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FUSION ENERGY FOR HYDROGEN PRODUCTION*

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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 ~40-60% and hydrogen production efficiencies by high temperature electrolysis of ~50-70% are projected for fusion reactors using high temperature blankets.

Introduction

While emphasis has been placed on the virtually limitless supply of deuterium fuel for the fusion process and the subsequent production of electrical energy, the unique properties of fusion itself may be significant to assure an adequate supply of chemical fuels produced at high efficiency. To be more precise in the application of fusion energy for synthetic fuel production, the greatest interest lies in the production of hydrogen or carbon monoxide, both fundamental building blocks for more convenient fuels and other chemicals [1].

The BNL conceptual design [2] coupling fusion with high temperature electrolysis (HTE) for the production of hydrogen serves to identify the problems and research areas as well as potential pay-off from such a system. The electrochemical decomposition of water is an endothermic reaction requiring both electrical and thermal energy. The ratio of these respective energies decreases with increase in temperature, thereby, decreasing the electrical energy requirements. Steam is transported from the fusion blanket system and distributed to the electrolyzers in ceramic-lined ducts. The balance of energy supplied to the electrolytic cells is generated by converting the remaining fraction of fusion energy to electricity in a standard thermal cycle. A simplified process flow sheet, which couples the three basic elements of the system for the production of hydrogen and oxygen, is shown in Figure 1.

The key elements in the design of the system include: i) the fusion blanket in which the kinetic energy of the high energy neutrons is converted to useful high temperature process heat, for example, steam ~1500°C; ii) the high temperature electrolyzers in which the steam is decomposed to hydrogen and oxygen; and iii) the overall process design--the coupling of the fusion and electrolyzer systems as well as power conversion system. Each of these elements are discussed in the body of the paper, with a brief assessment of economics and conclusions reached from the scoping study and conceptual design efforts. More details are given in Ref. [2].

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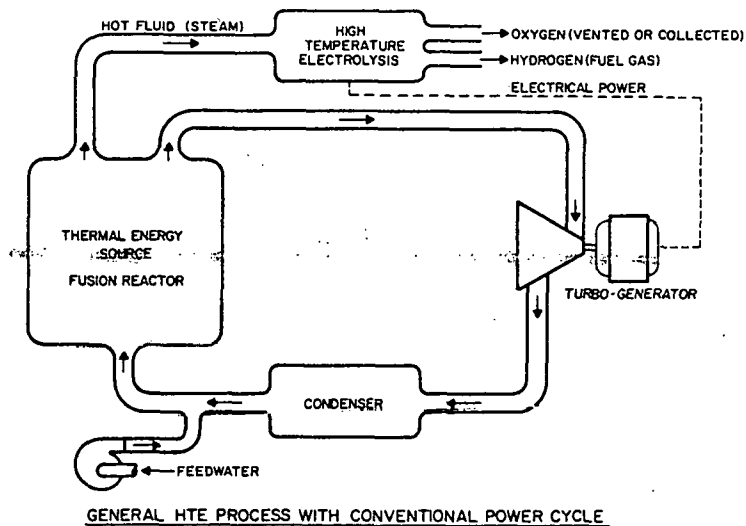


Figure 1

DESIGN OF BLANKETS

The blanket requirements are such that it must be able (a) to convert neutron energy to process heat (steam) for electrolysis; (b) to convert neutron energy to thermal energy for electrical needs; and (c) to breed tritium. All of these functions need not be carried out in the same blanket assembly. For example, the latter two functions may be performed by assigning a fraction of the total number of blanket modules for these tasks although as we shall see, it may be possible to breed tritium on the surface of the process heat modules.

The high energy neutrons from DT fusion reactions can penetrate very deeply into materials before their kinetic energy is transformed to heat. This deep penetration of the primary neutrons makes two temperature region blankets feasible. In this concept, a relatively low temperature metallic structure is the vacuum/coolant pressure boundary, while the interior of the blanket, which is a simple packed bed of non-structural material, small diameter (~ 1 cm) rods or balls, operates at very high temperatures $\sim 1500^{\circ}\text{C}$. Separate coolant circuits are required for the two temperature regions, as well as a thermal insulator between them. Only the oxide refractories (e.g., Al_2O_3 , etc.) and perhaps some carbides (e.g., SiC), would be compatible with steam or CO_2 coolant. The low peak power densities ($\sim 10 \text{ MW/m}^3$) and the large surface area in the blanket should result in relatively low temperature differences ($\sim 100^{\circ}\text{C}$) between the coolant and the packed bed.

