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FUSION REACTORS FOR HYDROGEN PRODUCTION
VIA ELECTROLYSIS*

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J.A. Fillo, J.R. Powell, and M. Steinberg
Brookhaven National Laboratory
Upton, New York 11973

MASTER

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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.

INTRODUCTION

The production of synthetic fuels is an extremely promising and important application of fusion energy. Commercial fusion reactors are expected to begin operation by the early decades of the next century; at that point, oil and gas, which now account for ~60% of the primary energy supply for the United States will not be an important source of energy. The critical need will then be for portable liquid and gaseous fuels which serve a myriad of uses--transport, space heating, process heat, chemical production, etc.. There appears to be no shortage of inexhaustible energy technologies that can potentially meet U.S. electrical needs, including fusion, fission, solar photovoltaic, solar thermal, and hot rock geothermal, but very limited options for supplying portable fuels. Coal conversion is expected to be costly, and in the long run, may be restricted by environmental and supply factors. Inevitably, there may be a shift to an economy where hydrogen and hydrogen-based fuels, which will be derived from inexhaustible energy sources, play the major role.

FUSION-SYNFUEL PROCESSES

Hydrogen can be produced from water by conventional low temperature electrolysis methods, but this route, which would use electricity from the inexhaustible energy sources, tends to be inefficient and expensive. The unique nature of fusion energy makes possible alternate routes to synthetic fuels that are more efficient and cheaper than conventional low temperature electrolysis. In the deuterium-tritium (DT) fuel cycle, most (~80%) of the fusion reaction energy is released as very high energy (14 MeV) neutrons, which penetrate deeply into the surrounding blanket. This energy can heat interior blanket modules to very high temperatures, while retaining a relatively cool first-wall

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structure around the hot interior. Depending on blanket design, approximately 50 to 70% of the fusion energy that is released can be extracted as high temperature heat from the hot thermally insulated interior. This heat can be used in a variety of synthetic fuel production processes, based on thermal or a combination of thermal and electric reactions that are potentially cheaper and more efficient than low temperature electrolysis. The temperature level available depends on choice of material; using ceramic or refractory blanket interiors, temperatures of ~ 2000 C appear achievable with inert gas coolants. Somewhat lower temperatures in the range of ~ 1200 to ~ 1500 C, appear necessary if chemically reactive coolant such as CO_2 or steam are used, based on materials compatibility experiments carried out. In addition to high temperature thermal processes uniquely suited to fusion, there are radiolytically based processes that can directly transform neutron and gamma energy into chemical energy for fuels production.

Table 1 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.

FUSION--HIGH-TEMPERATURE ELECTROLYSIS

Of the various processes for producing hydrogen from fusion which have been examined, [1,2] the most promising appears to be the high-temperature electrolysis [3] (HTE) of steam. In low temperature electrolysis of liquid water, virtually all of the energy for decomposition is put in as electricity, and

TABLE 1
FUSION SYN-FUEL PROCESSES

PROCESS TYPE	EXAMPLE	PROCESS COOLANT	PROCESS TEMPERATURE °C	MAXIMUM TRITIUM BREEDING RATIO	POTENTIAL PROCESS EFFICIENCY, FUSION TO HYDROGEN (HHV)	COMMENTS
1. CONVENTIONAL LOW TEMPERATURE ELECTROLYSIS (LTE)						
A) STANDARD POWER CYCLE	STANDARD STEAM CYCLE	HELIUM	~ 500	~ 1.5	~ 35	SPE ELECTROLYZERS HAVE $\sim 90\%$ EFFICIENCY
B) HIGH EFFICIENCY POWER CYCLE	FAST CYCLE	STEAM	~ 900	~ 1.0	~ 55	FAST CYCLE USES GAS TURBINE TECHNOLOGY
2. HIGH TEMPERATURE ELECTROLYSIS (HTE)	$\text{H}_2\text{O} + \text{ELEC} \xrightarrow{\text{HEAT}}$ $\text{H}_2 + \frac{1}{2} \text{O}_2$	STEAM	~ 1200	~ 1.5	~ 50 to 70%	ELECTROLYZERS TESTED ON SMALL SCALE - PILOT PLANT IS NEXT STEP
3. PURE THERMOCHEMICAL	A) $\text{FeO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{Fe}_2\text{O}_3$ B) $\frac{1}{2} \text{Fe}_2\text{O}_3 + \text{HEAT} \rightarrow \text{FeO} + \frac{1}{2} \text{O}_2$	HELIUM	~ 1700	~ 0.7	$\sim 50\%$ [OF THE HIGH TEMPERATURE BLANKET HEAT]	DIFFICULT MATERIALS PROBLEMS
4. THERMAL DECOMPOSITION	A) $\text{CO}_2 + \text{HEAT} \rightarrow \text{CO} + \frac{1}{2} \text{O}_2$ B) $\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$	CO_2	~ 2500	~ 0.7	$\sim 50\%$ [OF THE HIGH TEMPERATURE BLANKET HEAT]	RECOMBINATION OF CO MAY DESTROY PRODUCT
5. RADIOLYSIS	A) $\text{CO}_2 + \text{h}\nu \rightarrow \text{CO} + \frac{1}{2} \text{O}_2$ B) $\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$	CO_2	~ 500	~ 0.5	$\sim 10\%$	DEMONSTRATED - DIFFICULT TO EFFECTIVELY DEPOSIT RADIATION ENERGY IN CO_2 GAS

