WHY HYDROGEN PRODUCTION FROM NUCLEAR POWER?
(Is Nuclear Energy Compatible with Hydrogen Production?)

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ABSTRACT

The demand for hydrogen (H_2) is large and growing rapidly. Hydrogen is needed to produce fertilizer and for the conversion of crude oil into clean fuels. It requires more H_2 per barrel of crude oil (1) to produce liquid fuels from lower-quality crude oils and (2) to produce clean fuels. The decreasing quality of crude oils and the increasing demand for clean fuels is driving the rapid increase in H_2 demand. Hydrogen is produced from natural gas at refineries and merchant plants that are interconnected over long distances by pipelines. Research is underway to use H_2 as a transport fuel and to create a H_2 economy. In such a future, the quantity of energy to produce H_2 may be similar to that needed to produce electricity.

Nuclear power has been proposed for production of H_2 using (1) electrolysis, (2) hot electrolysis, (3) nuclear heat–assisted steam reforming of natural gas, and (4) thermochemical cycles where the overall net reaction is as follows: $2\ H_2O + \text{heat} \rightarrow 2\ H_2 + O_2$. The energy consumed today to produce H_2 is equivalent to 100+ large nuclear reactors; thus, the scale of nuclear power plants matches that of H_2 production. Using nuclear energy for H_2 production versus fossil fuels prevents generation of greenhouse gases, reduces dependence on foreign sources of energy, and reduces many of the problems defined by economists as "problems of the common."

The question remains, "Do the intrinsic characteristics of nuclear energy make it a good match for the production of H_2 ?" Nuclear energy production is a capital-intensive, low-operating-cost technology where siting considerations include seismic activity, availability of cooling water, and low population density. These characteristics suggest that the ideal product from a nuclear plant should be (1) easy to transport long distances to markets to minimize siting difficulties, (2) an energy-intensive product in very high demand to match the large energy output of a nuclear plant, and (3) storable to allow efficient full utilization of the capital intensive plants. This is a description of pipeline H_2 with storage in the pipeline or in separate facilities. These intrinsic characteristics indicate the potential for a good match between nuclear power and H_2 production. The economic viability depends upon successful development of appropriate competitive technologies.

Hydrogen growth projections, compatibility (economic, technical, and institutional) of nuclear energy for H_2 production, methods of H_2 production from nuclear power, economic constraints, and related issues are described.

1. INTRODUCTION

The world demand for hydrogen (H_2) is growing rapidly—primarily because of a rapid increase in refinery demand to convert low-grade crude oil into clean gasoline. If the world develops a H_2 economy, H_2 may supply a third or more of the total world energy demand. Nuclear energy is used to supply electricity in many countries. This raises the question whether the characteristics of nuclear energy make it suitable for the production of H_2. This question is addressed by examining future H_2 demands, the incentives to use nuclear power for H_2 production, and the compatibility of nuclear power for H_2 production.

2. HYDROGEN DEMAND

The world consumes about 50 million tons of H_2 per year (Stoll December 2000). If this H_2 were burned, energy would be released at a rate of 200 GW. Most of the H_2 is made from natural gas. In 1999, Ogden estimated that the energy value of all the H_2 consumed in the United States was about 1.5×10^{18} J/year (50 GW). Almost all of this H_2 is used for chemical and refinery purposes. In the United States, H_2 production has been projected to grow by as much as a factor of four to 6×10^{18} J/year (200 GW) by the year 2010, primarily because of the increased demand for H_2 by refineries to convert lower-grade crude oils into clean gasoline.

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 exceed the current energy output of all the nuclear reactors that exist in the United States today. Over the longer term, if the United States moves toward the popular concept of a "hydrogen economy," the demand for H_2 would increase by an order of magnitude beyond these H_2 consumption rates, with the energy requirements for H_2 production exceeding those for electric production.

2.1 Current Applications and Uses

Hydrogen has three principal uses in industrial processes: fertilizer production, manufacture of chemicals, and refining of crude oil stocks. Most of the H_2 used in these processes is manufactured from natural gas. The most rapidly growing component of H_2 demand relates to crude oil refining. The H_2 production capacity of the world's refineries is 1.15×10^{10} std ft^3/d (46 GW), with a U.S. refinery H_2 production capacity of 3.56×10^9 std ft^3/d. Hydrogen is used primarily to convert heavy crude oils into gasoline, diesel, and jet fuels. A combination of factors is rapidly increasing the demands for H_2 (Fig. 1). The world is exhausting its supplies of high-quality crude oils and, as a result, is using more lower-quality heavy crude oils. There is also a demand for higher performance, clean fuels. While, the demand for heating oils is decreasing, the need for gasoline and jet fuels is increasing.