A promising fabrication approach to the design of the process heat modules is shown in Figure 2. Several low temperature shells, typically 30 cm in width and several meters in length, are placed side by side on a strong structural backing plate. Modules are inserted and removed through small access ports in the plasma chamber.

In high temperature blankets for electric production, tritium is bred in a solid lithium compound (e.g., LiAlO_2) in the high temperature interior. The tritium diffuses into the inert gas coolant, e.g., He, from which it is recovered. With steam coolant, however, this mode of tritium breeding is not feasible, since the tritium cannot be readily extracted from

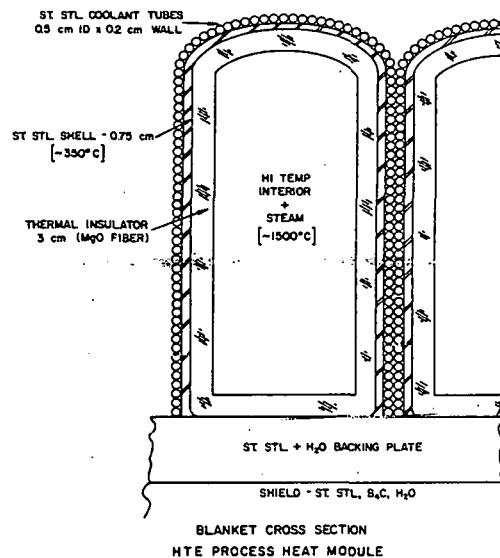


Figure 2

the steam circuit. Instead, a solid lithium compound can be placed on the outer surfaces of the module. The bred tritium will then diffuse to the vacuum chamber and be recovered from the plasma exhaust.

Breeding ratios of ~ 0.4 to ~ 0.6 can be achieved with MgO or Al_2O_3 interiors, but breeding ratios of ~ 1.0 require BeO interiors. This implies that two types of blanket modules may be required to satisfy tritium breeding requirements--the steam cooled type just described, as well as blanket modules which have a high tritium breeding ratio. These could be inert gas cooled, high temperature solid breeding blankets, capable of achieving breeding ratios of ~ 1.3 to 1.8 with either Pb or Be neutron multiplier, respectively. The fabrication approach to the design of the electric production modules is essentially the same as the process heat modules. Insertion and/or removal is through small access ports in the plasma chamber. Design efforts are currently underway to better define in more detail a blanket for either function.

No special operations and/or maintenance problems are foreseen for the HTE and electric generation modules. The steam circuit will probably be strongly activated by Na^{24} (15 hour half-life) released from the hot interior of the modules, but this will decay to negligible levels in a few days. Other relatively long-lived activations from blanket impurities and/or crud from low temperature piping systems will be present but should present fewer problems than now faced in LWR's.

The key issues for the blanket appear to be primarily related to materials. The blanket module structure has to maintain vacuum integrity in the radiation/thermal cycling environment for several years. This problem is common to all fusion reactor blankets and no new class of problems appears to be generated by fusion reactors using HTE process. More specialized material problems related to the HTE applications appear, however. These have to do with the integrity of the oxide interior in a steam/hydrogen atmosphere with radiation exposure and thermal cycling as well as the long-term stability of the thermal insulator.

DESIGN OF HIGH TEMPERATURE ELECTROLYZERS

In essence the design of a high temperature electrolyzer is a fuel cell run in reverse. At the cathode water is reduced to oxygen ions and hydrogen which mixes with the steam. The oxygen ions move across the electrolyte, via a vacancy migration mechanism, and react at the anode to form oxygen.

