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REVIEW OF FUSION SYNFUELS**

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Summary

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 450 to 65% 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.

able resources, and possible harmful environmental effects. For example, the potential long-range climatological effects of large additions of CO₂ 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.

These conditions have led to an increased interest to identify a way to produce substitute hydrocarbon-based fuels, e.g., synthetic fuels for oil and natural gas from the inexhaustible energy sources, that is, solar, geothermal, fission (breeder), and 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, including the United States 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.

Hydrogen's potential to be derived from renewable as well as from fossil resources such as coal is an important first step. 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 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.

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

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 avail-

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a 50%-by-volume mixture of H_2 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.

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, ^{233}U), 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.

The application of fusion energy to the generation of synthetic fuels and chemicals has received little attention. There have been a few scoping and conceptual design studies of various processes^{1,2} 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 with no apparent need for either replacement or substitutes.

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_2 and O_2 . 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_2 at high overall efficiencies, that is, 50% or greater.

The generated H_2 can be used directly as fuel for various end uses as proposed in studies of the "hydrogen economy," including industrial process heat, liquid H_2 -fueled aircraft, and automobile transport (using metal hydrides or other devices to store H_2 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_2). The oxygen coproduct 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,

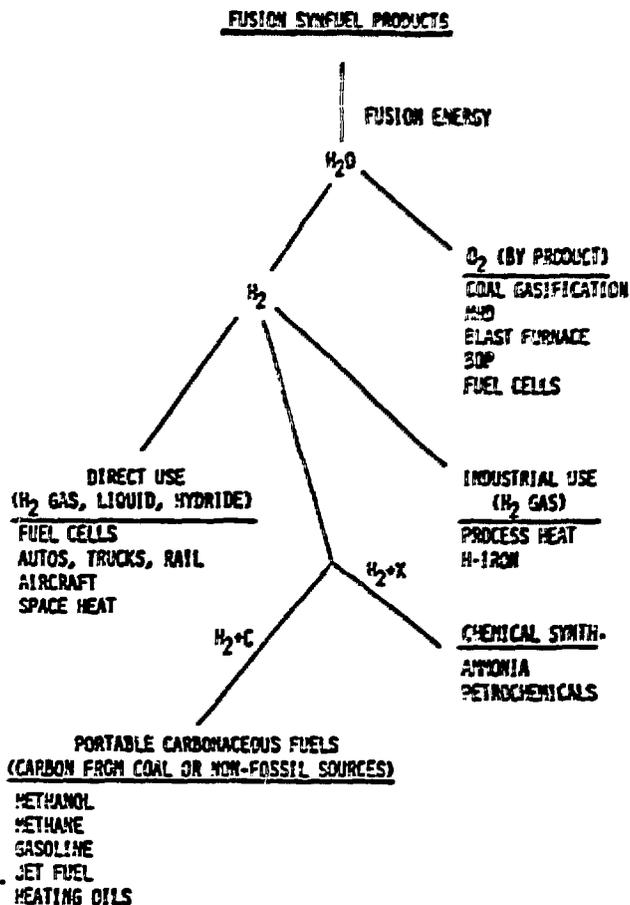


Fig. 1 Fuels and chemical products from chemical energy.

using 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

Table 1 Fusion synfuel demand potential.

DEMAND SECTOR	FUSION SYNFUEL PRODUCT	ENERGY DEMAND (1977 QUADS)	% OF FUSION REACTORS TO SUPPLY USE OF DEMAND SECTOR
Transport			
Auto	H ₂ (Hybrids) Gasoline Methanol	9.8	136
Truck, Bus	Methanol	6.2	86
Aircraft	Liquid H ₂ Jet Fuel*	7.2	10
Industrial			
Process Heat	H ₂ (Gas)	24.0	194
Iron and Steel	H ₂ (Gas)	2.0	28
Petrochemicals	H ₂ , CO ₂	4.4	61
Residential & Commercial			
Space, Hot Water Heat	H ₂ (Gas)	6.5	118
		Total	653
Electricity	-----	6.6	111

Conditions: Reactor Power = 1000 MW(th)
 H₂ Production Efficiency = 50%
 Plant Factor = 80%
 Electrical Production Efficiency = 35%

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)³ 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 H₂ energy produced by water splitting. Some of the generated H₂ would be used directly as fuel (e.g., for industrial process heat or H₂-fueled aircraft) and some for chemical production (e.g., ammonia), with the remainder being combined with some carbon-bearing material (e.g., coal, CO₂ 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/year of H₂ fuel.

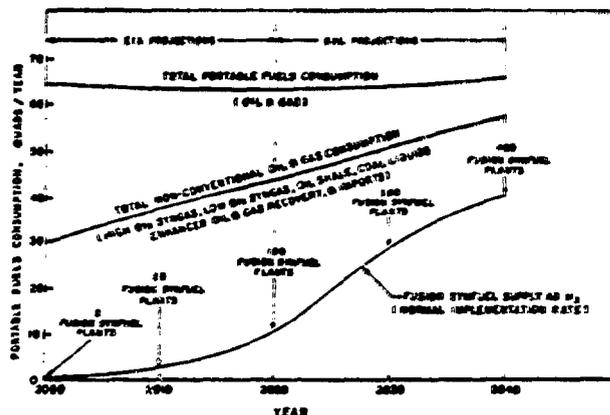


Fig. 2 Fusion synfuel contribution to U.S. portable fuels consumption until 2000 AD (normal implementation rate).

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 DHe³, require much higher plasma temperatures and densities for useful power outputs.⁴ Each DT fusion releases 17.6 MeV, 14.1 MeV as fast neutron energy, and 3.5 MeV as alpha particle energy.

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. Structural considerations probably will limit the maximum coolant temperature for the first wall to ~500°C. This relatively low coolant temperature limit will probably restrict its use to electrical power generation.