The consequences (Fig. 1) of these changes can be seen by comparing a refinery that processes high-quality, 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% 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% 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.* The very heavy oils have an H_2-to-carbon ratio as low as ~0.8. Refinery operations add H_2 to increase this ratio to between 1.5 and 2 (similar to gasoline), 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. Light, high-quality crude oils have H_2-to-carbon ratios between 1.5 and 2. The transition from less-abundant light crude oils to more-abundant heavy crude oils implies a massive growth in H_2 demand.

- *Reduction of toxicity.* Oils contain a variety of carcinogenic compounds such as benzene (C_6H_6). Recent laws require that these substances be removed or destroyed. This can be accomplished by adding H_2 to convert these compounds to noncarcinogenic clean fuels.

- *Production of clean fuels*. A sour crude oil may be 6% sulfur by weight. Sulfur and other impurities are removed using H_2 to produce clean-burning fuels.

For the refineries, there are only two ways to change the H_2-to-carbon ratio of crude oil to make clean gasoline: remove carbon or add H_2. Carbon is removed by a process called coking—the conversion of lower-value refinery streams into coke and H_2. The lower-value refinery streams are also converted to H_2 by steam reforming, in which the carbon is released to the atmosphere as carbon dioxide. Alternatively, H_2 can be added to the crude oil from an outside source. This H_2 is usually produced from natural gas.

2.2 Extended Hydrogen Applications

The concerns about the greenhouse effect have resulted in increased interest in gasoline that minimizes carbon dioxide emissions per unit of energy delivered, that is, *carbon-saver* fuels. This may be accomplished by further boosting the H_2-to-carbon ratio in the fuel to 2 or more. It is estimated that production of carbon saver fuels would increase the liquid-fuel yield per barrel of oil by an additional 15%—assuming nonfossil sources of H_2 were used. This is equivalent to a 15% reduction in crude oil demand. Although the concept of carbon-saver fuels was developed to address greenhouse impacts, such fuels would be quickly deployed independent of any concerns about climatic change if low-cost H_2 were available. The energy needed to produce the H_2 for carbon-saver fuels is similar in quantity to the existing capacity of all nuclear power plants in the United States.

2.3 Hydrogen Futures

2.3.1 Transportation

Major research programs are under way to develop fuel cells as replacements for gasoline engines in automobiles. Hydrogen is the preferred fuel. The President of the United States has recently announced a program (DOE February 2002) to encourage the development of a H_2 economy, and specifically, fuel cells for transportation. This program was initiated because of the potential of fuel cells to (1) reduce fuel consumption because they offer higher efficiency than the internal combustion engine, (2) lower carbon dioxide emissions, (3) decrease dependence on foreign oil, and (4) reduce air pollution. Because of their potential, fuel cells are the subject of a large number of sessions and papers at this conference.

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 a high H_2 content to minimize onboard processing of the liquid fuel to H_2. Such fuels would be similar or perhaps identical to carbon-saver fuel. This would further accelerate the refinery demand for H_2 and provide a bridge to any future H_2 economy.

In the longer term, many people predict the direct use of H_2 for transportation. For commercial aircraft applications, liquid H_2 will be preferred because of its low weight and high energy density. This requires H_2 liquification (probably at the airport) and appropriate cryogenic handling facilities; however, this is not a major constraint given the limited number of commercial airports, the quantities required per aircraft, and the quantities required per airport.

For use in automobiles and trucks, the form of H_2 that may ultimately be adopted is less clearly defined. The H_2 for use in fuel cells can be stored in various physical or chemical forms. The requirement is to store significant quantities of H_2 in a system with strict cost, weight, volume, and safety requirements. The leading candidate, as defined by the number of automobile manufacturers working on the technology, is storage of H_2 in vehicles as high-pressure H_2 in fiber-wound high-pressure cylinders. The large reductions in the cost of carbon fiber and vessel manufacturing suggest that light-weight, low-cost storage may be possible. Several other H_2 vehicle-storage technologies are also receiving consideration.

- *Cryogenic H_2.* Semiautomated cryogenic H_2 fueling systems have been built for cars. However, there are complications. Refueling is complex, and hydrogen will "boil off" if the car remains in storage for long periods of time. This technology is the most advanced in terms of being implementable.