The high temperature solid oxide electrolyzer is supported on a porous zirconia tube as shown in Figure 3. The length of each cell depends on the resistivities of the electrodes and interconnection materials but is approximately 1 cm on the 1 cm diameter tubes. The cell stacks which form tubes are placed in pressure vessels. The thickness of the electrolyte can be reduced to about 10 μm with the supported electrolyte constructed in this manner. The electrolyte must be as thin as practical in order to reduce losses or overvoltages. At temperatures close to 1650^oK a thickness of \sim 1.0 mm is acceptable whereas at 1000^oK a 10 μ electrolyte layer would be required. The materials of construction are, for example, $\text{ZrO}_2 - \text{Y}_2\text{O}_3$ electrolyte, doped In_2O_3 anode, a perovskite for high temperatures and nickel for low temperature cathodes, doped LaCrO_3 for the interconnection materials and conducting sides.

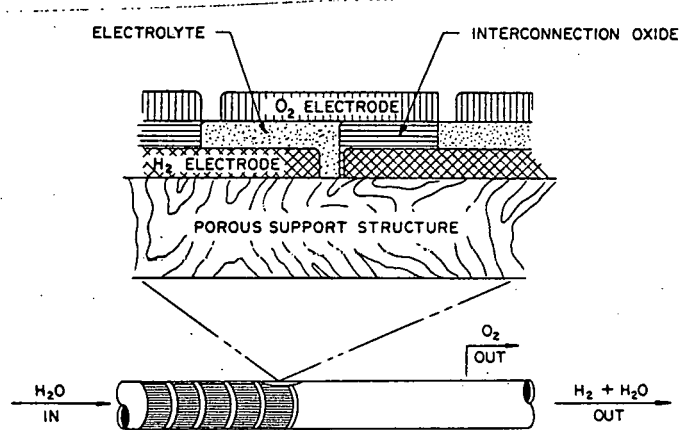


Figure 3

HTE CELL DESIGN (WESTINGHOUSE FUEL CELL)

There are a large number of variables which must be considered in the optimization of solid oxide electrolytes. These include the diameter and length of the electrolyte support tubes, the current density, the flow rate of the steam, etc.

While the R & D requirements are yet to be fully defined, the issues are centered about: 1) strength of materials as it relates to the porous support tube, temperature limits of the oxides and metals, pore size, sintering and mass transport effects; 2) electrochemical properties as they relate to high temperature electronic conduction in electrolytes, electrochemical kinetics; and 3) high temperature electrodes.

PROCESS DESIGN

The thermal efficiency of hydrogen production increases as the electrolysis reaction temperature increases. In order to maintain a high reaction temperature, the outlet stream of steam/hydrogen from the HTE is sent back to the blanket to absorb heat for temperature reheat. The mixture is then sent to the next electrolyzer unit, and the reheat process

repeated. When the hydrogen concentration has built up to the required level and for a given temperature drop along the electrolyzer tube, the gas mixture then passes into lower temperature electrolyzers where the endothermic reaction cools the gases during the last stages of electrolysis to a temperature at which conventional heat exchangers are used for water-hydrogen separation. For a maximum steam temperature of 1377°C , there are nine electrolyzers in series operating at the maximum reaction temperature. These are followed by three electrolyzers operating at lower temperatures, decreasing by 150°C per electrolyzer to an outlet temperature of 727°C . For the maximum steam temperature equal to 1827°C , the number of electrolyzers are six and six, respectively. The oxygen generated in the high temperature electrolyzers is passed directly to the low temperature electrolyzers without reheating. Maximum temperatures will be fixed by material limitations which in turn will set limits on optimum values. Electrical input to the electrolyzers is supplied from the power conversion cycle.

The outlet oxygen and steam/hydrogen mixture from the last set of HTE's is sent to heat exchangers where heat is recovered by the inlet make-up water stream. The make-up water stream from the outlet of the heat exchanger will take up heat from the helium loop of the superheater before returning to the breeding blanket of the fusion reactor. Hydrogen is separated from steam in the heat exchanger. The separated water will combine with the make-up water for recycle. Oxygen produced can be used as an oxidizing agent.