In contrast, 14 MeV neutrons have a long range in matter and will deposit their energy inside reactor blankets. This unique feature of the fusion neutrons can be used for high-efficiency hydrogen production processes. As they slow down, the 14 MeV neutrons cause nuclear reactions, generating high energy gamma rays; eventually, the neutrons will be captured by blanket nuclei, releasing several MeV of additional energy (the precise amount depends on the particular blanket design).

The neutrons (n) and gamma (γ) rays can split water directly by excitation and dissociation of water molecules. Alternatively, the (n,γ) energy could be deposited as heat in very high-temperature blanket interiors for thermal water splitting processes. Depending on choice of coolant and materials, interior temperatures could exceed 2000°C, for example, even though the first wall and module structure would be at or below 500°C. The interior region would have to be thermally insulated from the first wall and module structure.

Studies of such "two-temperature-zone" blankets indicate that the equivalent of ~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.

There are three generic 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 to minimize process losses. Some processes would use a combination of electrical and thermal inputs, rather than a separate thermal or electrical input.

There are many possible water splitting processes based on radiolytic, thermal, or electrical

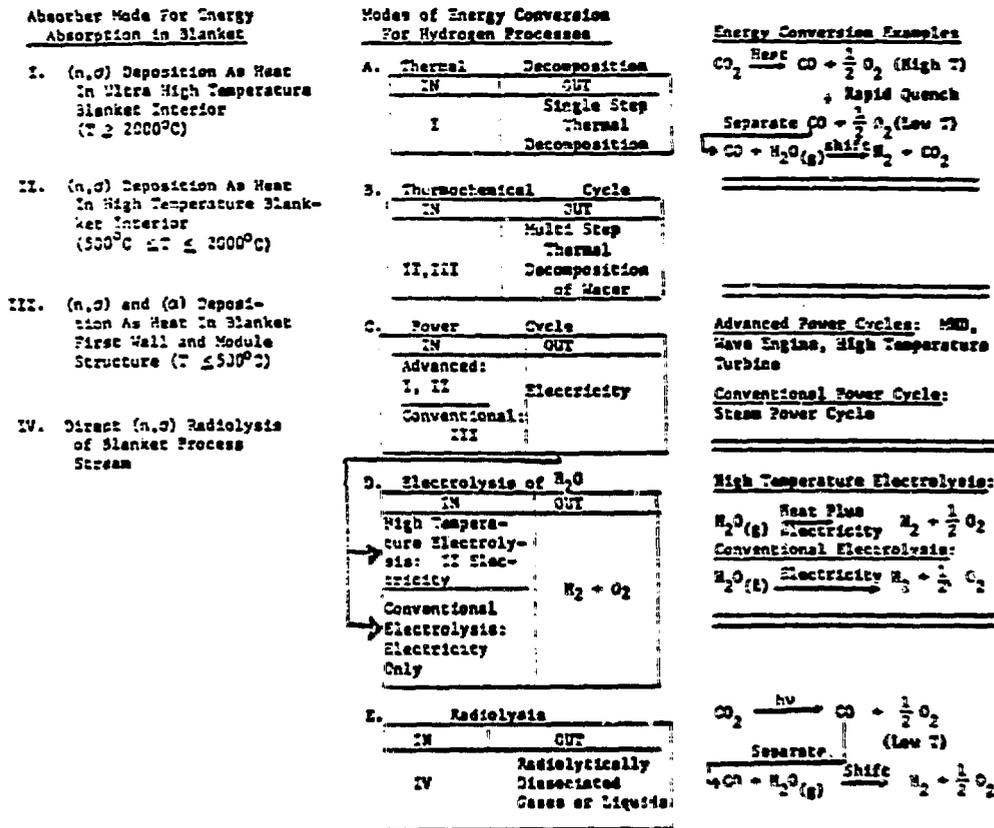


Fig. 3. Potential processes for producing hydrogen using fusion energy.

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.

Figure 3 summarizes the potential hydrogen production processes using fusion energy. Three temperature ranges are distinguished. In ultra-high temperature range (Mode I, $>2000^{\circ}\text{C}$), one could thermally decompose a process fluid to yield hydrogen and oxygen or by the decomposition of CO_2 with a subsequent shift reaction to hydrogen. To achieve these high temperatures, direct heating of blanket interiors which do not require heat transfer across intermediate heat exchangers will be required. The interior temperature level is set only by the capability of the inside materials. Mode I energy also could be used to generate electricity with an advanced power cycle (e.g., MHD) at ~ 50 to 60% efficiency (compared with the ~ 35 to 40% for a conventional electrolysis at a high-overall efficiency).

The Mode II high-temperature range ($\sim 500^{\circ}\text{C}$ to $<2000^{\circ}\text{C}$) could be used for multi-step thermochemical cycles for hydrogen production,⁵ electric power cycles,⁶ and high-temperature electrolysis.⁷ In the first alternative, a series of chemical reaction steps is driven by high-temperature heat inputs. The complete cycle splits input water into output hydrogen and oxygen, with the reaction chemicals being regenerated and recycled. An example of an attractive option for the second alternative is the closed Brayton gas turbine cycle. The third alternative, high-temperature electrolysis (HTE), involves the electrolysis of steam at high temperatures using ceramic electrodes and electrolytes. In the HTE process, a large fraction of the energy input is heat, not electricity. This results in a high efficiency for conversion of fusion-to-hydrogen chemical energy.

Mode III energy, at temperatures of $\sim 500^{\circ}\text{C}$ or below, appears useful only for electrical generation by conventional power cycles. Fusion syngas blankets would be designed to minimize the amount of energy in this mode. Process fluids can be radiolytically decomposed (Mode IV energy) to produce hydrogen, either:

directly ($\text{H}_2\text{O} \xrightarrow{\text{hv}} \text{H}_2 + 1/2\text{O}_2$) or indirectly ($\text{CO}_2 \xrightarrow{\text{hv}} \text{CO} + 1/2\text{O}_2$, followed by the shift reaction to H_2). However, 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.