- *Borohydride*. With a catalyst, sodium borohydride in an aqueous solution reacts with water to produce H_2 ($NaBH_4 + 2H_2O \rightarrow 4H_2 + NaBO_2$). The fuel cycle (Sharke February 2002) would involve (1) delivery to the vehicle $NaBH_4$ dissolved in water, (2) catalytic conversion of the $NaBH_4$ to produce H_2 on-board the vehicle, (3) transport of the spent $NaBO_2$ solution to a chemical plant, and (4) conversion of the $NaBO_2$ with H_2 back to $NaBH_4$ in water. Sodium borohydride is used to bleach paper, while the borax reaction

product is found in detergents. This option has potentially significant safety advantages; however, a substantial amount of work is required to develop efficient manufacturing methods for the conversion of the $NaBO_2$ back to $NaBH_4$.

- *Ammonia.* Ammonia (Faleschini November 2000; Choudhary 2001) is a potential candidate, with an onboard conversion system to convert the ammonia to H_2. Liquid ammonia has a high H_2 density and there is extensive experience in handling ammonia. Ammonia is produced from H_2 (with the H_2 currently from natural gas).

- *Sorption and Trapping*. A wide variety of materials are being investigated to reversibly store the H_2 on appropriate surfaces or in molecular structures. Examples include hydrides, bucky balls, nanotubes, and a variety of other materials. The challenges for these options are to minimize the weight, develop methods for fast refueling, and manage the heat loads (for most materials, H_2 absorption generates heat and desorption requires heat).

Estimates have been made of the storage efficiencies of different systems. Storage efficiency is the fraction of the total storage system weight that is H_2. This parameter includes the weight of the tank. A recent analysis provided the following comparison: pressure cylinder: 7.5 to 8.5%; ammonia: 14.1%; hydrides: 1.2%; bucky balls: 5%, and nanotubes: 5%. Technological advances can improve storage efficiencies for some technologies (e.g., gas cylinders with higher pressures and lower tank weights).

2.3.2 The Vision of a Hydrogen Economy

The concept of a H_2 economy is broader than any single application such as a transportation fuel. It is a long-term vision of how primary energy sources are used to provide services in a post-fossil-fuel world. The vision encompasses two energy carriers: H_2 and electricity. (The term "hydricity" is sometimes used to describe the concept.) The concept is based on the perspective that the strong synergisms between these two energy carriers will ultimately provide the incentives to implement this approach:

- *Services.* All the traditional services that man requires (heat, light, transportation, etc.) can be provided using these two energy carriers.
- *Convertibility.* Electricity and H_2 are interconvertible. Fuel cells convert H_2 to electricity, while electrolysis converts electricity to H_2. This interconvertibility creates an energy carrier system with the advantages of both. For example, the ability to store H_2 may create a system where all electric power plants are base load with the variable time-of-day load met by conversion of electricity to H_2 when electric demand is low and conversion of H_2 to electricity when the demand is high.
- *Environmental protection*. Hydrogen and electricity are clean energy sources at the point of use. This minimizes potential environmental impacts. The impacts are limited to primary production of electricity and H_2.

2.4 Implications for Nuclear Power

The existing demand for H_2 is very large and growing rapidly. This phenomenon is a consequence of two fundamental factors: the relative abundance of heavier crude oils and the demand for clean gasoline. If a H_2 economy becomes reality, the energy requirements for H_2 production may be equal or exceed those of electricity production. The existing and future markets are of sufficient size that the development of methods to produce H_2 using nuclear power is fully justified—provided that appropriate cost-effective technologies can be identified.

3. INCENTIVES FOR GENERATION OF HYDROGEN USING NUCLEAR ENERGY

Hydrogen is currently produced by the steam reforming of natural gas (most commonly used), hydrocarbon liquids, and coal, as well as by electrolysis. There are potential long-term incentives for use of nuclear power for H_2 generation. In this context, the incentives for using nuclear energy and renewables are similar.

3.1 National Security

World oil and natural gas prices are dependent upon the actions of a small number of countries in the Middle East, which contain the majority of the world's oil reserves. Multiple disruptions in oil supply and large spikes in prices have occurred. Many economists believe that the slow economic growth and inflation of the 1970s were a consequence of the shortages and spikes in oil prices in the early 1970s. This dependence is a threat to the economy and thus a threat to national security.

