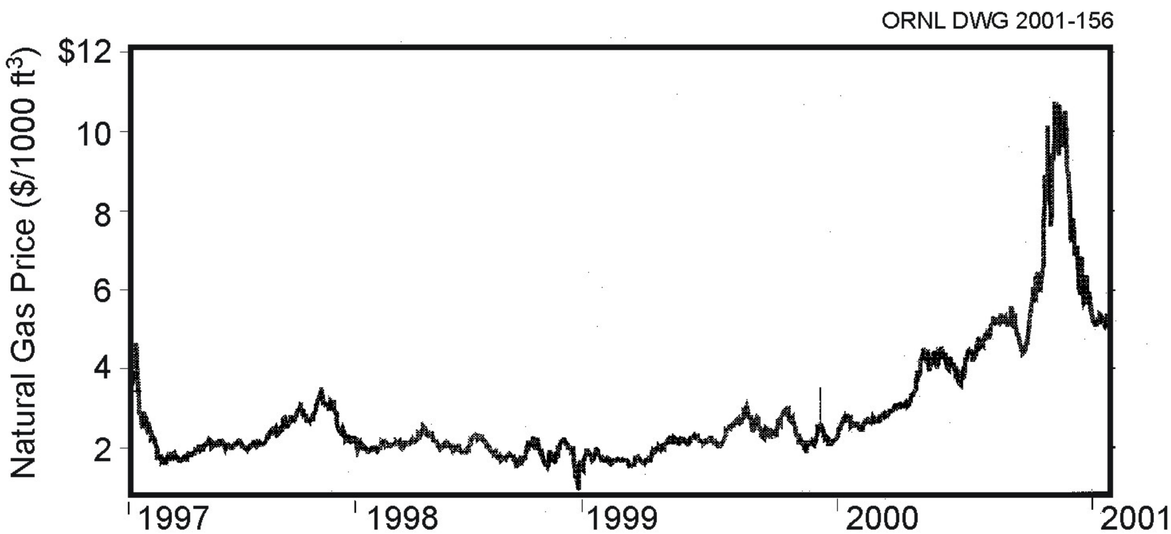

Fig 2. The increased natural gas prices may result in movement offshore of those parts of the chemical and refinery industry that are heavy consumers of hydrogen.

If the technology can be developed, H_2 from nuclear facilities would be expected to be competitive with that from natural gas at the same time or before electricity from nuclear facilities is comparable in cost with that from natural gas. Refineries and chemical plants have a nearly constant demand for H_2 that matches the base-load capabilities of nuclear facilities. The constant base-load demand for H_2 favors technologies with low fuel costs—such as nuclear energy.

In a financial context, the major oil companies are much larger than utilities. Several oil companies have annual sales in excess of a hundred billion dollars per year. For industrial applications, the total H_2 production cost (capital and operating) is the primary consideration. Large modern refineries cost many billions of dollars; thus, the capital cost of a reactor to produce H_2 is not a major constraint.

V. NUCLEAR PRODUCTION METHODS FOR HYDROGEN

Many direct thermochemical methods (Brown et al. 2000) are possible for producing H_2 with the input of heat and water. For low production costs, however, high temperatures are required to ensure rapid chemical kinetics (i.e., small plant size with low capital costs) and high conversion efficiencies (IAEA 1999; Miyamoto et al. 1998). The nuclear power application for H_2 production would also demand a high-temperature, low-cost source of heat.

Many types of thermochemical processes for H_2 production exist. The sulfuric acid processes (hydrogen sulfide, iodine–sulfur (IS), and sulfuric acid–methanol) are the leading candidates. In each of these processes, the high-temperature, low-pressure endothermic (heat-absorbing) reaction is the thermal decomposition of sulfuric acid:

$$H_2SO_4 \rightarrow H_2O + SO_2 + \tfrac{1}{2}\, O_2 .$$

Typically temperatures from 800 to 1000°C are needed for efficient hydrogen production. The high-temperature decomposition reaction is favored by low pressures. After oxygen separation, additional chemical reactions are required to produce H_2. A leading candidate for thermochemical H_2 generation is the IS process, which has two additional chemical reactions:

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \text{ (low temperature)}$$

and

$$2HI \rightarrow H_2 + I_2 \text{ (intermediate temperature)}$$

The flowsheet for this process is shown in Fig. 3. The Japan Atomic Energy Research Institute (Miyamoto et al. 1998) is currently investigating this and other H_2 production cycles with the objective of ultimately coupling one or more H_2 production cycles to their High-Temperature Engineering Test Reactor. Investigations (Brown et al. 2000) are also under way in the United States. Significant development work on H_2 thermochemical cycles is required, with the technology being applicable to both nuclear heat sources and those involving solar power towers.

