

### Abstract

The decreasing availability of fossil fuels emphasizes the need to develop systems which will produce synthetic fuel to substitute for and supplement the natural supply. An important first step in the synthesis of liquid and gaseous fuels is the production of hydrogen. Thermonuclear fusion offers an inexhaustible source of energy for the production of hydrogen from water. Depending on design, electric generation efficiencies of ~ 40 to 60% and hydrogen production efficiencies by high temperature electrolysis of ~ 50 to 70% are projected for fusion reactors using high temperature blankets. Fusion/coal symbiotic systems appear economically promising for the first generation of commercial fusion synfuels plants. Coal production requirements and the environmental effects of large-scale coal usage would be greatly reduced by a fusion/coal system. In the long term, there could be a gradual transition to an inexhaustible energy system based solely on fusion.

### Introduction

World reserves of oil and gas are being rapidly depleted and the general consensus is that they will be essentially gone in a short period of time. Many of the industrialized nations, the United States for example, are now importing a large fraction of their petroleum needs, with consequent worries about sources of supply to maintain continued growth patterns, future prices, and effects on the balance of payments.

It is generally believed that future energy demands which have, in the past, relied on oil and gas will, in the future, have to be supplied by alternate sources. This will mean an increased reliance on established energy sources such as coal and nuclear (LWR) to meet the projected energy deficit.

Coal can supply both electricity and synthetic portable fuels, but there appears to be concern as to the degree to which it can meet future demands, in terms of production rates, total available resources, and possible harmful environmental effects. For example, the potential long-range climatological effects of large additions of CO<sub>2</sub> to the atmosphere are being studied.

Nuclear (LWR) sources, though, can supply energy primarily to generate electric power. This will help to abate some of the demands for oil and gas. However, for a number of demand sectors, practical technology has not yet been developed (and may never be) for direct electrical use. Also, nuclear (LWR) may be found wanting as an energy source in a few decades due to heavy pressure on uranium reserves. The long-range prospects for nuclear energy deployment also depend upon demonstration of terminal waste disposal technology and resolution of broader energy policy questions.

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These conditions have led to an increased interest to identify a way to produce substitute fuels, e.g., hydrogen, from the inexhaustible energy sources, that is, solar, geothermal, fission (breeder), and fusion.

Hydrogen's potential to be derived from renewable as well as from fossil resources such as coal, has caught the imagination of many--here and abroad. Hydrogen can serve multiple functions: if derived from an inexhaustible or renewable source such as a chemical feedstock for much more efficient coal liquefaction and gasification; ammonia production and metal-ore reduction; as an efficient source of electricity by using fuel cells; and ultimately, as a primary transportation fuel. The supply of hydrogen would be virtually unlimited since it is obtained from water. It is generally recognized, though, that hydrogen's entry into the energy infrastructure, on a large scale, is not a near-term option. Before hydrogen can begin to play the role of a universal fuel, developments in pertinent technology will be required; but these do not appear to be radical departures from the current state-of-the-art.

It should be noted that prior to 1950, substantial quantities of hydrogen mixed with CO were produced from coal and distributed in cities as town gas. Some cities in the world still distribute a 50%-by-volume mixture of H<sub>2</sub> with CO in city distribution systems. Currently, hydrogen is an industrial commodity, derived primarily from natural gas and the technology for handling it is familiar to industry.

In summary, one may equate interest and commitment pertinent to hydrogen technology development to the availability (or lack) of special indigenous energy resources in a nation. The major thrust in hydrogen-related R & D is most evident in the resource-starved areas of the world, such as western Europe and Japan. World-wide interest is brought about by recognition of hydrogen as a future "insurance policy" and a present opportunity to exploit hydrogen's flexibility as both a chemical commodity and non-polluting fuel supplement as well as an efficient energy-carrying alternative to conventional and energy wasteful transport systems.

### Fusion Synfuels--Utilization

Fusion energy has the potential for a variety of applications, including: 1. electrical generation, 2. synthetic fuels, 3. production of fissile fuel (Pu, U-233), 4. process heat, and 5. space heat.

These applications could be met either with separate plants or multipurpose plants (e.g., hybrid fusion-fission reactors could produce both fissile fuel and serve as base-load electrical plants, or pure fusion reactors could generate both synfuels and electricity). Multipurpose plants may ultimately be more economic but this requires further study.

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The application of fusion energy to the generation of synthetic fuels and chemicals has received little attention. There have been a few conceptual design studies of various processes<sup>1,2</sup> for generating hydrogen using fusion energy, but no detailed reactor reference designs have as yet been made. This reflects the fact that, until relatively recently, liquid and gaseous fuels have been plentiful and cheap.

Figure 1 illustrates the range of fuels and chemical products that could be produced by fusion. The initial step for all products involves splitting of water molecules to generate H<sub>2</sub> and O<sub>2</sub>. Process technologies for hydrogen production are discussed in more detail in the next Section; it appears that the very high process temperatures possible with fusion energy can be used to generate H<sub>2</sub> at high overall efficiencies, that is, 50% or greater.