Present knowledge, though, about radiolysis indicates that fusion syngas processes based on radiolytic reactions will have low efficiency. Radiolysis of CO_2 gas, which has the highest G value

[$\text{F}(\text{CO}_2) \approx 10$ molecules decomposed to CO and O_2 per 100 eV absorbed⁸] can transform about 50% of the absorbed (n, γ) 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 CO_2 gas stream,⁹ 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 syngas processes could only be practical as a topping cycle carried out in conjunction with main thermochemical processes.

Thermal decomposition (Mode I) is potentially simple and efficient. However, no practical way has yet been found to cool the products fast enough to prevent recombination. Also, blanket materials suitable for long-term exposure to the process gas (a mixture of CO_2 , CO , and O_2) at very high temperature has not yet been demonstrated.

Advanced power cycles such as MHD,¹⁰ high-temperature gas and steam turbines, the wave energy exchange,¹¹ and the potassium topping cycle¹² have been proposed for fusion reactors, with projected thermal cycle efficiencies of ~ 50 to 60% . However, in most of these cycles, only the fusion heat extracted at high temperatures (Modes I and II) could be used. Lower temperature heat (Mode III) from the first wall structure would have to be used in separate, lower efficiency power cycles, making the average cycle efficiency for the reactor 5 to 10% lower.

High Temperature Blankets

The unique feature of fusion neutrons, namely long-range penetration in matter and deposition of energy deep inside reactor blankets, 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.

Several blanket concepts have been proposed, all of which have as general design objectives the two following features: a) capability to produce process heat at temperatures $\geq 2000^{\circ}\text{C}$, i.e. achieving maximum fraction of nuclear heating in the high-temperature zone and maximum blanket energy multiplication; and b) breed enough tritium to sustain the DT fuel cycle.

1. High-temperature falling pebble bed blanket (ANL).

The proposed approach¹³ uses a falling bed of ceramic pebbles, e.g., MgO or Al_2O_3 , 10 to 20 mm in diameter as a heat generation blanket. Figure 4 gives a schematic representation of the system. The pebbles would be gravity-fed through the blanket region at about 10 to 30 mm/sec where the temperature is raised by neutron capture. The pebbles then pass through the heat exchanger where they

give up their heat to a gas stream circulating counter-currently and in direct contact with them. The cooled pebbles are finally returned to the reactor via a preheater where they collect some of the lower temperature heat generated in the first wall and tritium-breeding blanket. Tritium breeding is accomplished using Li_2O modules both in front of (~ 6 cm thick) and behind (~ 50 cm thick) the high-temperature ducts. Steam is used as the first wall and front tritium-breeding module coolant while helium is used in the rear tritium-breeding region. Tritium breeding ratios ~ 1.1 are found.

The falling bed/heat exchanger concept avoids the temperature limitations (and temperature drop) associated with a conventional heat exchanger (using a metal barrier between two fluid streams) and due to the ease of continuous replacement of degraded pebbles, it is expected to be less sensitive to material damage than a static structure. No hydrogen chemical process has been coupled to the falling bed/heat exchanger concept, and it could strongly influence material choice and need for an additional isolative heat exchanger. Advantages of this concept are the built in thermal storage for the process in the hopper (but not the blanket), the possibility for on-line replacement of damaged balls, and avoidance of direct process fluid activation.

Major concerns are the capability for managing sodium to the ball flow, the physical integrity of the balls themselves, and any difficulties caused by fines worn from the ball surfaces. Shaping of the gravity-feed ducts in the upper and lower regions of the Tokamak must be carefully considered. While MgO is preferred for its low activation, higher

melting point, and advantages in breeding and energy deposition, MgO is rather sensitive to thermal shock. Other alternate materials that might be considered include SiC or Si_3N_4 (if a N_2 carrier gas could be used).

A mixed-mean ball temperature of 1100°C could probably be achieved. It would, however, be necessary to have a relatively complex, two-compartment flow chamber to keep maximum ball temperature below 1450°C . Working fluid pressures may be limited to about 2 atm which would be disadvantageous for most processes.

A variation¹⁴ on this design for synfuel applications is a flowing microsphere design using small diameter (~ 400 μm) pellets of lithium oxide as moderator, breeder, etc.

2. Li-Na cauldron design (ILL)

The basic idea of a pool boiling lithium blanket module had been proposed by Lee¹⁵ and Pendergrass.¹⁶ For the synfuel application,¹⁷ the Tandem mirror reactor (TMR) is surrounded by a number of individual blanket modules containing a 50-50 binary mixture of lithium and sodium. The pool boiler is shown in Figure 5.

The energy from the neutron-gamma reactions heats the fluid mixture (Li and Na) and causes the heats to preferentially vaporize (the vapor pressures of lithium and sodium at $\sim 930^\circ\text{C}$ are, respectively, 2×10^{-2} atm and 1.5 atm, a difference of 75 times) leaving the lithium behind in the liquid pool to breed tritium. Lithium alone could not be used because unreasonably high vapor velocities would be needed to carry the heat away. The sodium



Fig. 4. Schematic representation of high-temperature blanket system.

