

GA-A24224

PRODUCTION OF HYDROGEN BY FUSION ENERGY: A REVIEW AND PERSPECTIVE

by
K.R. SCHULTZ

DECEMBER 2002



DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

GA-A24224

PRODUCTION OF HYDROGEN BY FUSION ENERGY: A REVIEW AND PERSPECTIVE

by
K.R. SCHULTZ

This is a preprint of a paper to be presented at the 15th Topical Meeting of the Technology of Fusion Energy, November 17-21, 2002, Washington, DC, and to be published in *Fusion Science and Technology*

Work supported by
General Atomics IR&D Funds

GA PROJECT 49009
DECEMBER 2002



ABSTRACT

Hydrogen has captured the imagination of the technical community recently, with visions of improved energy security, reduced global warming, improved energy efficiency and reduced air pollution as potential benefits. A significant “Hydrogen Economy” is predicted that will reduce dependence on petroleum imports, and reduce pollution and greenhouse gas emissions.¹ Such a hydrogen economy will need significant new sources of hydrogen. Virtually all our current hydrogen is produced from natural gas and is equivalent to 48 GW(t). Replacing this growing demand with a non-fossil, non-greenhouse gas emitting source represents a huge potential market for fusion.

Hydrogen could potentially be produced from water using fusion energy by direct interaction of fusion products (charged particles, neutrons and gammas), and by electrolytic or thermochemical means. Significant effort was devoted to study of these possibilities in the 1970-80s. It is instructive to review these earlier studies today as interest in production of hydrogen is revived. Investigations into direct use of fusion products for radiolysis and “hot spot” chemistry found it was difficult to get much of the fusion energy into the reaction channels of interest. Use of fusion energy in heat-driven processes was more promising. Fusion blankets could give much higher temperatures than are possible from fission heat sources. Studies of high temperature electrolysis and thermochemical water splitting using this high temperature heat were promising. The requirement that fusion blankets breed tritium raises challenges, as the tolerance for tritium in the product hydrogen is extraordinarily low. Use of multiple coolant streams, multiple containment barriers and separate breeding and high temperature zones were proposed that appear to successfully address these concerns, but add complication. Fusion does have the potential to support the Hydrogen Economy as well as electricity production as long as care is given to maximizing the benefits and minimizing the liabilities inherent to fusion energy.

I. INTRODUCTION

Combustion of fossil fuels provides 86% of the world's energy.² Drawbacks to fossil fuel utilization include limited supply, pollution, and carbon dioxide emissions, thought to be responsible for global warming.³ Hydrogen is an environmentally attractive fuel that has the potential to displace fossil fuels, but hydrogen is an energy carrier, not an energy source. A primary energy source must be used to produce hydrogen from hydrocarbons, carbohydrates or water. Contemporary hydrogen production is primarily based on fossil fuels. More than 95% of the 11 million tons per year of hydrogen currently made and used in the U.S. is made by steam reformation of methane, releasing 74 million tons of CO₂. Most of this hydrogen is used in the ammonia and petroleum industries. The use of hydrogen to lighten heavy crude oils for production of clean-burning fuels is growing rapidly.⁴ Overall, production of hydrogen is growing at ~10%/yr. Use of hydrogen for fuel cell vehicles – “the Hydrogen Economy” – will further increase the growing demand for hydrogen.

When hydrogen is produced using energy derived from fossil fuels, there is little or no environmental advantage. A “Hydrogen Economy” only makes sense if hydrogen is produced with non-fossil, non-greenhouse gas-emitting energy. The options to provide this energy are limited: nuclear fission, solar energy, renewables (biomass) — *and fusion*. Hydrogen production is a potential opportunity for fusion.

There was intense interest in hydrogen during the “energy crisis” of the 1970s and early 1980s. Since that time, little has been done to investigate potential large-scale sources of hydrogen. With the resurgence in interest in hydrogen, it is useful to review earlier studies of possible ways to make hydrogen using fusion energy.

II. THE FAME STUDY

A number of studies were done in this 1975-1985 period, and these were reviewed and evaluated in the late 1980s by the Fusion Applications and Market Evaluation (FAME) study.⁵ The goal of FAME was to investigate potential applications of fusion energy and to evaluate the market potential for these application. It specifically was charged to look beyond electricity production, and to look for ways to capitalize on unique fusion characteristics.