The generated H<sub>2</sub> can be used directly as fuel for various end uses as proposed in studies of the "hydrogen economy", including industrial process heat, liquid H<sub>2</sub>-fueled aircraft, and automobile transport (using metal hydrides or other devices to store H<sub>2</sub> fuel). Hydrogen can also be directly used to produce chemicals (ammonia) or metals (iron and steel by the H-iron process). Finally, hydrogen can be combined with carbon to produce synthetic carbonaceous fuels, including methane, methanol, gasoline, diesel fuel, and various weight oils. The source of carbon can be fossil (coal) or non-fossil (limestone, biomass, atmospheric CO<sub>2</sub>). The oxygen co-product would also have many uses, including iron and steel manufacturing, power generation (MHD), and fuel production (coal gasification).

The potential importance of synfuel production for fusion is vividly illustrated in Table 1, using present (1977) energy use patterns. In order for fusion to supply one-half of present energy consumption for the various end-use demands, the number of fusion reactors generating synthetic fuels would have to be much larger, by a ratio of approximately 5:1, than the number generating electricity. In many instances, of course, substitution of electricity for liquid and gaseous fuels is possible; however, in many cases it is either not possible (airplanes) or not technically or economically practical (automobiles).

The degree of implementation and application of fusion in the U.S. energy system will depend on various uncertain factors such as: future U.S. energy demands both for electrical and portable fuels; future U.S. energy supplies, including the availability of imports, the cost of fusion energy, and the costs of competing energy sources; and finally, the time scale for commercialization of fusion.

With so many uncertainties, projections of future energy systems into the twenty-first century must involve many assumptions and subjective estimates. These inherently lead to a wide variability in possible energy futures. This variability is often explicitly dealt with by showing a number of "scenarios" that correspond to different assumptions and estimates, leaving it up to the reader to pick the one that he feels the most likely.

Figure 2 shows total portable fuel consumption in the U.S. for the interval 2000 to 2040 based on Energy Information Agency (EIA)<sup>3</sup> projections along with a BNL estimate of the potential fusion synfuel implementation level. The fusion synfuel contribution is given in terms of the quads of primary H<sub>2</sub> energy produced by water splitting. Some of the generated H<sub>2</sub> would be used directly as fuel (e.g., for industrial process heat or H<sub>2</sub>-fueled aircraft) and some for chemical production (e.g., ammonia), with the remainder being combined with some carbon-bearing material (e.g., coal, CO<sub>2</sub> from the atmosphere or limestone) to make portable carbonaceous fuels (synthetic liquids and gases).

Acceleration of fusion synfuel implementation would result in greater reductions in conventional fossil fuel requirements. The implementation curve in Figure 2 represents a reasonable market penetration rate, comparable to that for nuclear power. Two commercial plants are assumed to begin operation in 2000 AD, each of ~ 5000 MW(th) capacity, producing ~ 0.1 quad per year of H<sub>2</sub> fuel.

Faster implementation rates should be possible if an all-out crash program were instituted. Of prime importance is the achievement of an early as possible commercialization date, since the first two decades of growth must inevitably have a small impact on total U.S. energy requirements, due to the long lead time to design and build fusion reactors. With a crash program and commercialization in 1995, fusion synfuels could supply a large fraction of U.S. portable fuels by 2020 instead of the 2040 date as indicated in Figure 2.

#### Fusion Synfuels--Process Options

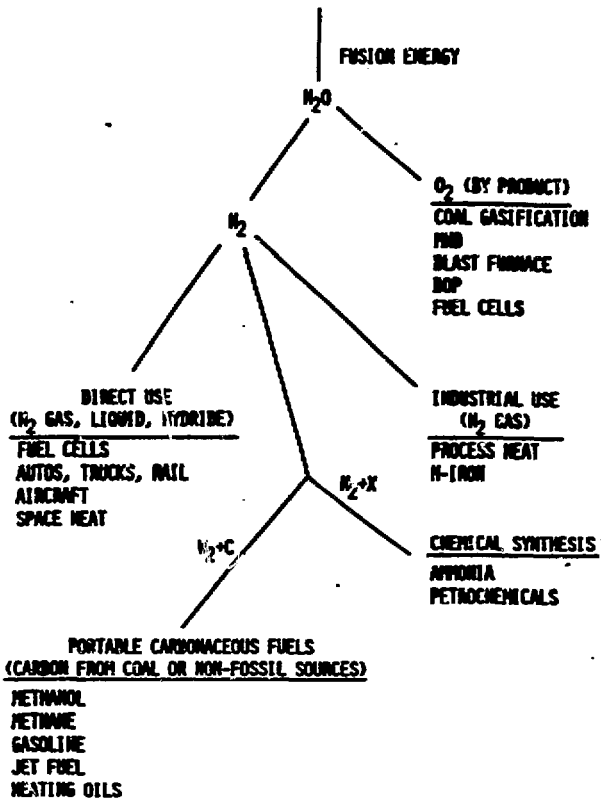
The DT fuel cycle is favored for the first generation of fusion reactors since advanced fusion fuels, like DD or DHe<sup>3</sup>, require much higher plasma temperatures and densities for useful power outputs.<sup>4</sup> Each DT fusion releases 17.6 MeV, 14.1 MeV as fast neutron energy, and 3.5 MeV as alpha particle energy.