The combination of oil dependence, politics, and other factors has resulted in several crises and wars. Multiple Iranian revolutions, the Suez Crisis, the oil embargoes, the Iraq-Iran War, the Gulf War, and the recent terrorist events are all linked to western dependence on oil. Oil is driving many national security policies and much of the world's expenditures on defense. Alternatives to oil would reduce the risks of war and terrorism.

3.2 Greenhouse Impacts

Various national and international studies indicate that the long-term increase in the carbon dioxide content of the atmosphere is causing changes in the global climate, the earth's geochemistry, and the biosphere. The increasing levels of carbon dioxide result from the burning of fossil fuels. The only methods to control atmospheric carbon dioxide emissions are to reduce consumption or sequestration of carbon dioxide in geological structures or the deep ocean. While some commercial carbon sequestration operations are under way in countries that have carbon taxes, the costs and viability are strongly dependent upon local factors (Kane and Klein June 2001). The use of nonfossil energy sources such as nuclear power avoids releases of carbon dioxide and avoids the uncertainties associated with the long-term sequestration of carbon dioxide.

3.3 Economics of the Commons

The use of nuclear power with H_2 production has the potential to internalize many energy costs. The most efficient use of resources occurs when the user pays the full cost of the resource. If the user does not pay the full cost, resources are misallocated and injury to third parties often occurs. In many cases, such misallocated results from what economists call the "problem of the commons". The term comes from the ancient practice of having common grazing pastures owned by the community. In such a situation, every owner of a cow has an incentive to graze his animals on the common. However, overgrazing reduces the total amount of grass that can be produced and may destroy the pasture. The community as a whole is poorer because it is not in the interest of any single individual to limit his use of the common. Commons include the atmosphere, the ocean, and much of the world.

This concept represents a major problem in energy consumption. No simple method exists for the user to be charged the full costs of (1) the added national security risk of dependency on foreign oil, (2) any health effects on individuals from air pollution from multiple sources, (3) the damage to buildings from air pollution, (4) the long-term impacts of greenhouse effects, and (5) various other consequences. No simple direct connection exists between the user and the person damaged by the use of the energy, because the damages are a result of the actions of many people. In many cases, the natural environment has some capability to absorb adverse impacts but not large impacts. This situation is in contrast to economic problems such as those arising from automobile accidents. In such cases, the insurance companies and courts have well-defined methods for the injured party to collect the economic costs.

Different nations use different strategies to address the problem of the commons. These methods include air pollution regulations, mileage standards for cars and trucks, and taxes on carbon dioxide (Kane and Klein June 2001). Each approach presents major difficulties, with the cost of commons being a significant fraction of the total cost of energy. A H_2 economy in which H_2 is produced from nuclear energy internalizes most of these costs. User-induced impacts on third parties are restricted. Furthermore, the number of facilities and owners generating the H_2 is limited and thus these entities can be made accountable for any externalities.

4. COMPATIBILITY OF NUCLEAR ENERGY WITH HYDROGEN GENERATION

Each energy technology has a set of characteristics that determine what applications are potentially viable in terms of both technical feasibility and economics. For example, the characteristics of internal combustion engines (small size, high energy output per unit mass, etc.) make them suitable for automobiles. However, the high cost of the fuel makes such engines unsuitable for central production of electricity. The viability of nuclear energy for H_2 production depends upon the match between the intrinsic characteristics of H_2 systems and nuclear energy systems.

4.1 Scale of Operations

Experience has demonstrated that nuclear energy production in small units on a small scale is not economically viable. If nuclear energy is to be used for economic H_2 production, the H_2 demand must match the scale of hydrogen production from a nuclear reactor.

A 600-MW(th) 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 and equal to ~2% of current H_2 production capacity of U.S. refineries. However, no refinery would want to depend upon a single H_2 production unit to meet its need for H_2. In the United States, pipelines are located along the Gulf Coast for the transport of H_2 between refineries, chemical plants, and merchant-H_2 generation plants. The pipelines provide a means for large industrial plants 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. Smaller industrial customers buy their H_2 from the pipeline. Merchant H_2 plants are located on these pipelines.

The newest "world-class" H_2 plants that are under construction have capacities of 200 million std ft^3/d—equivalent to a 1,600 MW(th) reactor. Hydrogen plant sizes, in terms of energy flows, are rapidly approaching the size of large nuclear power plants. Large plants are on H_2 pipeline systems. Thus, the scale of H_2 demand and the scale of nuclear power plants match.