The FAME study concluded that there were a number of useful products that fusion could make that had reasonable market potential, and a credible pathway to serve those markets. These promising products are listed on Table I.

Table I. Potential Products Identified by FAME

Electricity
Fissile fuel and tritium*
Fission waste burning*
Synthetic fuels (hydrogen)*
District and process heat*
Rare metals*
Space propulsion

*Most products require co-generation of electricity

Hydrogen was one of the more attractive potential products of fusion. A potentially huge market exists; more that twice a big as the market for electricity, and fusion appears well-suited for the production of hydrogen. The economics of hydrogen production as a simple energy replacement for fossil fuels, however, are challenging. At the time the FAME study was done, oil was selling for about \$20/bbl and the cost of a fusion heat source was estimated to be \$850/kW(t). For hydrogen made from fusion energy to compete, the price of oil would have to exceed \$50/bbl. This economic barrier put interest in fusion production of hydrogen on hold.

Today, hydrogen is looked to not as a simple energy replacement of fossil fuels, but as a specialty fuel that has higher value than just its energy content. Currently hydrogen sells for about \$8/MBtu (\$1.10/kg) and is made from natural gas that costs \$4/MBtu. Its value is twice that of its energy content. Hydrogen is used in petroleum refineries to upgrade heavy crude oils. It is used to produce NH₃ for fertilizers and it is used to power fuel cells for vehicles and stationary applications. Because of this value, and because of the resurgence of interest in hydrogen, fusion production of hydrogen deserves another look. The conclusions of the FAME study are reviewed in the sections below.

III. DIRECT USE OF RADIATION

The nature of the fusion reaction gives rise to unique processing techniques. Possibilities include utilizing the radiation or the energetic particle plasma exhaust, or, in inertial confinement, the target debris. For D-T fusion, 80% of the fusion energy is carried by high energy neutrons. These neutrons are highly penetrating and pass through the wall of the plasma vacuum chamber and are absorbed in a thick blanket. The neutrons may be employed directly as in radiolytic chemistry or their energy may be used to generate very high temperature heat in a non-structural refractory ceramic which is thermally insulated from the structural components. Temperatures $\geq 1000^{\circ}\text{C}$ should be achievable, which is beyond that possible from contemporary fission reactors.

The neutrons convey these potential advantages but also cause transmutations which produce unwanted radioactive products. The problem is unavoidable for processes which utilize the neutrons directly. For thermal applications, isolating heat exchangers may be employed; but they could severely limit achievable temperatures or heat transfer rates. The magnitude of the problem is specific to the chemical process under consideration and depends on the materials employed, the chemical process steps, and the possibility for isolation of the activation products downstream. The D-T fuel cycle also requires tritium bred from neutron interactions with lithium. This function requires space in the reactor blanket and control of tritium migration downstream.

Direct process utilization of neutrons may seem simple, but there is a basic difficulty coupling the neutron energy into the reacting medium. Some energy will be deposited in the structure, but for solid or liquid media the majority of the neutron energy can be deposited in the medium. However, if a gas is being reacted, only small fraction of the neutron energy is likely to be available.

IV. RADIOLYSIS AND THERMAL SPIKE CHEMISTRY

Radiolysis is the use of the neutron or secondary gamma ray energy to directly sever chemical bonds, breaking H₂O into H₂ and O or CO₂ into CO and O, for example. Thermal spike chemistry is the use of very energetic knock-on atoms to create microscopic regions of very high temperature where non-equilibrium chemical reactions can occur. In the case of radiolysis, the most energy efficient processes use less than 30% of the deposited energy. The reject energy must therefore be utilized in a co-process or for co-generation. To do so, it must be removed from the radiolysis medium at high temperature, which for systems of interest implies gaseous cooling media and very low capture fractions for the neutron energy.

One of the more interesting radiolytic reactions is the decomposition of carbon dioxide to carbon monoxide.⁶ The radiolytic decomposition could be one step of a closed two step thermochemical water splitting cycle.



If the reject energy is used for generating additional hydrogen by normal low temperature electrolysis, an upper limit on the estimated overall efficiency would be about 40%. The actual efficiency achieved in practice would probably be only slightly better than the 32% for a reactor plant devoted entirely to conventional electrolysis, which serves as a useful reference base. Radiolysis does not therefore appear to be particularly attractive at present although it might find a role as a topping cycle in special circumstances because of its conceptual simplicity. An additional problem is the production of radioactive carbon, ¹⁴C.