There are three types of processes for hydrogen production using fusion energy:

1. Radiolytic--the energetic fusion products (neutrons, alpha particles, and gammas from nuclear reactions in the blanket) can radiolytically decompose a process fluid to produce hydrogen.
2. Thermochemical--the energy of the fusion products can be converted to high-temperature heat in the blanket. This heat can then decompose a process fluid (or fluids) in a single- or multi-step process to produce hydrogen.
3. Electrochemical--some of the high-temperature heat from the blanket can be converted to electricity by a thermal power cycle. The electricity can then generate hydrogen by an electrochemical reaction, e.g., the electrolysis of water.

All of these proposed processes require water as the feedstock, and generate hydrogen and oxygen as the output products. The various materials used internally in a process would be recovered and recycled, so that process losses would be very small. Some processes would use a combination of electrical and thermal inputs, rather than a

**FUSION SYNFUEL PRODUCTS**

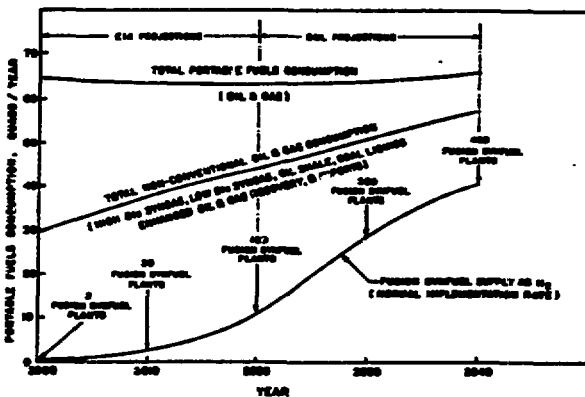


**Table 1 Fusion synfuel demand potential.**

DEMAND SECTOR	FUSION SYNFUEL PRODUCT	ENERGY DEMAND [1977 QUANT]	# OF FUSION REACTORS TO SUPPLY 50% OF DEMAND SECTOR
<b>Transport</b>			
Auto	H <sub>2</sub> (Hydride)	9.8	136
Truck, Bus	Methanol	6.2	86
Aircraft	Liquid H <sub>2</sub> , Jet Fuel	2.2	30
<b>Industrial</b>			
Process Heat	H <sub>2</sub> (Gas)	14.0	174
Iron and Steel	H <sub>2</sub> (Gas)	2.0	28
Petrochemicals	H <sub>2</sub> , CH <sub>4</sub>	4.6	61
<b>Residential &amp; Commercial</b>			
Space, Hot Water Heat	H <sub>2</sub> (Gas)	8.5	113
			<b>Total .... 653</b>
<b>Electricity</b>		6.6	131

**Fig. 1 Fuels and chemical products from chemical energy.**

Conditions: Reactor Tower = 3000 MW(th)  
 H<sub>2</sub> Production Efficiency = 50%  
 Plant Factor = 80%  
 Electrical Production Efficiency = 35%



**Fig. 2 Fusion synfuel contribution to U.S. portable fuels consumption until 2000 AD (normal implementation rate).**

separate thermal or electrical input.

There are many possible water splitting processes based on radiolytic, thermal, or electrical energy inputs. The suitability of these processes for fusion energy will depend on what technology is required, the overall efficiency for conversion of fusion energy to chemical energy, the cost of the hydrogen product, and the environmental impacts of the production process.

Some processes can be immediately eliminated from consideration. For example, processes involving radiolytic dissociation by fusion alpha particles inevitably lead to unacceptable tritium contamination of the hydrogen product. Radiolytic processes based on neutrons and gamma rays are possible which will yield a hydrogen product without radioactive contamination.

However, present knowledge about radiolysis indicates that fusion synfuel processes based on radiolytic reactions will have low efficiency. Radiolysis of  $\text{CO}_2$  gas, which has the highest G value [ $F(\text{CO}_2) = 10$  molecules decomposed to CO and  $\text{O}_2$  per 100 eV absorbed<sup>5</sup>] can transform about 30% of the absorbed (n, $\gamma$ ) energy to chemical energy, with the remainder appearing as heat. The product CO can be converted to hydrogen by a shift reaction with steam. However, only about 30% of the original fusion energy could be absorbed in the  $\text{CO}_2$  gas stream<sup>6</sup>, even at very high pressure. Thus the maximum overall efficiency for fusion energy to hydrogen chemical efficiency will only be about 9% for radiolytic processes. Pure radiolytic fusion synfuel processes could only be practical as a topping cycle carried out in conjunction with main thermochemical processes.

The efficiencies of thermochemical processes, as well as the efficiency of conversion of heat to electricity for electrochemical processes, generally increase with increasing temperature. Fusion offers the potential for very high process temperatures, which should lead to high efficiency for hydrogen production.

The fusion alpha particle energy will only be available at relatively low temperatures, i.e., up to 500°C. The short range of alpha particles in solid matter will result in their energy appearing as a heat flux on the first wall surrounding the plasma, along with x-rays (Bremsstrahlung) and ions from the plasma. [The total energy carried by alpha particles, x-rays, and ions is 3.5 MeV per fusion event, since the energy of the x-rays and hot ions species result from plasma heating by alpha particles.] Structural strength considerations probably will limit the maximum coolant temperature for the first wall to ~500°C, and the energy extracted from it will be primarily useful for electrical power generation.