One set of large H_2 users, ammonia plants, are not usually on the pipelines. Today, ammonia is made from air and natural gas in a process where the H_2 that is produced is a mixture of nitrogen and H_2—incompatible with other pipeline customers. Before natural gas was used, ammonia plants produced pure H_2, mixed it with nitrogen, and synthesized ammonia. If economic large-scale H_2 production from non-fossil fuels was developed, the ammonia industry would use updated versions of the older processes and become a pipeline customer.

4.2 Demand Versus Time

Nuclear power plants are characterized by high capital costs and low operating costs. The economics are strongly dependent upon base-load operations with continuous output. In the production of electricity, nuclear power plants are used for base-load operations. The variable demand for electricity is met by natural-gas-fired turbines and similar technologies that have lower capital costs but high operating costs. In many industrialized countries, nuclear power is economic for base-load electricity production but uneconomic for peak-load electricity production.

The characteristics of the H_2 system, unlike those of electricity, decouple production from consumption. Hydrogen transport is by pipeline, where packing (increasing the pressure) creates significant storage capacity. Hydrogen storage in large volumes, using the techniques developed by the natural-gas pipeline industry, is expected to be relatively low cost. In a large H_2 economy, the production and consumption are coupled with a time constant of weeks, versus milliseconds for the electric grid. The system characteristics indicate that the system match between nuclear power and H_2 production is better than that between nuclear power and electricity production.

4.3 Siting

There are multiple constraints in the siting of a nuclear power plant including seismic activity, availability of cooling water, and low population density. These constraints often result in the colocation of multiple nuclear power plants. Because of these siting restrictions, the ideal product from a nuclear plant should be (1) easy to transport long distances to markets (to minimize siting difficulties), (2) energy intensive and in very high demand (to match the large energy output of multiple nuclear plants), and (3) storable (to allow efficient full utilization of multiple capital intensive plants). These qualities describe pipeline H_2 with storage in the pipeline or in separate facilities and indicate the potential for a good match between nuclear power and H_2 production.

5. GENERATION OF HYDROGEN FROM NUCLEAR POWER

The viability of H_2 production from nuclear power ultimately depends upon the economics, which, in turn, depend upon both the proposed methods of H_2 production and the available reactors.

5.1 Hydrogen Production Techniques.

Four methods have been proposed to produce H_2 from nuclear power.

5.1.1 Electrolysis

The electrolysis of water to produce H_2 is an old technology that is used today to produce ultrapure H_2 and to produce H_2 in small quantities at dispersed sites. It is the current H_2 production technology from nuclear power and all other energy sources that produce electricity. Electrolysis is not currently competitive for the large-scale production of H_2, except where low cost electricity is available.

Electrolysis has received significant attention as a transition technology to a H_2 economy. If fuel-cell cars are developed, this technique could provide H_2 across the country until a large-scale H_2 economy with supporting pipelines is developed. Electrolysis may also be the technology required to couple various renewable energy sources to the H_2 economy. The primary wind resources are in and near North Dakota. Pipeline H_2 may be the most viable method to transport that energy to the market. In this context, H_2 from nuclear energy and renewables depends upon many of the same technological factors.

The long-term viability of electrolysis for large-scale H_2 production depends upon the evolution of the electric grid, the capital costs of electrolysis (Sheffield June 2000), and other factors. Current capital costs are estimated to be near $600/kW, with future capital costs that may approach $300/kW. Conventional alkaline electrolyzers have efficiencies of 70 to 85%, with proton-exchange-membrane electrolyzers projected to have efficiencies of 80 to 90%. In

many industrialized countries, the peak electrical demand is twice the minimum demand. Consequently, low-cost off-peak electricity is available (e.g., in the middle of the night). Electrolysis may be viable provided there is successful development of efficient, low-cost electrolysis systems and associated local H_2 storage systems.

Under most future scenarios, no incentives would exist for colocating nuclear facilities and H_2 production via electrolysis. There are two exceptions.

- *Energy parks*. Pipelines are an efficient method for transport of energy in the form of H_2 over very long distances. If remote energy parks provide much of a nation's energy supply, pipelines may be preferred over electricity lines for long-distance transport.

- *Energy conversion*. With current technology, there is no incentive for colocation of nuclear and H_2 production systems. The equipment is the same in both cases. However, much of the cost of electrolysis is associated with the process of converting alternating-current electricity to direct current. To reduce plant costs, developers of some proposed advanced reactors, such as helium-cooled gas-turbine reactors, plan to use very high speed helium turbines for electric production. The electricity produced from the associated generators requires solid-state converters to produce electricity of the appropriate frequency and voltage for the electric grid. With some concepts, the same equipment could be used to provide direct current to electrolyzers. Under these conditions, efficiency and capital cost gains result form colocating the power plant with the H_2 production facility.