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_2) on which a succession of thin electrode layers of suitably doped ceramics have been deposited. The H_2 and O_2 ceramic electrodes are separated by a thin (several mils) electrolyte layer of yttria-stabilized ZrO_2 . Electrodes are electrically connected in series along each tube to minimize I^2R 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 synfuels program at Brookhaven National Laboratory (BNL) is investigating HTE technology for fusion reactors [3,4]. Analytical studies of synfuel 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 1 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_2 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, (Fig. 2) 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

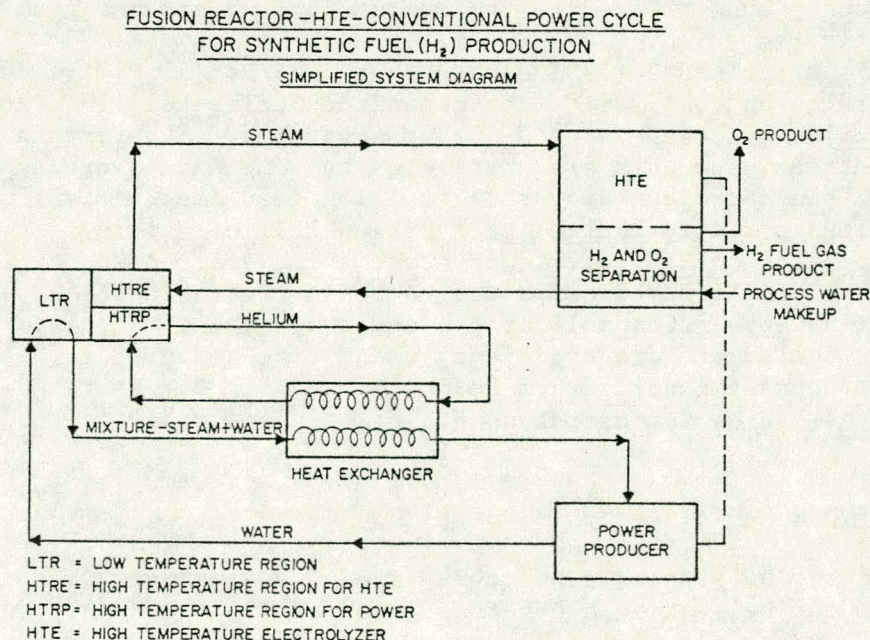


Figure 1

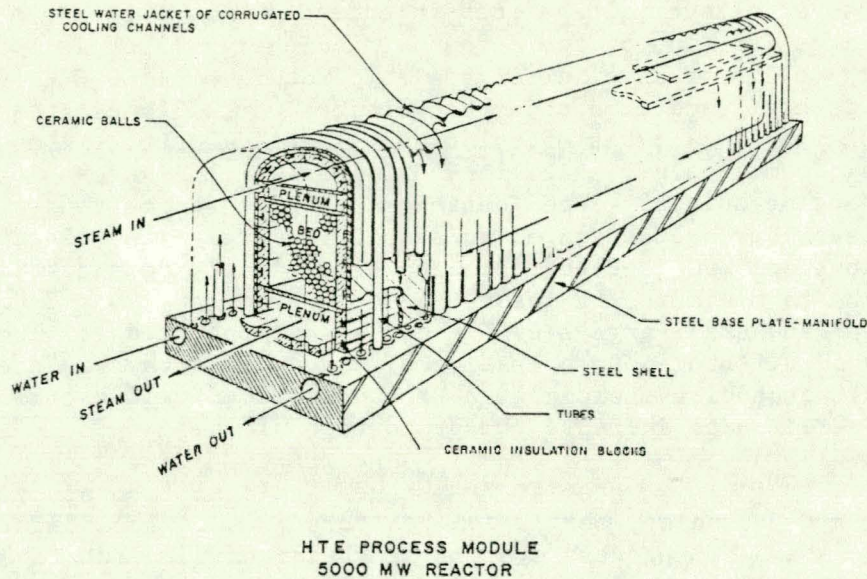


Figure 2

heated by neutron and gamma energy and absorb ~50 to 60% of the total fusion energy. The steam or CO₂ 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 [5] 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 streams. Experiments with SiC and MgO indicate these materials are restricted to somewhat lower temperatures.