Thermal spike chemistry is the interaction of high energy neutrons with materials, which results in transient localized hot spots having sufficient temperature to produce chemical dissociation, but which cool off so quickly that reverse reactions cannot occur. The idea is to yield useful products more valuable than the original chemicals. While this is a novel and unique application of fusion, calculations show that less than 5% of the neutron energy captured by the reacting medium is funneled into the thermal chemical reactions. Unless more favorable neutronic interactions are found, the yield would be too small.

V. ELECTROLYSIS

Hydrogen can be produced by electrolysis of water using electricity generated by fusion. However, in this case, fusion offers no advantages over other sources of electricity. By using the potential of fusion to produce high temperature heat, and using that heat in a high temperature electrolysis process, higher hydrogen production efficiency can be achieved. Brookhaven National Laboratory (BNL) studied fusion high temperature electrolysis⁷ in a three-year program to examine the commercial and technical feasibility of utilizing fusion power to generate hydrogen synthetic fuel. A tokamak fusion reactor of the STARFIRE design was proposed to generate high-temperature steam (~1700 K) for electrolysis to hydrogen and oxygen gas in a high-temperature electrolysis (HTE) unit. This combination of STARFIRE and HTE hydrogen production is called HYFIRE. The direction of this study was driven by the optimization for high hydrogen thermodynamic conversion efficiencies.

The HYFIRE blankets were designed to provide high-temperature steam for the electrolysis process, to produce thermal energy for efficient generation of electricity to operate the plant, and to breed sufficient tritium to compensate for burnup and process losses. Two types of blanket modules were designed to meet these requirements, a steam-cooled “HTE” module with a tritium breeding zone (Fig. 1) and a He-cooled tritium breeding “power” module. In each case, the first wall and blanket structural material is PCA (Prime Candidate Alloy) stainless steel as in STARFIRE; however, in HYFIRE, only the steel shell is cooled by pressurized water, the interior is cooled by either steam or helium. The modules are arranged toroidally since this minimizes differences in overall blanket configuration and associated maintenance procedures between STARFIRE and HYFIRE.

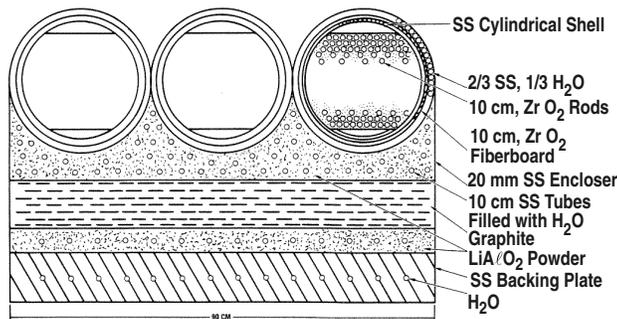


Fig. 1. Steam-cooled blanket module.

The interior of the HTE steam modules, shown in Fig. 1, consists of rods of ZrO_2 which are thermally insulated from the steel shell. The module utilizes a relatively thin tritium breeding layer outboard of the steam-cooled HTE zone. Consistent with the STARFIRE design, the tritium breeding medium is $LiAlO_2$. The design employs at

least two structural steel boundaries to minimize the potential of tritium leakage into the HTE steam circuit.

The tritium breeding/power production module, also employs a low-temperature water-cooled shell. The interior region is He-cooled and contains two distinct zones. The inboard zone contains a beryllium multiplier as well as LiAlO_2 ; the outboard zone consists of SiC and LiAlO_2 . Since interior structural materials are minimized, the blanket may operate at relatively high temperatures, which promotes tritium removal as well as the efficient power conversion

This design, utilizing HTE, has the highest potential efficiency for production of synfuels from fusion; a fusion-to-hydrogen energy efficiency of ~70% is claimed possible with 1800°C HTE units and 60% power cycle efficiency. An efficiency of ~50% appears possible with 1400°C HTE units and 40% power cycle efficiency.

VI. THERMOCHEMICAL WATER-SPLITTING

Thermochemical water-splitting is the conversion of water into hydrogen and oxygen by a series of thermally driven chemical reactions. The Sulfur-Iodine cycle is a prime example of a thermochemical cycle. It consists of three chemical reactions, which sum to the dissociation of water.