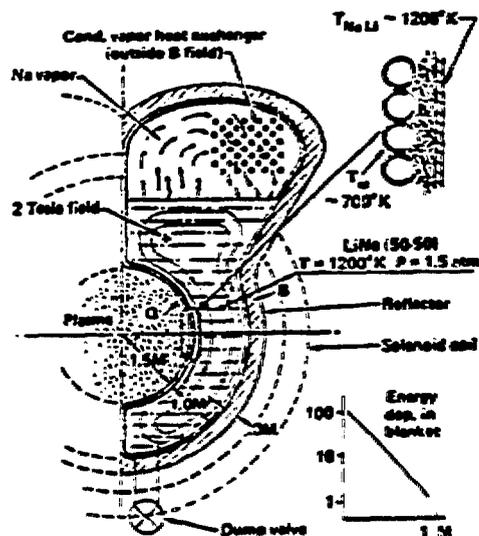


Fig. 5. The cauldron concept-housing a hot fluid in a cool container.

vapor, transporting energy as latent heat, condenses on heat exchanger tubes that are outside of the magnetic field zone, where they are free from MHD effects. Energy is then transferred from the condensing vapor heat exchanger to the sodium which acts as the heat transfer fluid in an intermediate loop carrying the heat outside the nuclear island, and then to other loops feeding the large number of process exchangers within the thermochemical hydrogen production cycle.

Within the cauldron, the Li and Na are miscible and circulation patterns are set up by two effects: a) the exponential decrease in energy deposition in the blanket as a function of radius, and b) the density difference between liquid sodium and lithium. Additional means to drive the circulation may be provided by sparging with helium gas. The effect the magnetic field will have on the overall process is not known. It is an established fact that the magnetic field will act to inhibit turbulent mixing. To what overall extent this will occur in the pool boiling case must be analyzed, assessed, and tested.

The structural container for this hot, 930°C fluid mixture as shown in Figure 5 is held at a temperature of 430 to 480°C with the significant ΔT taken across felt metal between the cool first wall exchanger tubes and a compressively loaded membrane on the hot, 930°C side. The felt metal is a metallic fiber with low thermal conductivity, perhaps 10% that of common metals, and is fitted between these surfaces. This fiber is designed for performance at a thickness of 0.5 cm with about a 40% void fraction of fibers. It is proposed to cool the first wall tubes with an organic coolant. One of the favorable characteristics of this module is its low operating pressure (~1.5 atm) and consequent low stresses. These low stresses, coupled with the low structural temperature, make safety and integrity of containment a major attraction of this design.

As a design concept, the cauldron blanket module offers some interesting features. The module completely encapsulates the liquid metal Li-Na mixture and avoids the problem of pumping large quantities of liquid metals into and out of the fusion blanket areas through neutron fluxes or magnetic fields. This means that one obtains the safety-isolation barrier at the condensing vapor heat exchanger installed in the vapor dome, as shown in Figure 5.

3. Two-temperature-zone steam cooled blanket design (BNL).

The direct heating of steam in high-temperature blanket interiors for H₂ process heat applications places design constraints on both the portion of the blanket that generates the high-temperature steam, as well as the reactor system as a whole. Tritium cannot be bred inside the high-temperature steam cooled region of the blanket modules. Not only would it be impractical to ex-

tract it from the H₂ product (which would have objectionably high tritium levels) but the steam would chemically react with whatever lithium material was used for tritium breeding. Separate tritium breeding modules must be introduced.

The steam coolant must be prevented from leaking to the plasma chamber by some type of vacuum/coolant structural pressure boundary. The top working temperature of the first wall structural metal is in the range of ~300° to 500°C, depending on material, wall thickness, blanket module size, and internal pressure. Because of the temperature limitation, the metal structure must be cooled by a separate coolant circuit (e.g., water) which operates at a considerably lower temperature than the high temperature (~1400°C) steam cooled interior.

Blanket designs of the low-temperature structure/hot interior concept were first proposed in connection with studies on minimum activity blankets using an aluminum structure.¹³ A conceptual synfuel blanket module design is shown in Figure 6. The first wall intercepts the charged particle energy and α radiation and removes its heat. The neutron/gamma energy deposited interior to the blanket, is used to raise the high-temperature steam. A good thermal insulator is required between the hot interior and the cool structure in each blanket module. This material must be compatible with both the steam coolant and the refractory interior. The most promising insulator option is to use the same material as used in the interior, e.g., ZrO₂ or Al₂O₃, but in a low density form perhaps as a fibrous layer. The key questions are the long-term stability of the thermal insulator and integrity of the oxide interior in a steam atmosphere with radiation exposure and possible thermal cycling.

Materials experiments¹³ indicate that ZrO₂ and Al₂O₃ are suitable for long-term service up to ~1500°C (the present experimental limit at BNL) in steam, steam plus hydrogen, and CO₂ process

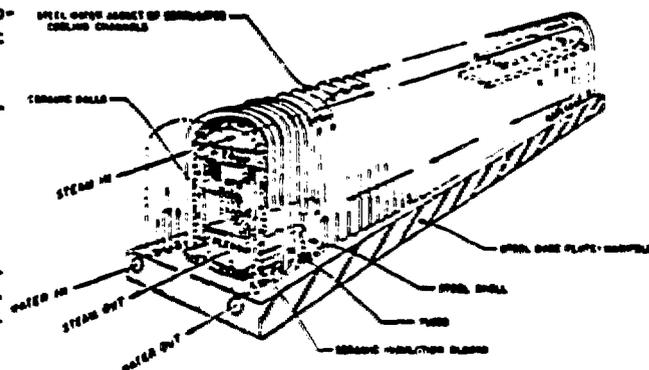


Fig. 6. High Temperature Electrolysis module, 5000 MW reactor.

streams. Experiments with SiC and MgO indicate these materials are restricted to somewhat lower temperatures.

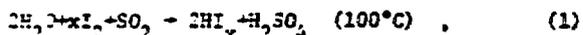
Neutron activation of the blanket interior will occur and it is very important to prevent this activation from variously contaminating the high-temperature steam circuit and the H₂/O₂ product gases from the HTE process. Use of minimum activity materials like MgO, Al₂O₃, SiC, etc., should eliminate this problem. Considerable ²⁴Na activation (15 hour half-life) will be produced in MgO and Al₂O₃ but will decay to negligible levels in a few days. Activation of impurities should be negligible, since the impurity levels in these blanket materials will be in the ppm range.