5.1.2 Hot Electrolysis

Electrolysis (Dutta 1990; Quandt 1986) can be operated at high temperatures (700 to 900°C) to replace some of the electrical input with thermal energy. Because heat is cheaper than electricity, the H_2 costs via this production method could ultimately be lower than for traditional electrolysis. However, the technology (Sheffield June 2000) is currently in an early state of development with very high capital costs (>$1300/kW). Hot electrolysis requires colocation of H_2 production with the nuclear reactor to provide the heat.

5.1.3 Steam Reforming

Today, H_2 is produced primarily from the steam reforming of natural gas (net reaction: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$). Steam reforming is an energy-intensive endothermic process requiring high-temperature heat input. The natural gas (Stoll December 2000) is (1) used as the reduced chemical source of H_2 and (2) burnt to produce heat to drive the process at temperatures of up to 900°C. The amount of natural gas required for steam reforming can be significantly reduced when heat is provided by a nuclear reactor. Japan (OECD-NEA 2000) is currently developing the technology to deliver high-temperature heat from a high-temperature reactor to a steam reforming plant. The nuclear power plant provides heat that replaces heat from a gas flame.

5.1.4 Thermochemical Hydrogen Production

Hydrogen can be produced by direct thermochemical processes in which the net reaction is heat plus water yields H_2 and oxygen. These are the leading long-term options for production of H_2 using nuclear energy. For low-production costs, however, high temperatures (>750°C) are required to ensure rapid chemical kinetics (i.e., small plant size with low capital costs) and high conversion efficiencies.

Many types of thermochemical processes for H_2 production exist. The sulfuric acid processes (hydrogen sulfide, iodine–sulfur, 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 to produce oxygen:

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

Typically temperatures in the range of 800 to 1000°C are needed for efficient H_2 production. After oxygen separation, additional chemical reactions are required to produce H_2. The leading candidate for thermochemical H_2 generation is the iodine–sulfur (IS) process (Fig. 2), which has two additional chemical reactions:

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

and the H_2-producing step

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

The Japan Atomic Energy Research Institute is currently preparing to demonstrate the production of H_2 by steam reforming of natural gas with the heat-energy input provided by their High-Temperature Engineering Test Reactor (HTTR). The iodine–sulfur process is being developed with the ultimate goal of subsequently connecting it to the HTTR. Research on this process is 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 and solar-power tower heat sources.

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 approximately 34% (in current light-water reactors) to 50 % (for advanced systems), the overall efficiency would be approximately 25 to 40%. A significant capital investment in electrolytic cells is also required. For thermochemical approaches such as the iodine-sulfur process described previously, an overall efficiency of >50% has been projected. Combined-cycle (H_2 and electricity) plants may have efficiencies of ~60%.

The current estimates are that thermochemical H_2 production costs could be as low as 60% of those from electrolysis. This reflects the capital and operating cost penalties of converting thermal energy to electricity and then to chemical energy (H_2) versus converting thermal energy directly to chemical energy (H_2).

5.2 Nuclear Reactors for Hydrogen Production

Hot-electrolysis, methane steam reforming, and thermochemical production of H_2 impose somewhat similar requirements on the reactor:

- *Temperature*. Temperatures of between 750 and 1000°C are required. Higher temperatures are preferred.

- *Low pressure*. In most of these systems, the equilibrium thermodynamics for the high-temperature step favor low pressure to maximize H_2 production. At these high temperatures, there are strong incentives to minimize pressure differences to minimize materials strength requirements. There are also significant inventories of hazardous chemicals. If low pressure is on the chemical plant side, it is desirable to have low pressure reactor coolants.

- *Isolation*. 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 hydrogen production facility.

- *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 molten-salt-cooled reactor (Forsberg November 2001) that uses a coated-particle graphite-matrix fuel. The AHTR is similar to an HTGR except that high-pressure helium coolant is replaced with a low-pressure molten salt. Reactor exit coolant temperatures may be somewhat higher than those for the HTGR (better heat transfer with lower temperature differences between fuel and coolant), and the coolant operates at atmospheric pressure.

- *Lead-cooled fast reactor*. The operating temperatures are somewhat lower than those for the HTGR. Lead cooling is required because sodium (the traditional coolant in fast reactors) boils at 883°C—near the same temperatures that are required for H_2 production.