Energy, as heat, is input to a thermochemical cycle via one or more endothermic high-temperature chemical reactions. Heat is rejected via one or more exothermic low temperature reactions. All the reactants, other than water, are regenerated and recycled. In the S-I cycle most of the input heat goes into the dissociation of sulfuric acid. Sulfuric acid and hydrogen iodide are formed in the exothermic reaction of H_2O , SO_2 and I_2 , and the hydrogen is generated in the mildly exothermic decomposition of hydrogen iodide. The combination of high temperature endothermic reactions, low temperature exothermic reactions and energy neutral closing reactions is not sufficient for a cycle to be thermodynamically realizable. Each reaction must also have favorable ΔG (Gibbs free energy). A reaction is favorable if ΔG is negative, or at least not too positive.

Sulfur-Iodine Cycle. The Sulfur-Iodine cycle was developed at General Atomics and first described in the mid 1970's.⁸ The key to successful implementation of the cycle was using an excess of molten iodine in reaction (4) to give a two-phase solution, a light phase containing sulfuric acid and a heavy phase containing hydrogen iodide and iodine. Figure 2 shows a block flow diagram of the cycle based on this separation. Bench scale experiments were made of the total process and the process was matched to a high-temperature nuclear reactor with predicted efficiencies of ~50%.

Researchers at the University of Aachen demonstrated experimentally that the hydrogen iodide need not be separated from iodine before the decomposition step. They predicted significant increases in efficiency and a 40% decrease in the cost of hydrogen compared with the standard flowsheet. The cost decreases not only because the efficiency increased, but also because the capital intensive heavy phase separation

was eliminated. These proposed improvements are just now being incorporated into an integrated flowsheet. High temperature is important to achieving high efficiency with the S-I cycle, as shown on Fig. 3. This provides an opportunity for fusion as the high energy neutrons that carry most of the energy from a fusion reaction can penetrate a cooled structural wall and deposit their energy in an insulated, non-structural zone, thus potentially achieving very high temperatures.

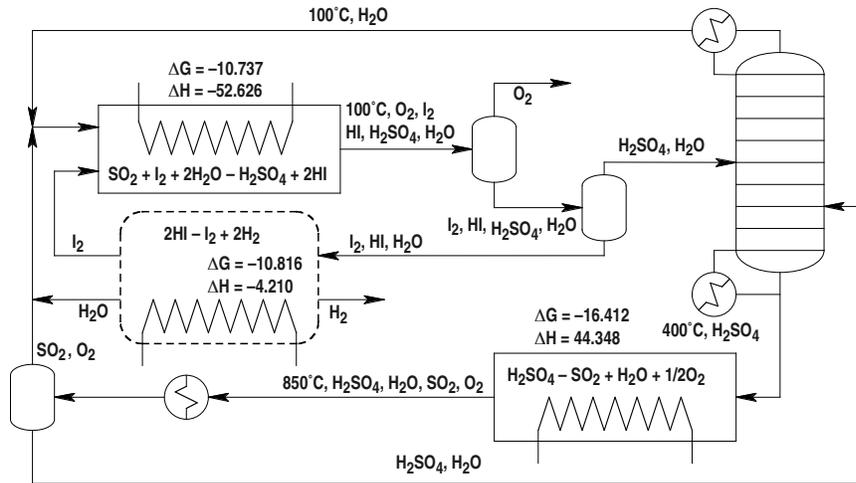


Fig. 2. Sulfur-iodine cycle process flow diagram

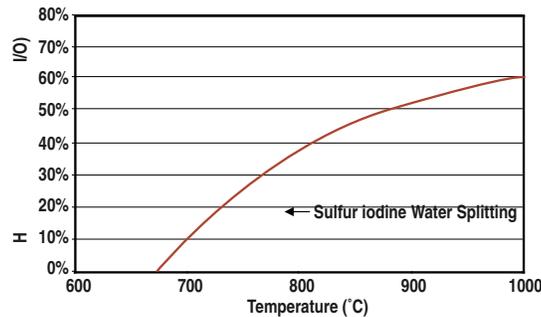


Fig. 3. Estimated S-I Cycle efficiency versus peak temperature

Two studies were done investigating the application of the sulfur-iodine thermochemical water-splitting cycle to fusion energy, one at General Atomics⁹ and one at Lawrence Livermore National Laboratory.¹⁰

GA Utility Synfuel Study. In the GA study, a conceptual fusion synfuel production system was developed.⁹ The blanket design developed in this study is illustrated in Fig. 4. This design can be applied to both tokamak and mirror reactors.