In contrast, 14 MeV neutrons have a long range in matter and will deposit their energy deep inside reactor blankets. This unique feature of fusion neutrons can be used to generate very high temperatures for high efficiency hydrogen production processes. The interior of the blanket can be kept at much higher temperatures than the first wall and module structure, if the latter is thermally insulated from the interior and cooled by a separate coolant circuit.

Studies of such "two-temperature zone" blankets<sup>7</sup> indicate that the equivalent of approximately 60% of the total fusion energy can appear as high-grade heat in the blanket interior. Heat leakage from the hot interior will be only a few percent of that deposited in the interior. Fusion thus appears to have the highest temperature capability of all the inexhaustible energy sources. Containment of fission products limits operating temperature in fission reactors; achieving comparable temperatures with solar energy requires excessively high mirror concentration factors.

Table 2 lists some of the types of processes now being considered for synthetic fuels production from fusion energy, together with an example of each type. The process efficiency is defined as the chemical energy in the generated hydrogen [at the higher heating value (HHV)] divided by the total fusion energy release, including alpha particles and secondary neutron reactions in the blanket. Except where specifically noted, both high and low temperature blanket heats are counted as part of total fusion energy release.

Thermal decomposition is potentially simple and efficient. However, no practical way has yet been found to cool the products fast enough to prevent recombination. If the process gas could rapidly be cooled in a device extracting expansion work<sup>8</sup>, recombination could be prevented and much of the gases sensible heat would be converted to useful work. However, such an expansion requires dropping gas temperature from ~2000°C down to ~400°C, which is very difficult. Also, blanket materials suitable for long term exposure to potential process gases ( $\text{H}_2\text{O}$  or  $\text{CO}_2$ ) at very high temperatures have not yet been demonstrated.

Advanced power cycles such as  $\text{MHD}$ <sup>9</sup>, high temperature gas<sup>10</sup>, and steam turbines<sup>11</sup>, the wave energy exchanger<sup>12</sup>, and the potassium topping cycle<sup>13</sup> have been proposed for fusion reactors, with projected thermal cycle efficiencies of ~50 to 60% (fusion heat to electricity). However, in most approaches, only the high-temperature fusion heat could be used. Lower temperature heat from the first wall structure would have to be used in a separate, lower efficiency power cycle. The average cycle efficiency for the reactor would thus be substantially lower than that of the advanced cycle. For Rankine cycles, however, e.g., a high-temperature cycle, it appears possible to use heat effectively if it is used to evaporate the working fluid<sup>11</sup> in the cycle.

The advantages of achieving a high electrical generation efficiency are considerable. Using advanced low temperature electrolysis technology, such as solid polymer electrolytes (SPE)<sup>14</sup>, an electrical generation efficiency in the range of 50 to 60% would yield hydrogen production efficiencies (fusion energy to hydrogen chemical energy) of 50 to 55%.

Multi-step thermochemical cycles for hydrogen production have been investigated based on maximum heat input temperatures of ~900°C<sup>15,16</sup>. This temperature level can be provided by HTGR (High Temperature Graphite Reactor) type fission reactors. Many processes have been studied during the last ten years, with no clear consensus on which is the most promising approach. Most interest has focused on hybrid thermochemical cycles, in which one of

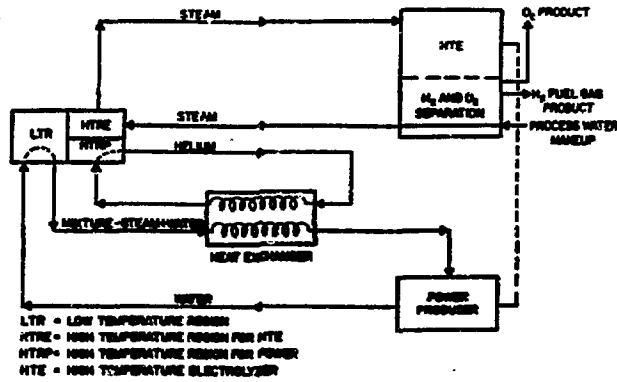


Fig. 3 Fusion reactor-HTE-conventional power cycle for synthetic fuel (H<sub>2</sub>) production (simplified system diagram).

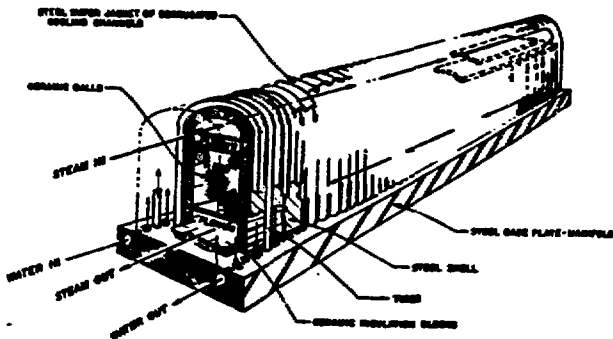


Fig. 4 HTE process module, 5000 MW reactor.