Status of Current Water Splitting Research¹⁰

1. Thermochemical water-splitting process.

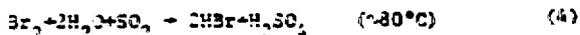
There are a number of thermochemical water-splitting processes under development in the U.S. and abroad. Three major processes are based on sulfuric acid decomposition and their efficiencies are in the range of 40 to 50%. The development for these processes has progressed to the bench-scale level and engineering flow sheets have been designed for all three processes. There are other thermochemical processes under development in this country which are at a somewhat earlier stage of development. These processes involve the use of solids.

The process presently under development at General Atomic Company primarily requires thermal energy and is given by the following equations:



In this thermochemical process hydrogen-iodide and H₂SO₄ are produced in a low-temperature reaction from water, iodine, and SO₂. The resulting sulfuric acid is decomposed in a high-temperature step to the SO₂ for recycle and the hydrogen-iodide is decomposed in a low-temperature step to yield hydrogen and regain iodine for cycle. The process is being demonstrated at the bench-scale level with a hydrogen production rate of 4 l/min. The presently projected efficiency is 47%. The GA sulfur-iodine cycle was selected by Lawrence Livermore Laboratory for their initial fusion symsuel point design study.

The process presently being developed by EURATOM at ISPRA, Italy is a hybrid process requiring thermal and electrical energy. It is described as follows:



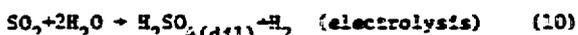
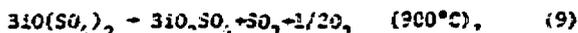
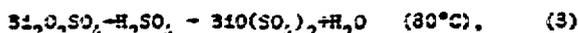
This hybrid process has been demonstrated at a production rate of 4 liters of hydrogen per minute at the bench-scale level. A sulfuric acid decomposition loop at a scale of 1 T H₂SO₄/day is planned for FY 1980. Presently, projected process efficiency is 50%. The high-temperature step is the H₂SO₄ decomposition step which requires a maximum temperature of 870°C. The process also requires a significant amount of electrical energy for the electrolytic decomposition of HBr.

The process presently under development at Westinghouse is another hybrid cycle and is described as follows:



In this hybrid process, hydrogen is produced in a low-temperature electrochemical step where sulfuric acid and hydrogen are produced electrolytically and a high-temperature step where the sulfuric acid is decomposed to regain the SO₂ for the first reaction. The process is being demonstrated at the bench-scale level at a hydrogen production rate of 2 l/min. The currently projected process efficiency is 45%.

The LASL bismuth sulfate process can be described as follows:



This hybrid process is in the laboratory development stage. The solid decomposition step has been demonstrated to be rapid, but the electrolysis step requires additional development. The presently projected efficiency for the process is 50%. The potential advantages are: 1) achieving lower voltages for electrochemical step, 2) minimizing energy required for drying solutions, and 3) minimizing corrosion problems in the dry system vs sulfuric acid cycles. Disadvantages are primarily those inherent in handling and transferring heat to solids. This example represents a family of potential solid-sulfate processes using other metals.

An inhibiting influence in the search for effective cycles has been the absence of a high-temperature heat source that could be matched to the chemistry. As the GA, Westinghouse, and ISPRA cycles require a thermal decomposition of SO₂ and SO₂ and oxygen, efficient decomposition calls for a process temperature of 320° to 330°C which is 100 to 300 degrees higher than can be obtained in the secondary loop of a high-temperature gas-cooled

reactor. The developing interest of the fusion program in synthetic fuels gives an impetus to the search for simpler, more effective cycles, as well as placing the current SO₂-SO₃ cycles on a sounder footing.

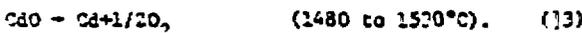
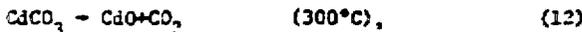
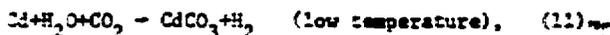
With the current work in thermochemical cycles, the materials problems are mainly concerned with sulfuric acid evaporation and decomposition. Sulfuric acid is produced at 50 wt % and needs to be concentrated at 98 wt % to avoid recycle of large quantities of water. Boiling H₂SO₄ solutions are highly corrosive and laboratory experiments have used quartz for containment. Current work involves SiC and other materials at temperatures from 230° to 530°C.

The problem with sulfuric acid decomposition is one of SO₂ contact with a hot heat transfer surface. Here, an extreme materials research program is being conducted. Avoidance of the problem is direct contact heat exchange of the decomposing SO₂ with air, say, in a ceramic tube may be a possible solution at temperatures in the range of 730° to 1030°C.

Other problems at lower temperature involves containment of acidic solutions (HI, HBr, and H₂SO₄) at moderate temperatures of 30° to 230°C. Here plastics may be of use. Solid sulfate or other solid systems may avoid certain of these problems but have the possible disadvantage of having to handle solids at high temperatures.

Although current engineering materials could not cope with 1230°C in the type of systems under discussion, it is within the realm of credibility to believe that materials and techniques can be developed to function reliably at 1230°C.

The principal reason for research on higher temperature (~1230°C) cycles is the potentially higher efficiency attainable. An example of such a cycle has been proposed by LASL as follows:



This process has not been demonstrated in the laboratory, although the second two steps are known to proceed at reasonable rates. The first step may require catalysis to proceed at a reasonable rate. The ideal efficiency is 78%.

The design target for the fusion reactor blanket would be to deliver 1530°C heat at the exit of an intermediate heat exchanger. This, of course, implies that the maximum temperature for the acceptance of heat, by the water splitting cycle, will have to be at least 100 degrees lower to provide adequate cooling to the blanket without dissipating excessive energy in circulating the coolant.