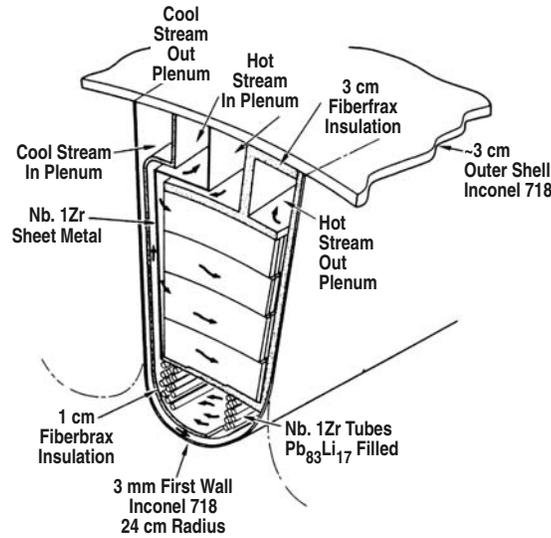


Fig. 4. High temperature blanket with two coolant streams.

This system incorporates a two-zone blanket which can achieve a tritium breeding ratio of 1.1 while delivering a high fraction (30%) of the fusion heat at high temperatures (1250°C). The tritium breeding material is $\text{Li}_{17}\text{Pb}_{83}$ which is contained in Nb-18 alloy tubes. The high temperature region consists of SiC tiles. The multiple barriers to tritium permeation in the blanket design permit the hydrogen product to meet 10CFR20 regulatory requirements without stringent requirements on the tritium recovery systems. A ceramic heat exchanger, incorporating SiC tubes and headers to contain the process stream and a cooled, Inconel 718 pressure shell to contain the helium, was designed for transferring the heat from the high-temperature coolant to the process. A good heat-line match of the blanket heat-source temperature distribution to the requirements of the thermochemical plant was attained under the dual goal of maximizing process efficiency and minimizing the hydrogen cost. The results showed a process efficiency of 43%, and an estimated cost of hydrogen of \$12 to \$14 per GJ of hydrogen.

LLNL Study. In the LLNL study, the fusion driver was the Tandem Mirror Reactor (TMR).¹⁰ The blanket design was a modest temperature blanket operating at 825 K to 950 K exit gas temperature. This design relies on electrical heating (a process called Joule Boosting) using electricity from the tandem mirror direct convertors to do the high temperature SO_3 decomposition step in the chemical process. The blanket design (Fig. 5), which operates at low to medium temperatures, uses solid lithium oxide as the breeder and helium as the coolant.

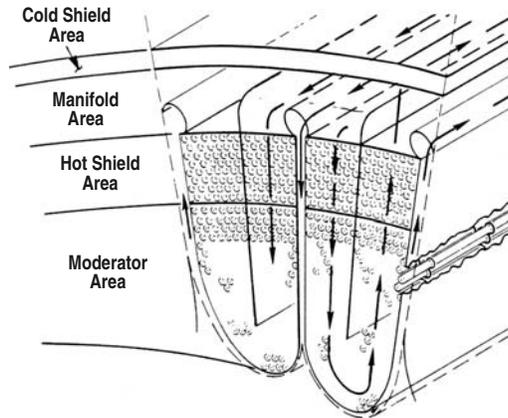


Fig. 5. Multiple-pass blanket.

To assure that the hydrogen product is tritium-free, “*in-situ*” tritium control is used rather than slip stream processing. This isolates the tritium from the main helium flow. Recovery of the tritium is by an independent purge circuit. Tenelon stainless steel was selected as the structural material.

The basic blanket geometry uses a two-dimensional lobe or canister configuration as shown in Fig. 5. A subassembly of the canister is one of the long tubes (~2 m) containing the lithium oxide. The tube protects the oxide from the mainstream coolant and contains the tritium purge flow. The estimated net hydrogen production efficiency of the process is about 33%. The estimated cost for producing the hydrogen was \$12 to \$15 per GJ.