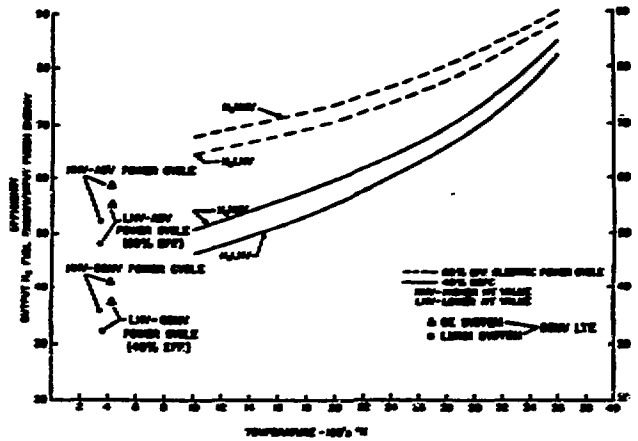


Fig. 5 Overall efficiency (fusion to hydrogen chemical energy) as a function of HTE temperature.

Table 2 Fusion syngas processes.

PROCESS TYPE	EXAMPLE	PROCESS COOLANT	PROCESS TEMPERATURE °C	MAXIMUM TRITIUM BREEDING RATIO	POTENTIAL PROCESS EFFICIENCY, FUSION TO HYDROGEN (HW)	COMMENTS
1. CONVENTIONAL LOW-TEMPERATURE ELECTROLYSIS (LTE)						
A) STANDARD POWER CYCLE	STANDARD STEAM CYCLE	HELIUM	~500	~ 1.5	~35	SPE ELECTROLYZERS HAVE ~50% EFFICIENCY
B) HIGH-EFFICIENCY POWER CYCLE	FAST CYCLE	STEAM	~900	~ 1.0	~55	FAST CYCLE USES GAS TURBINE TECHNOLOGY
2. HIGH-TEMPERATURE ELECTROLYSIS (HTE)	H <sub>2</sub> O +HELOC +HEAT → H <sub>2</sub> +1/2 O <sub>2</sub>	STEAM	~1200	~ 1.5	~50 to 70%	ELECTROLYZERS TESTED ON SMALL SCALE - PILOT PLANT IS NEXT STEP
3. PURE THERMOCHEMICAL	A) FeO+H <sub>2</sub> O → H <sub>2</sub> O + 1/2 Fe <sub>2</sub> O <sub>3</sub> B) 1/2 Fe <sub>2</sub> O <sub>3</sub> +HEAT → FeO + 1/2 O <sub>2</sub>	HELIUM	~1700	~0.7	~50% [OF THE HIGH-TEMPERATURE BLANKET HEAT]	DIFFICULT MATERIALS PROBLEMS
4. THERMAL DECOMPOSITION	A) CO <sub>2</sub> +HEAT → CO + 1/2 O <sub>2</sub> B) CO + H <sub>2</sub> O → H <sub>2</sub> + CO <sub>2</sub>	CO <sub>2</sub>	~2500	~0.7	~50% [OF THE HIGH-TEMPERATURE BLANKET HEAT]	RECOMBINATION OF CO MAY DESTROY PRODUCT
5. RADIOLYSIS	A) CO <sub>2</sub> +hv → CO + 1/2 O <sub>2</sub> B) CO + H <sub>2</sub> O → H <sub>2</sub> + CO <sub>2</sub>	CO <sub>2</sub>	~500	~0.5	~10%	DEMONSTRATED - DIFFICULT TO EFFECTIVELY DEPOSIT RADIATION ENERGY IN CO <sub>2</sub> GAS

the process steps is electrolytic, e.g., the Westinghouse sulfur cycle<sup>17</sup> and Mark-13 bromide cycle<sup>18</sup>.

So far, cycle irreversibilities have limited the projected overall efficiencies to values not much greater than could be achieved with low-temperature electrolysis using a conventional power cycle<sup>19</sup>. Higher temperatures from fusion reactors may permit efficient thermochemical processes by reducing the number of irreversible steps in the cycle. A conceptual hybrid thermochemical cycle for fusion reactors has been proposed<sup>2</sup>. Even if efficient thermochemical or hybrid cycles can be achieved, however, materials and chemical processing problems will be difficult since the process streams are generally corrosive and complex separations are required. Losses of expensive intermediate process chemical materials—such as iodine, bromine, cesium, or bismuth—could easily render the system uneconomical.

The remaining process, high-temperature electrolysis (HTE), is described in detail in the next section. HTE appears to have the highest potential efficiency for hydrogen production; the projected overall efficiency (fusion to hydrogen chemical energy) ranges from 50 to 70%, depending on process conditions and the power cycle efficiency. Small HTE cells have operated satisfactorily for thousands of hours at ~1000°C. Engineering development of large systems would be necessary, but no fundamental barriers are foreseen. Experiments with blanket materials for an HTE/fusion process are encouraging. Though HTE appears to be the most promising process, other options cannot be ruled out and further exploration of all approaches is desirable.

#### Fusion—High-Temperature Electrolysis

In low temperature electrolysis of liquid water, virtually all of the energy for decomposition is put in as electricity, and there are substantial overvoltage inefficiencies due to the oxygen electrodes. With HTE, a large fraction of the decomposition energy input is heat instead of electricity (e.g., at an electrolysis temperature of 1500°C, ~40% of the energy input is heat) and electrode overvoltages virtually disappear.