ORNL DWG 2001-102

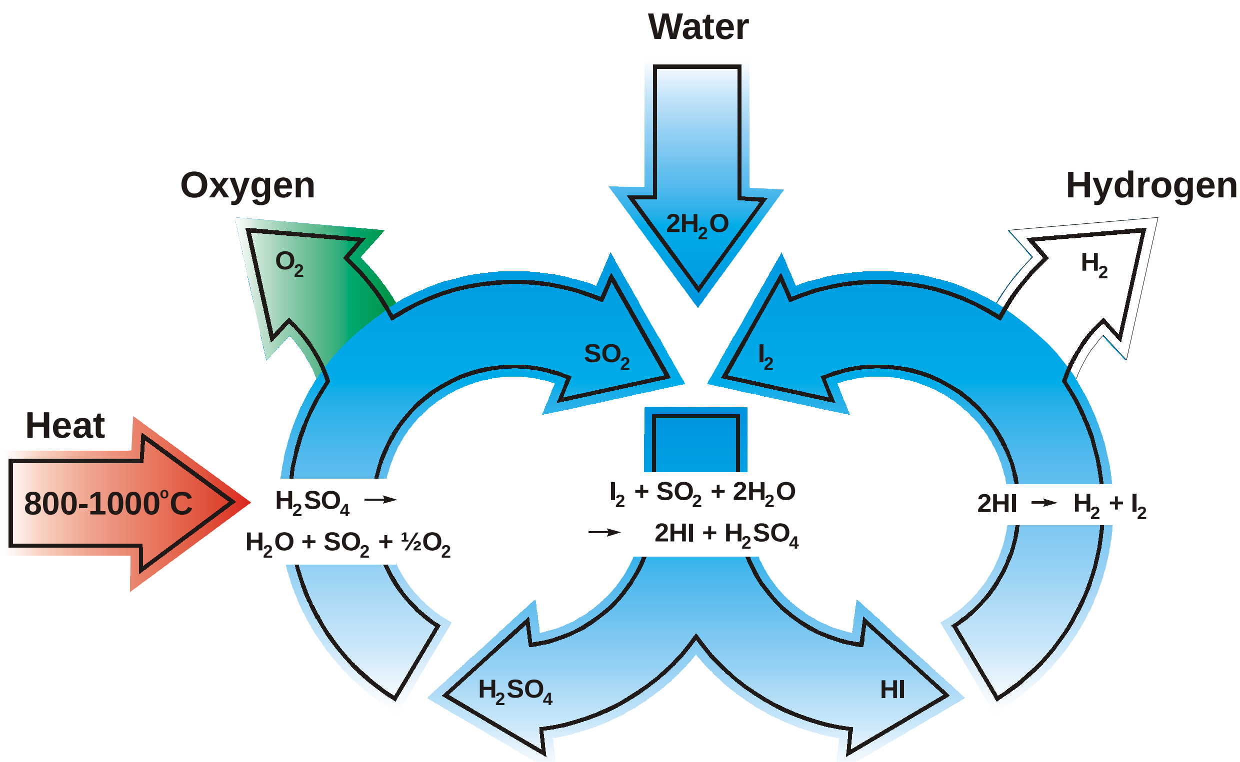

Fig. 3. IS process for thermochemical production of hydrogen.

The economics of H_2 production strongly depend on the efficiency of the method used. Production efficiency can be defined as the energy content of the resulting H_2 divided by the energy expended to produce the H_2. Hydrogen production by electrolysis is relatively efficient (-80%). However, when this factor is combined with the electrical conversion efficiency—which ranges from -34% (in current light-water reactors) to 50% (for advanced systems)—the overall efficiency would be -25 to 40%. For thermochemical approaches such as the IS process described above, an overall efficiency of >50% has been projected. Combined-cycle (H_2 and electricity) plants (Brown et al. 2000) may have efficiencies of -60%. All of the efficient, potentially low-capital cost thermochemical processes require high temperatures.

VI. REACTOR REQUIREMENTS

Thermochemical production of H_2 imposes a set of technical requirements on the reactor:

- *Temperature*. Temperatures between 750 and 1000EC are required. Higher temperatures are preferred.

- *Heat transfer*. Heat must be transferred from the nuclear system to the chemical plant at high temperatures. Because the nuclear plant and the chemical plant have significant inventories of hazardous materials, each must be protected from the other. This requirement imposes still-to-be-defined constraints on the reactor.

Three reactor concepts have been identified that may be compatible with coupling to a thermochemical H_2 production facility. The primary requirement is to provide heat at high temperatures.

- *High-temperature gas-cooled reactor (HTGR)*. Many variants to the HTGR exist, including a pebble-bed reactor and a hexagonal fuel-block reactor.

- *Advanced high-temperature reactor (AHTR)*. This is a modular, molten-salt-cooled reactor that uses a coated-particle graphite-matrix fuel. The AHTR is similar to an HTGR except the high-pressure helium coolant is replaced with a low-pressure molten salt. Allowable temperatures may be somewhat higher than for the HTGR, and the coolant operates at atmospheric pressure.

- *Lead-cooled fast reactor*. This is a lead-cooled, nitride-fuel reactor. The operating temperatures are somewhat lower than those for the HTGR. Lead cooling is required because sodium boils at 883EC—considerably below the required operating temperatures.

VII. CONCLUSIONS

Hydrogen represents is a second potential market for nuclear energy. Ultimately, the energy consumption for H_2 production may approach or exceed that for electricity. If the technical and economic issues can be resolved, the expected growth in H_2 industrial demand will create a large near-term application for nuclear power. The refinery market for H_2 provides a pathway for a future H_2 economy. This is a unique market with specific requirements. High temperatures (750–1000EC) are required, and significant incentives exist to reach the higher temperatures in this range. Because of its potential, the use of nuclear power for production of H_2 should receive serious attention.

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