Figure 3 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 synfuel 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. HTE process technology has been successfully demonstrated on a relatively small scale and can be demonstrated on a pilot-plant scale in the next few years.

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 CO₂), 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.

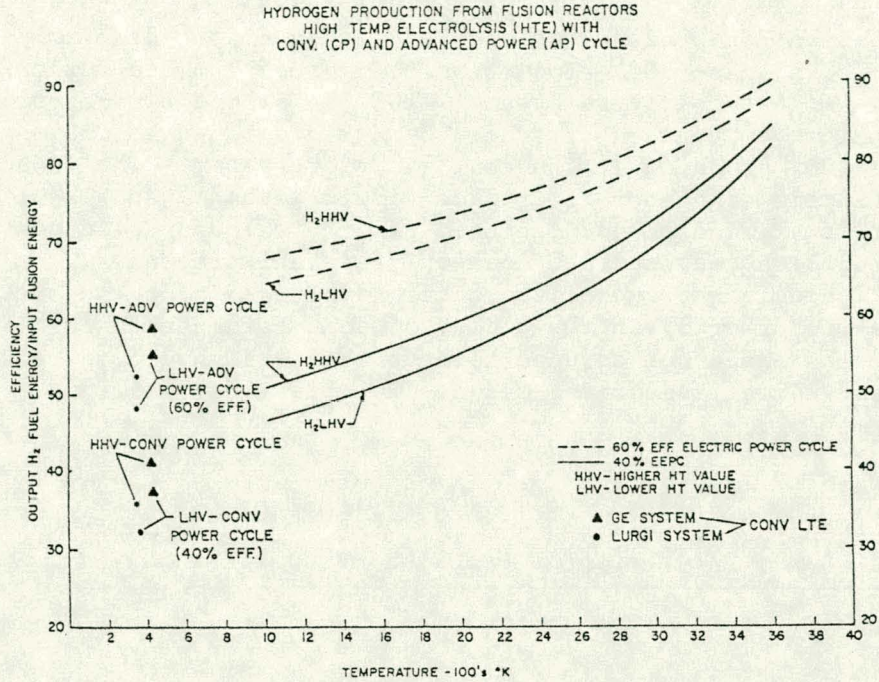
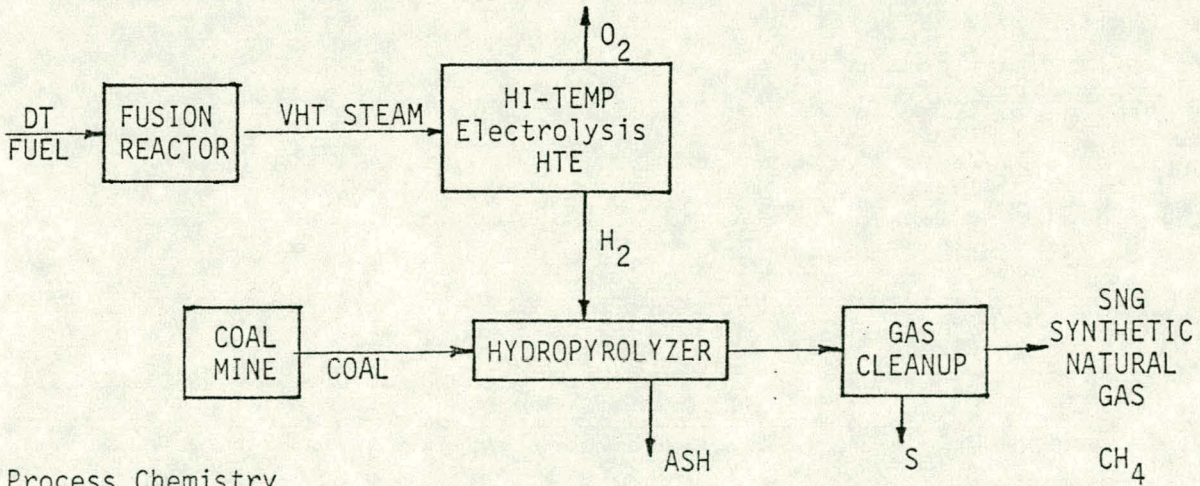