HTE uses arrays of tubes of relatively small diameter (~1 to 2 cm), thick-walled porous ceramic (e.g., stabilized ZrO<sub>2</sub>) on which a succession of thin electrode layers of suitably doped ceramics have been deposited. The H<sub>2</sub> and O<sub>2</sub> ceramic electrodes are separated by a thin (several mils) electrolyte layer of yttrium-stabilized ZrO<sub>2</sub>. Electrodes are electrically connected in series along each tube to minimize I<sup>2</sup>R losses.

Individual and small arrays of HTE cells have operated at ~1000°C for many thousands of hours. Long term operation of large HTE arrays is needed to fully demonstrate HTE technology, along with R & D on improved cell materials for higher temperature operation to increase the proportion of energy put in as high temperature heat.

The fusion syngas program at Brookhaven National Laboratory (BNL) is investigating HTE technology for fusion reactors.<sup>1</sup> Analytical studies of syngas blankets and HTE process systems are being carried out together with materials compatibility

studies of candidate high temperature ceramics for potential HTE process streams (steam, steam plus hydrogen, and carbon dioxide). Materials studies for HTE cells capable of operating at ~1500°C are also being performed.

Figure 3 shows an idealized flowsheet for an HTE/fusion synthetic fuel plant. In this example, all electrical production goes to the HTE cells to make hydrogen/electricity for sale, depending on market demand. Two blanket module types are indicated; the first type heats steam or CO<sub>2</sub> to high temperatures for the HTE cells (T ≥ 1000°C), while the second heats a working fluid for an electrical power cycle and breeds tritium. In the first type, (Figure 4) module shells operate at relatively low temperatures (~300°C), with the coolant providing heat for a power cycle. The hot insulated interiors of the modules are directly heated by neutron and gamma energy and absorb ~50 to 60% of the total fusion energy. The steam or CO<sub>2</sub> coolant is electrolyzed in the HTE cells with the heat input coming from sensible heat.

The second module type is a two temperature zone module design with a hot (~800°C) He-cooled interior and a separately cooled, lower temperature (~300°C) structural shell. The lower temperature coolant generated steam and the higher temperature heat superheats for a steam power cycle. Tritium is bred in solid lithium compounds and released to the helium coolant streams from which it can be subsequently recovered.

Materials experiments<sup>20</sup> indicate that ZrO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> are suitable for long term service up to ~1500°C (the present experimental limit at BNL) in steam, steam plus hydrogen, and CO<sub>2</sub> process streams. Experiments with SiC and MgO indicate these materials are restricted to somewhat lower temperatures.

Figure 5 shows projected overall efficiencies, i.e., total fusion energy (including alpha particle energy) to hydrogen chemical energy for the HTE/fusion process. Depending on HTE cell temperature and overall power cycle efficiency, overall syngas efficiency is expected to be in the range of 50 to 70%.

Fusion thus appears capable of producing hydrogen, the basic raw material for synthetic fuels at high efficiency using high temperature electrolysis of steam.

#### Fusion-Coal Systems

As a transition step to a hydrogen-based fuels economy with hydrogen and hydrogen-derived fuels using a non-fossil source of carbon (e.g., from atmospheric CO<sub>2</sub>), hydrogen produced by water splitting in reactors can be used in conjunction with coal gasification and liquefaction processes. Several examples are given which serve to illustrate these concepts.

The high temperature steam gasifier (HTSG) would use steam from the fusion reaction to generate syngas (CO and H<sub>2</sub>), eliminating an air liquefaction plant and increasing the gasifier capacity. Hydrogen from the HTE would be added to the syngas produced by HTSG. The shift converter would be eliminated and the acid gas removal equipment considerably reduced, compared with coal-only syngas

processes. Table 3 shows significant increases in yield possible by using fusion/coal processes to produce SNG and liquid fuels, compared with coal-only processes. For the same coal feed rate, using fusion hydrogen from HTE units increases SNG production by a factor of 2.2 over conventional steam-oxygen gasification and methanation. Using both the HTE and HTSG increases production by a factor of 3.2, and all the carbon in the coal feed appears in the SNG product. Using the HTSG alone will increase SNG production by a factor of 2.2. For synthetic liquid fuels, direct hydrogenation with fusion hydrogen increases yield by 1.8; with methanol production and dehydration to gasoline, the use of fusion hydrogen increases yield by a factor of 2.4.

Overall thermal efficiencies for fusion/coal systems include 60% for the fusion reactor-HTE conversion to hydrogen. These efficiencies are comparable to those of coal-only processes, so that thermal penalty is minimum.

The coal requirements for coal-only synfuel plants and fusion/coal plants for the U.S. are compared in Table 4. The fuel demands shown are for 1977 and do not include fuels for electrical power generation. Future U.S. demands will probably be higher than shown here. Three synthetic fuel categories are shown: SNG, to replace natural gas; synthetic liquids for transport, to replace gasoline, diesel, and jet fuels; and other synthetic oil products, to replace oil for industrial process heat, space heat, and petrochemicals. With coal-only synfuels, coal production is 2180 million tons/year or 3.7 times the current production of 600 million tons/year<sup>21</sup>. Present production goes to coal-steam power plants and the iron and steel industry, which will continue to consume coal in the future. If this consumption remains constant, total future production would have to be almost five times the present level.