Heat Exchangers. To effectively couple the very high temperatures fusion blankets can produce to the S-I cycle requires use of innovative heat transport loop and heat exchanger designs. The extreme temperatures and aggressive process fluids require use of ceramic components. Conceptual designs, such as that shown on Fig. 6, indicate that the technologies required are challenging but not impossible. An advantage to the use of a heat transport loop to carry the high temperature heat from the blanket to the externally-located hydrogen process is the avoidance of any neutron activation concerns in the process fluids and the hydrogen product. Tritium permeation from the breeding blanket into the process stream must be avoided, as clean up of the hydrogen product stream would be expensive. Use of two coolant streams, one at moderate temperature to cool the tritium breeding zone and the other at high temperature to cool the process heat zone appears essential. This approach, used in the blanket shown on Fig. 4, kept the calculated tritium permeation rate into the product hydrogen below 2.1 Ci/day, which would result in a tritium concentration in the product hydrogen that was below the 10CFR20 limits for unrestricted use.

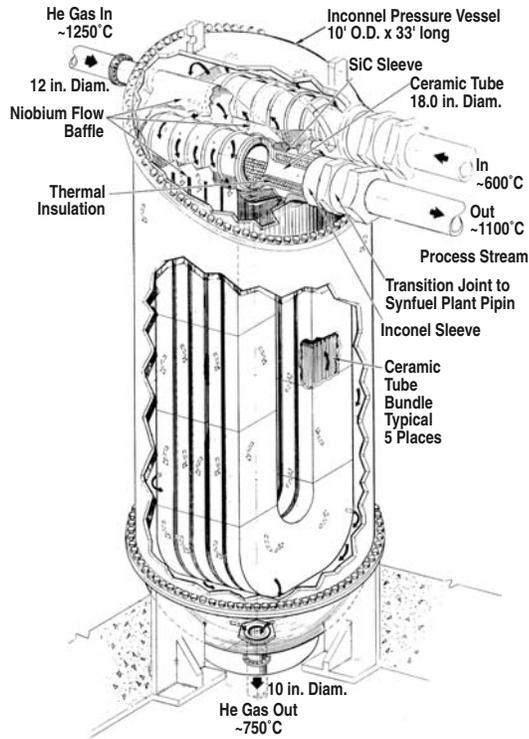


Fig. 6. Innovative heat exchangers are needed.

VII. ECONOMIC PROJECTIONS

The economics of hydrogen production are challenging. Virtually all of the 11 million tons per year of hydrogen that are produced and consumed annually in the USA is produced by steam reformation of methane. At the current cost of natural gas of about \$4.00/MBtu, the cost of the hydrogen is about \$1.10 per kg. The price of natural gas will rise and is expected to be in the \$5–6/MBtu range during the next 20 years or more. This translates into a cost of hydrogen by steam reformation of about \$1.40/kg of hydrogen.¹⁰ Assuming the capital recovery factor for a 10% interest rate and a 40 year lifetime with zero recovery value at the end, a 90% plant availability, and an annual O&M cost of ~7% of initial capital cost allows one to estimate the capital that could be spent on the fusion heat source to produce hydrogen at this \$1.40/kg cost. Subtracting the \$250/kWt cost of the hydrogen plant would leave an allowed expenditure of about \$450/kW(t) for the fusion plant. This appears to be a believable cost goal for fusion.

VII. CONCLUSION

On the basis of this review of the earlier work done on production of hydrogen using fusion energy some perspectives can be drawn for future directions. It is clear that there already exists a large market for hydrogen, and that this market will grow significantly before fusion will be available. Several processes exist by which fusion energy could be used to produce large quantities of hydrogen. Direct utilization of fusion products (radiolysis) appears to be limited to fractional topping cycles that would add considerable complexity to the fusion blanket design. The most promising approaches are use of high temperature heat from a fusion blanket in a thermal process such as high temperature electrolysis or thermochemical water-splitting. Fusion can potentially provide very high temperatures, which are needed for high efficiency. However, fusion introduces additional requirements and concerns that must be considered. These include the need to produce tritium in the blanket, which will limit the fraction of heat that could be delivered at high temperature and will require strict permeation limits. The value of hydrogen appears to be twice its energy value, which will help the economics of hydrogen production by fusion energy. The cost target for fusion to compete is a not unreasonable goal. With development, fusion could help fill the future needs for hydrogen.

REFERENCES

- [1] “A National Vision of America’s Transition to a Hydrogen Economy — to 2030 and Beyond” National Hydrogen Vision Meeting document, U.S. Dept. of Energy, February 2002.
- [2] Annual Energy Outlook 2000 with projections to 2020: DOE/EIA-0383(2000), The Energy Information Administration of the Department of Energy (www.eia.doe.gov).