2. High-temperature electrolysis (HTE) process.

The electrochemical decomposition of water into hydrogen and oxygen is an endothermic reaction requiring both heat and electricity. The efficiency of production of electricity from fusion reactor heat is limited by the Carnot relationship and various irreversibilities in the power cycle. With conventional steam power cycles, electrical generation efficiency will be on the order of 40%. Since the heat input component for water decomposition is used directly at essentially 100% efficiency, there is a definite advantage to make the ratio of the direct heat input to the electrical energy input as large as possible. At a temperature, T, the input thermal energy equals TΔS, where ΔS is the entropy change for the reaction. The electrical energy input equals the Gibb's free energy change, ΔF, for the reaction, and the sum of these energy changes equals the reaction enthalpy, ΔH.

The energy splits are shown, as a function of temperature, in Figure 7.

As temperature increases, the reaction enthalpy remains virtually constant. The Gibb's free energy or electrical energy input, however, decreases with increasing temperature and the thermal energy input, TΔS, increases. The ratio of thermal energy (TΔS) to electrical energy (ΔF) increases with electrolysis temperature; this results in higher process efficiency so that more hydrogen production can be generated for a given fusion energy input.

The heat input, TΔS, absorbed by the HTE cells during electrolysis is supplied from the sensible heat content of the process streams. For practical electrolyzer designs, the steam/H₂ stream will cool by 100° to 200°C as it proceeds through the electrolyzer.

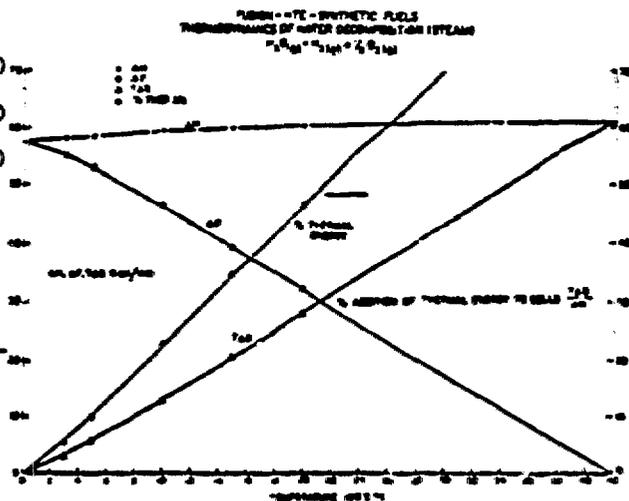


Fig. 7.

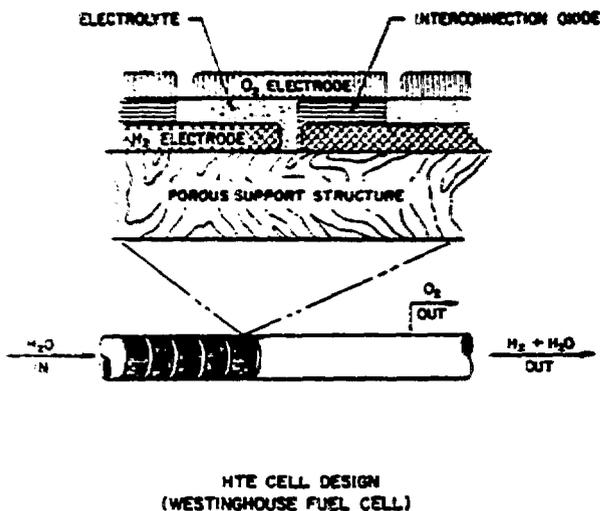


Fig. 3.

A schematic of the Westinghouse fuel cell is shown in Figure 3. This design also serves as the basis for the high-temperature electrolyzer since an electrolyzer is a fuel cell in reverse. High-temperature electrolyzers use arrays of tubes of relatively small diameter (~1 cm), thick-walled porous ceramic (e.g., stabilized ZrO_2) on which a succession of thin electrode layers of suitably-doped ceramics are deposited. The H_2 and O_2 ceramic electrodes are separated by a thin (a few mils) electrolyte layer of yttria-stabilized ZrO_2 . Electrodes are electrically connected in series along each tube to minimize IR losses. A large number ($\sim 10^6$) of electrolyzer tubes are then connected in parallel in a large pressure vessel. Typically steam pressures in a high-temperature electrolyzer are on the order of 10 to 20 atm.

Major developments in high-temperature solid-oxide electrochemical cells have resulted from studies done at Westinghouse Research and Development Laboratories. There is a distinct advantage in the Westinghouse cell approach as the electrolyte thickness can be reduced significantly. In earlier designs, the electrolyte acted as the load bearing member which limited its thickness. The cell has the additional advantage of being adaptable to mass production, where each component of the cell is laid down successively in a manner somewhat similar to the production of integrated semiconductor circuits.

Brown-Boveri in Germany has tested solid-oxide fuel cells for extended periods of time. Operation of single cells has been for 50,000 hours and lifetimes of more than 10 years are expected. This cell consists of nickel anodes, lanthanum-nickel oxide cathodes and a 1.2-mm thick electrolyte. Westinghouse has operated a multi-cell (15) stack at $1000^\circ C$ for an extended period of time.

The work conducted with fuel cells has shown that high-temperature solid-oxide electrochemical cells can be operated at $1000^\circ C$. The major limitation with these cells has been the difficulty with the connection between cells. However, recent developments have made available mixed oxides with all the required properties for the interconnectors.

Reactor Studies

1. Tandem mirror reactor/hydrogen production coupling (LLL/UW)¹⁷

The coupling of a Tandem Mirror Fusion Reactor (TMF) to one of three thermochemical cycles is being studied at LLL. The central-cell solenoid contains modular blanket sections that produce both high-temperature (i.e., $950^\circ C$) process heat and the required tritium to run the DT reactor. This central-cell zone is about 260 meters in length and the system is designed for ~ 5000 MW(th) output with a first wall neutron wall loading of 2.0 MW/m².