With a fusion/coal system, the additional coal production would be smaller, i.e., 960 million tons/year, for the same synfuel demand. Furthermore, since some of the fuel demand, in Table 4, could be met by hydrogen from fusion reactors, the additional coal would probably be only about 600 million tons/year, the present U.S. production level. It appears difficult to reach the level of coal production required if the U.S. energy system is to be based only on coal and coal-derived synfuels. Environmental costs would be high and the large increase in the coal industry work force would pose serious health and safety problems. Even if such a massive shift to coal were possible, a transition to inexhaustible energy sources would only be delayed by a few decades. A fusion/coal system could allow a smoother transition to inexhaustible energy sources.

Approximately 250 fusion reactors (5000 MW(th) capacity) could produce all of the carbonaceous portable fuels now consumed by the U.S. This would reduce the needed coal production by 1200 million tons/year, compared with coal-only synfuel processes.

In the long term, when CO<sub>2</sub> additions to the atmosphere must be minimized, CO<sub>2</sub> could be extracted from the atmosphere by absorption-stripping with dilute carbonate solutions, or carbon could be obtained from biomass (agricultural waste, forest products, etc.). Carbonaceous synfuels, using fusion hydrogen and non-fossil CO<sub>2</sub>, could be produced

by catalytically combining fusion hydrogen and CO<sub>2</sub> to methanol, with subsequent dehydration to gasoline and oils. There would be no net addition of CO<sub>2</sub> to the atmosphere regardless of the synthetic fuel production level, and the CO<sub>2</sub> concentration in the atmosphere would remain constant. It is likely that pure hydrogen fuel will be widely used at this time for a variety of end-use demands. The economy could thus rely on a mixture of hydrogen and carbonaceous fuels both derived from fusion energy. The amount of usage of the different fuel forms would be determined by trade-offs involving relative costs, technical suitability, convenience, environmental effects, etc. It is not possible to predict what the relative mix of fuels will be, since there are so many unknown factors, but it seems likely that both hydrogen and carbonaceous fuels would be used.

Production costs for fusion synfuels are difficult to predict. Costs for coal-only synfuel processes are not certain, even though much more is known about their technology. A number of fusion reactor reference designs for electrical generation have been carried out. In these studies the projected cost of the reactor and associated plant is on the order of \$400 to \$800 MW(th)<sup>22</sup>. Fusion synfuel plants should have roughly comparable costs. Figure 6 shows projected costs for synthetic fuels as a function of coal cost, assuming a fusion-hydrogen plant cost of \$500/MW(th), a fusion-to-hydrogen efficiency of 60%, and 15% fixed charges on capital investment. Additional capital investment for the conversion of fusion hydrogen with coal-to-SNG or synfuel gasoline is also included. Coal-only synthetic fuel costs have been derived from other studies<sup>23</sup>. Projected O & M costs are also included for both fusion and coal-only synfuels.

The size of projected coal-only synfuel plants are on the order of 250 x 10<sup>6</sup> SCF/d for SNG and 50,000 bbl/d for synfuel gasoline. To apply the needed hydrogen and steam in fusion/coal plants of these capacities would require reactor ratings of 3000 MW(th) and 3900 MW(th), respectively. These ratings are to the thermal rating of standard central station electric generating plants.

The projected cost of fusion hydrogen is \$45/GJ [1 GJ = 0.95 million Btu] and is independent of coal cost. The cost of synfuels from fusion/coal plants will depend on coal cost since coal is a raw material. However, fusion/coal synfuel cost will be much less sensitive to coal cost than coal-only synfuels since the former uses much less coal. Fusion/coal synfuels become cheaper than coal-only synfuels at a coal cost of \$60/ton for SNG production and \$35/ton for liquid hydrocarbons. The crossover point for gaseous fuels occurs at higher coal costs because more hydrogen addition is required.

Cost projections are uncertain because of the many unknown factors. However, the trends--shown in Figure 6--are valid and at some coal cost fusion synfuels will be cheaper than coal-only synfuels. Present coal costs for long term contracts are on the order of \$25/ton. However, spot market prices are running up to \$50/ton for low-sulfur coal. The much greater demand likely for coal and the depletion of lower cost deposits will probably drive up coal costs. Thus fusion synfuels could be economically attractive when the first generation of fusion reactors come on-line--somewhat after the year 2000.

In the long term, the primary factors determining synfuel economics will be the relative unit costs of the inexhaustible resources--fission, fusion, and solar--and their efficiency for hydrogen production. The high hydrogen efficiency that appears possible with fusion should make fusion a major source of synthetic fuels when this occurs.

#### Summary and Conclusions

Portable liquid and gaseous fuels presently supply the major part of the U.S. energy needs and are likely to continue in this role for the foreseeable future. Natural oil and gas will be largely gone within the next few decades and will have to be supplanted by synthetic fuels. These could be derived from coal or other fossil sources (oil shale, tar sands, etc.) or from any or all of the inexhaustible energy sources (fission, fusion, and solar).