6.0 ECONOMICS

The potential large-scale production of H_2 from nuclear energy is several decades away. The economics that determine if and when H_2 is produced from nuclear power depend upon several factors.

- *Cost of commons*. The fraction of commons costs that is internalized for production of energy strongly impacts "free-market" economics. Most of these costs have been internalized for nuclear energy, but not as fully for many other energy sources.

- *Natural gas*. Steam reforming of natural gas is the primary source of H_2 today. Existing economic studies (OECD-NEA 2000) indicate that use of nuclear energy to provide heat for steam reforming of natural gas is competitive in areas with high costs for natural gas—such as in Japan where the natural gas is imported in liquified form.

  Future natural gas prices depend upon traditional market forces and technological developments. In many countries, natural gas is replacing coal for power production. As lower-grade crude oils become dominant in gasoline production, the requirements for H_2 will increase rapidly, with corresponding increases in natural gas demand. Simultaneously, several plants have been built and more are under construction for the conversion of natural gas to gasoline. New technologies (CEP August 2001), that are lowering the capital cost of such plants, are beginning to couple natural gas prices gasoline prices. These forces are likely to drive up the long-term costs of natural gas.

- *Technology*. The technology for H_2 from nuclear energy is only now being developed. The long-term viability of this option depends upon the success of these programs. The available information indicates the potential for economic production of H_2 from nuclear energy.

7. CONCLUSIONS

While much attention has been given to potential future uses of H_2, a robust and rapidly growing H_2 economy does, in fact, already exist today and is linked to the worldwide chemical and refining industry. As a result, H_2 represents an existing market for nuclear energy that may ultimately grow to exceed that for electricity. The intrinsic characteristics of the H_2 market (scale of operations, demand versus time, and siting) match the expected characteristics of H_2 production from nuclear energy. The economics of H_2 production from nuclear energy depend upon (1) the fraction of common costs that is internalized by different H_2 production routes, (2) the long-term natural gas prices, and (3) technology. The technology has the potential for economic production of H_2. If nuclear energy is to be a supplier of much of the world's future energy needs, the production of both electricity and H_2 needs to be considered.

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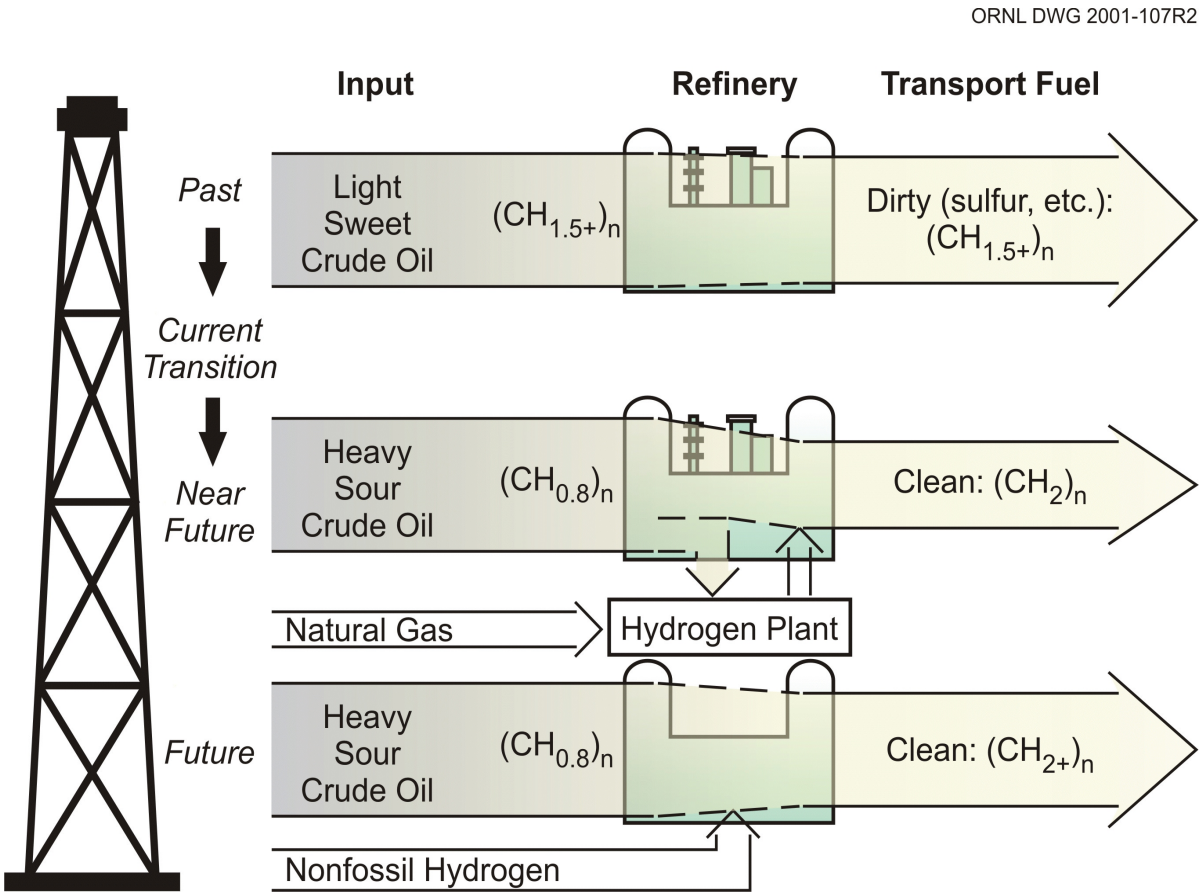