Two tandem mirror blanket concepts are being explored: (1) a lithium-sodium liquid-metal pool boiler, and (2) a lithium-oxide microsphere moving bed. Three thermochemical cycles ([1] General Atomic's (GA) sulfur-iodine process, [2] Westinghouse's sulfur cycle, and [3] The Commission of the European Communities Joint Research Center at ISPRA ISPRA, Italy, Mark 13-V2 process) are being examined to reveal their specific advantages or disadvantages in interfacing to the Tandem Mirror Reactor. The GA sulfur-iodine cycle was selected for the initial point design study. It might be noted that the GA cycle is also being studied at GA with a three-zone blanket concept, where the high-temperature zone is placed between two solid breeder tritium breeding zones.²¹

The blanket concept supplying the heat for the process uses the pool-boiling configuration surrounding the cylindrical plasma chamber. The pool boiler contains a binary mixture of lithium and sodium liquid metals--the lithium atoms to provide tritium breeding nuclei and large cross sections for generating heat by neutron scattering and the sodium atoms to provide a high-heat capacity vapor carrying this heat to the tubes of a condensing vapor heat exchanger. The tritium will be generated within the lithium-sodium mixture and the concentration will be allowed to build up to a 1-kg inventory or ~ 10 ppm on a molar basis or about 1000 Ci/m³.

In the GA sulfur-iodine process, the dominant (i.e., 90%) energy requirement is for the H_2SO_4 concentration, boiling and decomposition steps. For this version of the process (released last year) ~ 564 kJ of thermal energy per unit g-mole of hydrogen product manufactured is required for this step. Of the 564 kJ/g-mole H_2 , about 1/3 is for H_2SO_4 boiling, 1/3 for H_2SO_4 concentration, and 1/3 for decomposition ($SO_3 = SO_2 + 1/2 O_2$).

In the GA concept driven by High-Temperature Gas Reactor (HTGR), helium is used to couple the

HTGR with the thermochemical process steam heaters. In the Li-Na pool boiler concept, sodium is used inside the condensing vapor heat exchanger and this sodium supplies the 564 kJ for the H_2SO_4 step and generates process steam to supply the remaining 44 kJ for the rest of the process thermal load, plus some 112 kJ for pumps, compressors, and other parasitic hardware. Process heat requirements were broken down as follows: 28% of the heat is supplied at 940°C and is returned at 480°C, 37% is supplied at 670°C and returned at 260°C, and 37% is supplied at 950°C and returned at 480°C. These energy splits are provided from heat from the blanket-pool boiler condensing-vapor exchanger, from the direct converter and from the first wall cooling tubes. For the thermochemical process, in general, a close match between the heat requirements and blanket output is required.

The design temperature for the hot liquid sodium at the cauldron blanket outlet was 980°C. Sodium is double-piped a few hundred meters to separate containment building structure housing the SO_3 decomposer which is designed to operate at 930°C. Heat to the decomposer is some 65°C hotter than in GA's design. Potentially substantial increases in thermal efficiency of H_2 -production and the elimination of previous metal catalysts in this unit can be achieved with higher temperature.

A SO_3 decomposer design operating at higher temperature and without a catalyst was examined. The unit is basically a shell- and tube-heat exchanger using INCOLOY 900H tubes, 3 mm thick with an aluminized coating on the SO_3 side to reduce possible corrosion to acceptable levels. With regard to plant siting of the process units, initial pressure drop calculations indicate that economic and performance restrictions on piping sodium long distances into the chemical process plant are prohibitive. The SO_3 decomposer is sited close-coupled to the nuclear island in an adjacent, separate building. The sodium loop coupling between the cauldron pool-boiler condensing-vapor exchanger and the heat exchanger in the SO_3 decomposer provides sufficient safety isolation through two barriers--one in the cauldron and one in the decomposer.

Based on thermal energy input for each g-mole of hydrogen produced initial studies indicate that the efficiency to produce hydrogen is in the mid-forty percent range.

2. HYFIRE: A Tokamak--high-temperature electrolysis system (SNL).²²

Brookhaven National Laboratory is carrying out a comprehensive scoping design study called HYFIRE of a commercial fusion Tokamak reactor, high-temperature electrolysis system. The purpose of the study is to provide the basis for a point reference system and to further assess the commercial potential of fusion via a Tokamak reactor for the production of synthetic fuel. The HYFIRE design is based on the Tokamak power reactor, STARFIRE,²³

the primary difference residing in the type of blanket between the two reactors. The study is placing particular emphasis on the adaptability of a Tokamak power reactor to a synfuel application.

Figure 9 shows a simplified flow sheet for a HTE/fusion synthetic fuel plant. All of the fusion energy goes into making hydrogen. The HYFIRE blanket must perform three functions: a) provide high-temperature (~1400°C) process steam at moderate pressures (in the range of 10 to 30 atm) to the high-temperature electrolysis (HTE) units; b) provide high-temperature (~700° to 800°C) heat to a thermal power cycle for generation of electricity to the HTE units; and c) breed enough tritium to sustain the DT fuel cycle. The dual requirements, generation of high-temperature process steam for the HTE's and high-temperature heat for the thermal power cycle, differentiates the HYFIRE and STARFIRE blanket systems.

Setting the requirement that the global breeding ratio equal 1.1 for HYFIRE places a premium on space, i.e., it will probably be necessary to breed tritium in regions of the process steam blanket, e.g., in front of or in back of the steam modules. Tritium from the power cycle part of the blanket must make up the tritium deficit.

The two-temperature zone blanket approach as already discussed, is mandatory for the process steam portion of the energy supply. The modules will have relatively cool shells (~300°C) with thermal insulation between them and the high-temperature (~1400°C) interior. The two-temperature design concept is also carried over for the power cycle modules.