Figure 3

FUSION REACTOR FOR COAL GASIFICATION
SYNTHETIC NATURAL GAS (SNG) PRODUCTION



Process Chemistry

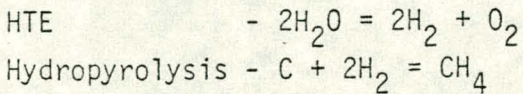


Figure 4

With reference to Fig. 4 and a fusion/coal gasification scenario, hydrogen, produced by a fusion/HTE process, is coupled with a coal/hydrolysis process for synthetic natural gas (SNG) production. Figure 5 shows a fusion/coal liquefaction system. High temperature steam (~ 1000 C) from the reactor is fed to the gasifier while the hydrogen, produced by HTE, is added to that hydrogen and carbon monoxide (CO) produced in the coal/gasifier system. The CO and H_2 is sent to the catalytic convertor to produce liquid methanol and gasoline. The shift convertor is eliminated and the acid gas removal operation considerably reduced, compared with conventional coal-only synfuel processes.

As currently envisaged one of the chief advantages of these systems is the reduction (by a factor of 3) in the amount of coal feed needed for SNG production, since the coal need not be used to meet the total hydrogen requirements. This would conserve coal resources, reduce CO_2 emissions, and reduce coal feed costs.

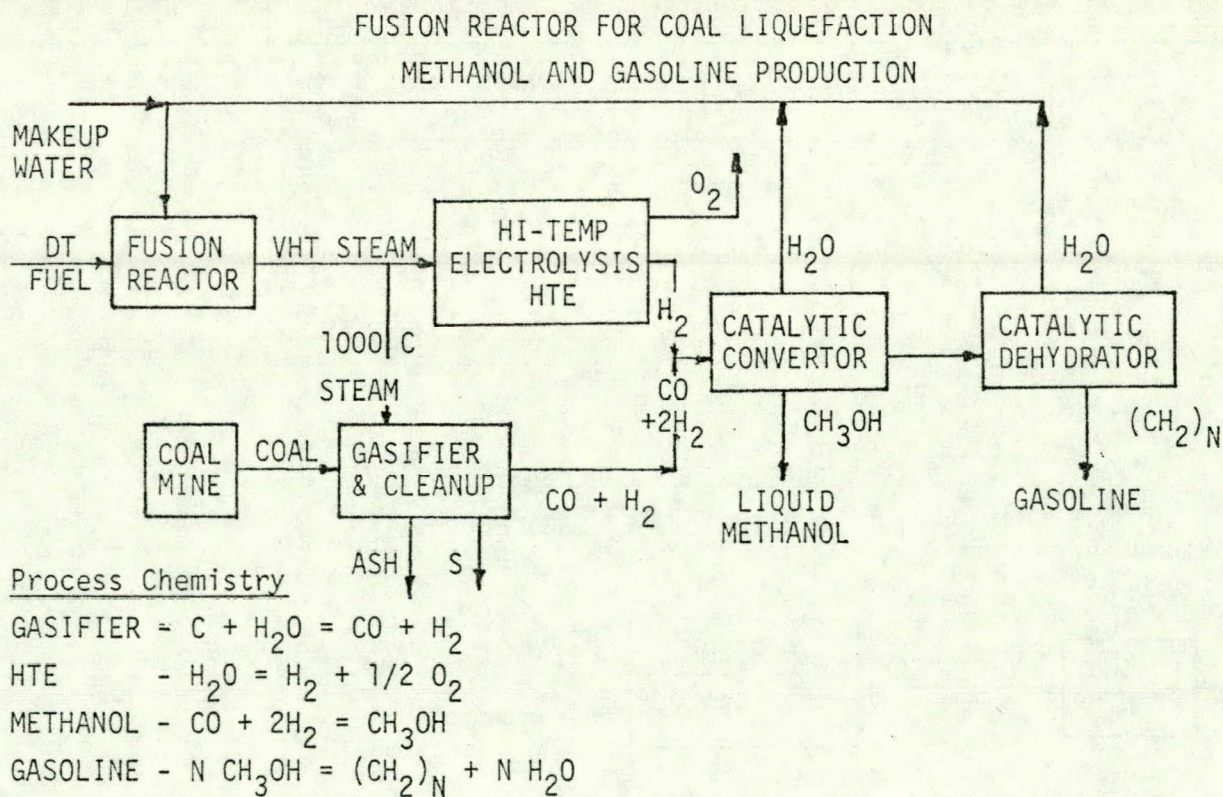


Figure 5

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