Fusion is a promising source for synthetic fuels. The unique ability of fusion energy to generate very high process temperatures should result in efficient processes for the generation of hydrogen from water decomposition. Hydrogen can be directly used as a fuel or combined with carbon to produce portable liquid or gaseous carbonaceous fuels. This carbon could come from a variety of sources, including coal, biomass, and atmospheric CO<sub>2</sub>. High temperature steam from a fusion reactor could also be used to gasify coal directly to synthetic gas.

Of the many potential processes for hydrogen production, high temperature electrolysis (HTE) of steam appears to be the most promising. HTE cells have operated at high temperatures for long periods. The process steam would be supplied from high temperature fusion blankets. The overall efficiency, fusion-to-hydrogen chemical energy, is projected to be in the range of 50 to 70% depending on the process conditions and type of power cycle. Large scale HTE technology can probably be developed by the time that the first commercial fusion reactors would be operating.

Fusion/coal symbiotic systems appear economically promising for the first generation of commercial fusion synfuel plants. Coal production requirements and the environmental effects of large scale coal usage would be greatly reduced by a fusion/coal system. In the long term, there could be a gradual transition to an inexhaustible energy system based solely on fusion.

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Table 4 Resource requirements to meet synfuel demands.

	Coal Only	Fusion/Coal
<b>SNG</b>		
1977 Demand, Quads Coal Consumption, T/year Number of 5000 MW(th) Fusion Reactors	16.8 $7.8 \times 10^8$ -----	16.8 $7.6 \times 10^8$ 116.0
<b>Synfuel for Transport (Automobiles, Trucks, Aircraft, etc.)</b>		
1977 Demand, Quads Coal Consumption, T/year Number of 5000 MW(th) Fusion Reactors	19.1 $8.6 \times 10^8$ -----	19.1 $4.3 \times 10^8$ 82.0
<b>Solar Oil Products (Industrial Process Heat, Base Heat, Petrochemicals)</b>		
1977 Demand, Quads Coal Consumption, T/year Number of 5000 MW(th) Fusion Reactors	11.8 $5.4 \times 10^8$ -----	11.8 $2.7 \times 10^8$ 51.0
<b>Total Coal Consumption, Tons/year</b>	$2.2 \times 10^9$	$9.5 \times 10^8$
<b>Annual U. S. Coal Production Required for Synfuels</b>		
<b>Ratio 1977 United States Coal Production (<math>6 \times 10^8</math> T/year)</b>	3.7	1.6

\* Does not include oil and gas used for electrical generation (1 Quad =  $10^{15}$  Btu =  $1.6 \times 10^8$  bbl oil)

Table 3 Coal process efficiencies.

	Ideal Process Efficiencies	
	Thermal Efficiency <sup>a)</sup>	Coal Utilization <sup>b)</sup>
	(a)	(b)
<b>1. All Coal SNG Processes</b>		
a) steam-O <sub>2</sub> gasification and methanation	72	32
b) catalytic gasification	100	44
c) direct hydrogenation	88	39
<b>2. All Coal Liquid Fuel Processes</b>		
a) direct catalytic hydrogenation	53	36
b) steam-O <sub>2</sub> gasification; methanolation and dehydration	70	42
c) Fischer-Tropsch synthesis	70	42
<b>3. Fusion/Coal SNG Processes</b>		
a) fusion HTSC, methanation	78	50
b) fusion HTSC, oxygen-oxygen and methanation	32	60
c) fusion HTSC, HTSC <sup>c)</sup> and methanation	39	100
d) fusion HTSC and direct hydrogenation	66	100
<b>4. Fusion/Coal Liquid Fuel</b>		
a) fusion HTSC with direct catalytic hydrogenation of coal	75	100
b) fusion HTSC and HTSC to ethanol with subsequent catalytic dehydration	63	100

<sup>a)</sup> Assume 60 percent thermal efficiency for conversion of fusion energy to hydrogen by the HTS process.

<sup>b)</sup> Chemical energy in fuel (Btu) divided by input thermal energy input (combustion energy for coal-only processes, coal plus fusion energy for fusion/coal processes).

<sup>c)</sup> Moles of carbon in product divided by moles of carbon input to process.

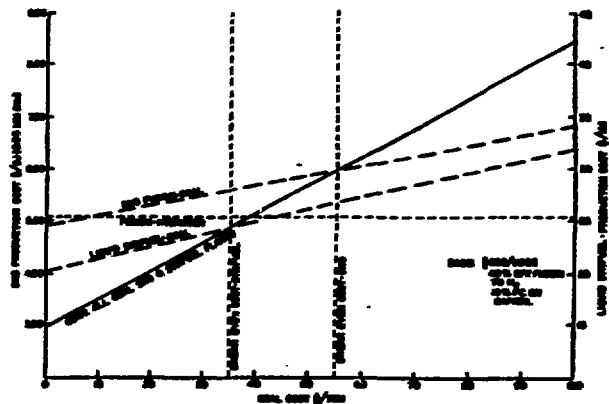


Fig. 6 Projected costs for synthetic fuels as a function of coal cost.