Three blanket options are under study for HYFIRE. Each option will have a HTE steam module region and a power cycle module region with tritium breeding in each region, breeding to be

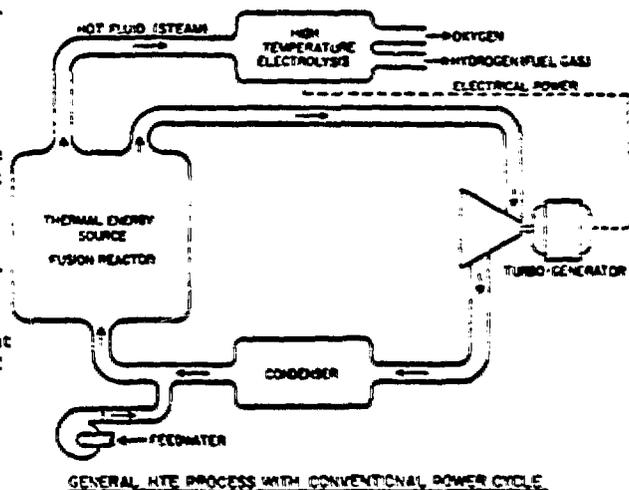


Fig. 9.

accomplished with solid breeders. Tritium will be released to He purge streams, and not into the main He circuit. Module arrangement along toroidal field lines, as in STARFIRE, is preferred, since this minimizes differences in maintenance procedures between HYFIRE and STARFIRE. The inboard blanket-shield region will probably be used for HTE steam modules, with a thin secondary zone behind for tritium breeding.

Two HTE process options have been identified during the scoping design study. In the first case, high fractional conversion of steam to hydrogen (~90% H₂ at the exit of the last HTE) is considered. Transport of thermal energy to the electrolyzers is either through a direct or indirect process. In the direct process, steam/H₂ are recycled through the blanket to the electrolyzers in series. In the indirect process electrolyzers are heated in the entrance section by recycled steam from the blanket; the electrolyzers being in series. A variant on the indirect process is the parallel indirect process. Heat and electricity are simultaneously input to the electrolyzers, the thermal energy being supplied from additional tubes carrying coolant, e.g., steam, from the blanket. Electrolyzers are in parallel.

Low fractional conversion (~10% H₂ at the exit of the HTE) has a number of attractive features. Most important is the fact that a higher percentage of energy is supplied as thermal energy to decompose water than at the higher conversion. In the direct process, process steam from the blanket passes through one or two electrolyzers in series. The indirect and parallel indirect processes are similar to those in high fractional conversion. In all three cases H₂ separation is by one of three low-temperature separation methods: (a) compression/condensation, e.g., the H₂ product stream is compressed; (b) membrane separation, e.g., H₂ separation from water is by membrane diffusion; and (c) expansion/condensation, e.g., steam/H₂ mixture from the HTE units is expanded through a turbine accompanied by a temperature drop which is followed by a condensation process to condense out the remaining water. For reasons of ducting and connections to the 24-blanket sectors of HYFIRE, the number of electrolyzers are fixed at 12, one for each two-blanket sectors, and process parameters are adjusted to reflect the fixed numbers.

Depending on whether steam is directly transported to the electrolyzer or an intermediate heat exchanger is introduced between the electrolyzer and blanket, or whether only a small fraction (10%) of the steam is converted to hydrogen in a single pass and extracted or a string of electrolyzers are placed in series, coupling between the blanket, electrolyzer and power cycle can be quite different. Each case must be analyzed separately.

Preliminary studies and calculations indicate that gross power cycle efficiency in the 40 to 45% range appear achievable in HYFIRE using STARFIRE

power recirculating parameters and He power requirements. Corresponding H₂ production efficiency (total fusion energy to the chemical energy of the hydrogen produced) is in the 50 to 55% range with the potential of reaching 60%. A 4000 MW(th) fusion reactor will supply energy to produce ~1100 MT/day of hydrogen.

Other Studies

There have been other studies on fusion/syn-fuels several of which we cite here. In contrast to the studies just discussed which use pure fusion reactors with very high-temperature blankets to produce hydrogen, the approach here²⁴ is to use a fusion-fission hybrid reactor to produce substitute natural gas from a low-temperature catalytic coal gasification process and simultaneously to breed fissile fuel.

Nitrogen fixation with fusion heat²⁵ has been investigated by GA. The Wisconsin pebble-bed process for fixing nitrogen involves heating air to about 2000°C, followed by a rapid quench to avoid decomposition of the nitric oxide formed. Fusion would make such conditions available in a ceramic oxide blanket.

High-temperature steam electrolyzed in a high-temperature electrolyzer (HTE) and/or converted in a high-temperature steam gasifier (HTSG) with coal has been considered by Steinberg.²⁶ The HTSG would eliminate the need for oxygen and excess coal to provide the exothermic heat of reaction for the water-gas reaction. Fusion reactors, in combination with HTE and HTSG, would convert coal to synthetic natural gas (SNG) and liquid gasoline, the efficiency of utilization of coal could be improved from 2 to 3 times for SNG and 2 to 2.5 times for liquid fuel, compared with coal-only processes.

Summary and Conclusions

A large market for fusion energy can be the production of synthetic portable fuels. The unique ability of fusion neutron/gamma energy to generate very high process temperatures in two-temperature zone blankets 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.

Of the many potential processes for hydrogen production, high-temperature electrolysis (HTE) of steam appears to be a more advanced and promising method. The overall efficiency, fusion-to-hydrogen chemical energy, is projected to be in the 50 to 65% range depending on the process conditions and type of power cycle. High-temperature electrolysis cells have operated at high temperature (~1000°C) for long periods of time. The process has been demonstrated on a small scale and is scalable. Large-scale HTE technology (and possibly, thermochemical) can probably be developed by the time that the first commercial fusion reactors would be operating.

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