Fig. 1. The changing characteristics of available crude oil supplies are increasing the refinery demand for H_2.

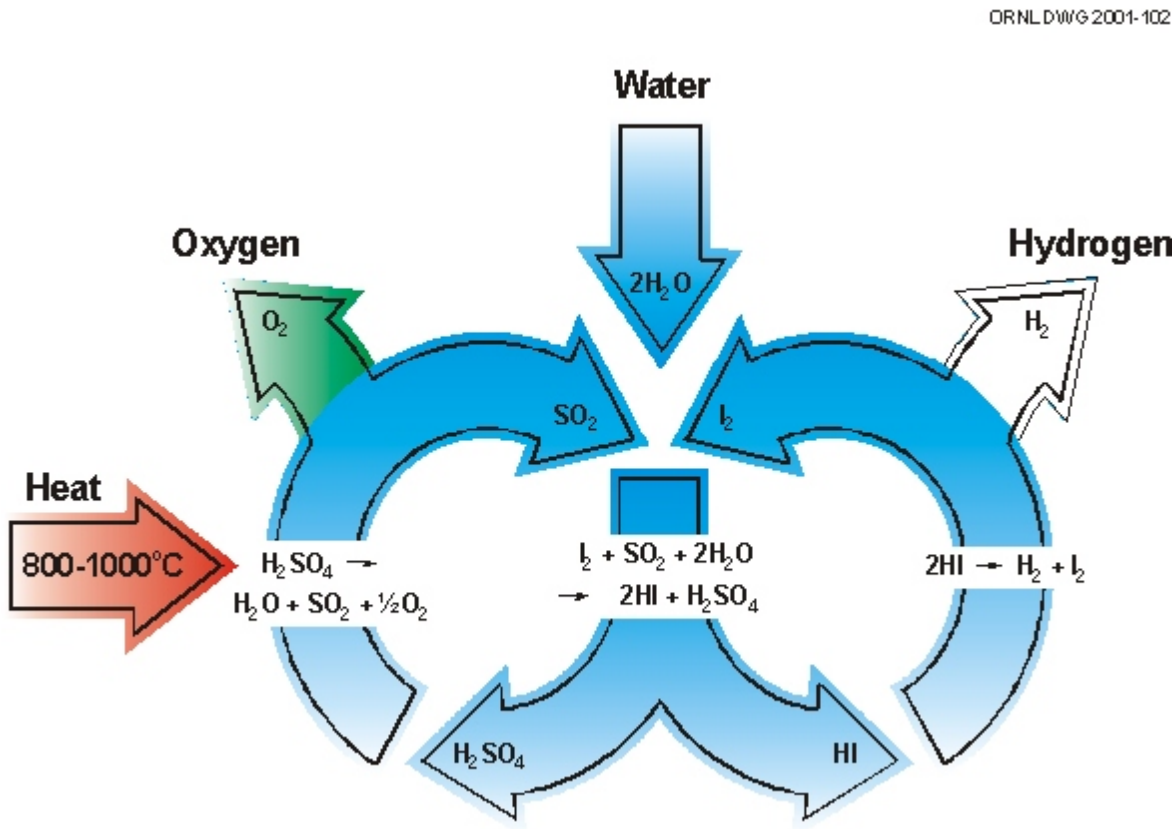

Fig. 2. Iodine–sulfur process for thermochemical production of H_2.