The electrical power generation plant is similar to a conventional power plant. Low temperature steam from the low temperature blanket region is pumped through a superheater where the temperature of steam is raised by heat absorption from the helium loop. Power is generated through high or intermediate pressure turbines. Steam from the turbine is condensed in a low pressure condenser before returning to the blanket. The cycle efficiency is shown to be ~ 38 percent. The unique ability of fusion neutrons to directly heat the interior of a blanket to very high temperatures offers great potential for high efficiency power cycles using fusion heat. Typical values may be ~ 55 - 60 percent with a FAST (Fusion Augmented Steam Turbine) cycle (discussed in Ref. [2]). This implies that the overall hydrogen process efficiencies would be high, ~ 60 percent, for high temperature electrolysis.

RESULTS OF DESIGN STUDY

1. Efficiency Considerations

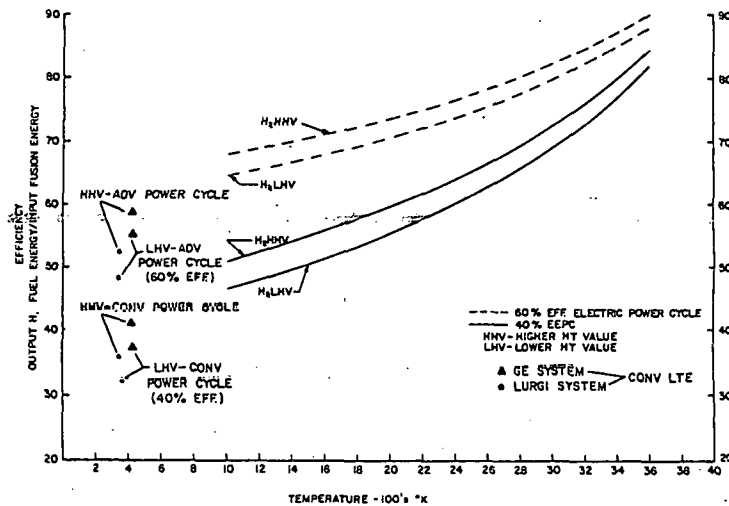
The constraint placed on the system is that it must be energetically balanced. This means that the energy generated by the fusion reactor is only used to produce hydrogen gas. With reference to Figure 4, the cycle efficiency of the entire system is defined as conversion of total fusion energy to hydrogen fuel gas energy for both the lower heating value (LHV) and the higher heating value (HHV) of hydrogen. There is approximately 7 to 8 percentage points improvement in HHV over LHV. The efficiencies as calculated are idealized in that pumping and heat losses from the various process units will reduce the efficiency. In addition at very high temperatures ($>2300^{\circ}\text{K}$) material temperature limitations may impose practical operating limits. Below 1000°K the over-voltage problem may impose a lower operating limit. Furthermore, 40 percent efficiency may be too high a value for the conventional power cycle. All these additional inefficiencies are taken into account in the actual process design of the reference system.

The value of the HTE system can be compared to conventional fusion power with low temperature or conventional electrolyzers. The well-known Lurgi electrolytic cells operate at

Figure 4

HYDROGEN PRODUCTION FROM FUSION REACTORS
HIGH TEMP ELECTROLYSIS (HTE) WITH
CONV. (CP) AND ADVANCED POWER (AP) CYCLE

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30 atm and 80°C at an efficiency of 80 percent. The advanced GE-solid polymer electrolyzers (SPE) operate at 125°C and are reported to yield efficiencies of 90 percent. When combining these efficiencies with the 40 percent conventional power cycle, the range of LHV efficiency values of 32 to 36 percent are obtained and the HHV efficiencies are 42.2 to 45.4 percent. At 1700°C (1426.8°C), which is a reasonably high temperature for HTE cells, a HHV efficiency of 56.9 percent can be obtained. Thus, the HTE cycle yields from 14.5 to 17.7 percentage points higher than a conventional electrolyzer cycle and thus yields an improvement of from 31.2 to 42.0 percent in efficiency over conventional systems on a comparable basis. This improved efficiency should be translated to lower operating and capital cost for a synthetic fuel process.

In addition to the H₂ efficiency gains as a consequence of high temperature, a substantially higher H₂ efficiency can be achieved with the inclusion of an advanced power cycle (60% efficiency) in the system. For example, at 1700°C a HHV efficiency of 72 percent can be realized (compared with 57% with a lower power cycle efficiency). This improved efficiency should likewise be translated into lower operating and capital cost for a synthetic fuel process.

Two point designs were carried out for the maximum steam temperatures equal to 1377°C and 1827°C. The power cycle efficiency is found to be ~38% (the net efficiency accounting for pumps, etc). It is assumed that the reactor operates in an ignited state, with long plasma burn and minimal extra recirculating power for special portions of the fusion reactor, i.e., beams, magnets, tritium recycle, etc., that would not be included in the recirculating power requirements associated with the power conversion. This accounts for 2% of electrical requirements. The hydrogen thermal process efficiencies are 49% and 51% for the maximum steam temperatures, 1377°C and 1827°C. While the efficiency increases with temperature, the increase is not that great between ~1400°C and 1800°C as born out by the theoretical calculations.

2. Economics

While complete economic studies of the system were not attempted, estimates of the capital investment costs as well as fuel production cost evaluations were made. This phase of the

study relied on cost estimate assumptions for individual components, such as the fusion reactor, coal-synthetic fuel plant, etc.

Before any costing can be done, some idea as to the fuel production capacity for a given fusion reactor size is necessary. For a fixed reactor thermal rating, the hydrogen produced, i.e., standard cubic feet/day (scf/d), increases in direct proportion with the system efficiency. In terms of equivalent gasoline production in barrels/day, a 2000 MW(th) fusion reactor-HTE system is a relatively small fuels plant. Such a plant, operating at 70 percent efficiency for H₂ production would produce the energy equivalent of 20,000 bbl/day. A factor of three reduction in coal feed (tons/day) is achieved in syngas (methane) production if fusion produced hydrogen is used, as compared to a conventional syngas plant fed by coal. This large savings in coal usage realized with the fusion produced hydrogen would greatly extend coal resources and reduce environmental effects.

The assumed costs of the fusion reactor plus electrolyzers are taken to be in the range of \$400 to 800/KW(th) [\$1000 - 2000/KW(e) equivalent] based on reference designs for fusion reactors producing electricity at conventional efficiency (30 - 40 percent). A conventional syngas fuel plant costs ~ one billion dollars and an additional one billion dollars is needed for coal feed operating costs which can be considered as a tradeoff for the additional capital investment for the fusion reactor process. Results show that the cost of the fusion-HTE system based on the lower fusion costs is slightly more than the total cost of a syngas system at the lower efficiency (50 percent) and slightly less at the higher efficiency (70 percent). Doubling the fusion plus electrolyzer costs increase the total costs accordingly.

Assuming fixed charges to be 15 percent in a fusion-synfuels plant, the fuel costs based on the lower fusion costs are competitive with those based on a conventional coal-synfuels plant. Fuel costs resulting from the fusion-synfuels plant would be approximately one-half that of a comparative fission electrochemical system. Looked at from another perspective, the hydrogen produced from a fusion-synfuels plant is equivalent to any energy cost corresponding to ~45¢ to 60¢/gallon of gasoline. Since all of these comparisons are based on assumed costs, no definitive conclusions can be drawn except that if the cost per unit of thermal output of a fusion HTE plant is comparable to that projected for fusion electric plants, fusion produced hydrogen should be economically competitive.

SUMMARY

Based on results obtained from the study as well as comparisons with other methods of hydrogen production, the following tentative conclusions reached are: 1) HTE has the highest potential efficiency for production of synfuels from fusion; a fusion to hydrogen energy efficiency of ~70 percent appears possible with 1800°C HTE units and 60 percent power cycle efficiency; an efficiency of ~50 percent appears possible with 1400°C HTE units and 40 percent power cycle efficiency. 2) Relative to thermochemical or direct decomposition methods HTE technology is in a more advanced state of development, e.g., single cell units have been built and tested at 1000°C. 3) Based on efficiency results HTE methods would appear to have potentially lower unit process or capital costs compared with thermochemical or direct decomposition methods. 4) While design efforts are required HTE units offer the potential to be quickly run in reverse as fuel cells to produce electricity for restart of Tokamaks and possible spinning reverse for a grid system.

[1] "Fusion Energy Applied to Synthetic Fuel Production", DOE Report, CONF-770593, Oct. 1977.
[2] "Fusion Reactors-High Temperature Electrolysis (HTE)", DOE Report, HCP/T0016-01, Jan. 1978.