Submitted to the 15th IECEC, Seattle, Washington, August 17-22, 1980 BNL 28007
Sponsored by the American Institute of Aeronautics ~~and As~~tronautics

HYFIRE: FUSION-HIGH TEMPERATURE ELECTROLYSIS SYSTEM[*]

J.A. Fillo, J.R. Powell,[+] M. Steinberg, R. Benenati, V-D. Dang, F. Horn, H. Isaacs,
O. Lazareth, H. Makowitz, and J. Usher
Brookhaven National Laboratory
Upton, New York

Abstract

The Brookhaven National Laboratory (BNL) is carrying out a comprehensive conceptual design study called HYFIRE of a commercial fusion Tokamak reactor, high-temperature electrolysis system. The study is placing particular emphasis on the adaptability of the STARFIRE power reactor to a synfuel application. 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 D-T fuel cycle. In addition to thermal energy for the decomposition of steam into its constituents, H_2 and O_2, electrical input is required. Power cycle efficiencies of ~40% require He cooling for steam superheat. Fourteen hundred degree steam coupled with 40% power cycle efficiency results in a process efficiency (conversion of fusion energy to hydrogen chemical energy) of 50%.

1. Introduction

Brookhaven National Laboratory is carrying out a comprehensive conceptual design study called HYFIRE of a commercial fusion Tokamak reactor, high-temperature electrolysis system. The purpose of the study is to provide a mechanism for DOE to further assess the commercial potential of fusion via a Tokamak reactor for the production of synthetic fuel. The HYFIRE reactor design is based on the Tokamak commercial power reactor, STARFIRE,[1] 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.

Details of the STARFIRE reactor study are documented in Ref. 2. The key technical objective of the STARFIRE study has been to develop an attractive embodiment of the Tokamak as a commercial power reactor consistent with credible engineering solutions to design problems. This same philosophy is carried over to the HYFIRE study with an eye towards assessing what major changes are required for the synfuel reactor. HYFIRE is based on the deuterium/tritium/lithium fuel cycle.

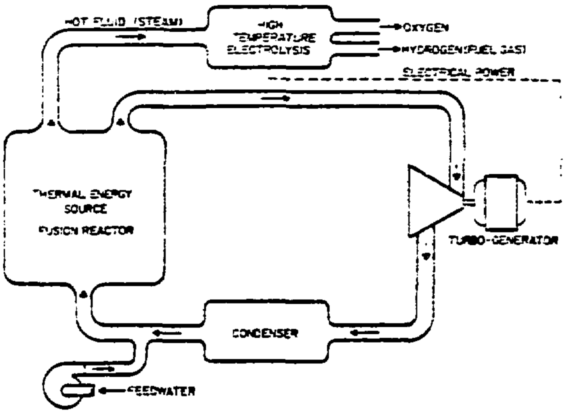
The primary criteria for commercial attractiveness emphasized in the STARFIRE study are economic, safety, and environmental impact. These criteria are, of course, of equal concern for HYFIRE where economics must include the economics of producing hydrogen and safety and evironmental impact include the production of hydrogen and oxygen.

Section 2 is an overview of the reactor concept. Section 3 covers blanket design of the synfuel process modules as well as tritium breeding/power cycle modules. Section 4 is an overview of the HTE process and design of the electrolyzer, including some aspects of product conditioning. Section 5 covers the overall process design including the thermal power cycle for electrical power generation and coupling the HTE process. Section 6 presents the key conclusions based on preliminary analysis.

2. Overview of Reactor Concept

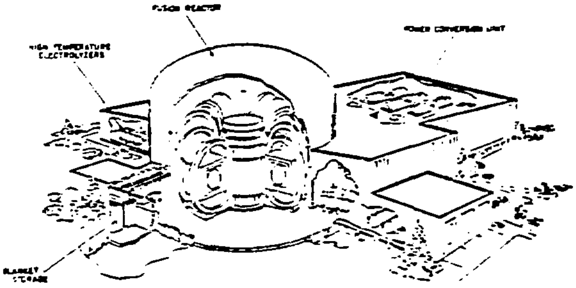
Figure 1 shows a simplified flow sheet for an HTE/fusion synthetic fuel plant. All electrical production goes to the HTE cells (and to operation of the fusion reactor) to make hydrogen/electricity for sale, depending on market demand. Two blanket types are inferred; the first type heats steam to high temperatures (T≥1000°C) for delivery to the HTE cells, while the second heats a working fluid for the thermal power cycle and electricity generation as well as for tritium breeding.

Major systems of HYFIRE are shown in Figure 2.



GENERAL HTE PROCESS WITH CONVENTIONAL POWER CYCLE

Figure 1



FUSION REACTOR-HIGH TEMPERATURE ELECTROLYSIS SYSTEM (FR-HTES)

Figure 2

---

[*] Work performed under the auspices of the U.S. Dept. of Energy, Washington, D.C.

[+] Member AIAA.

The reactor major radius is 7.0 m, plasma half-width is 1.94 m with a plasma elongation of 1.6. All superconducting equilibrium field coils are located outside the 12 *toroidal-field coils* and 4 small segmented copper coils are located inside for plasma stability control. The shield provides neutron- and gamma-ray attenuation and serves as the primary vacuum boundary for the plasma. Twelve shield access doors are provided to permit removal of 24 toroidal blanket sections. Twelve electrolyzer units and associated heat exchangers are housed in a building circumferentially surrounding the reactor. In addition, the power generating units are shown.

Steady state operation of the Tokamak is assumed. As the STARFIRE study indicates, and which is equally applicable to HYFIRE, there are a number of technological and engineering benefits for a commercial reactor that would be derived from steady state operation. Among these are: (1) component and system reliability is increased; (2) material fatigue is eliminated as a serious concern; (3) higher neutron wall load is acceptable, (4) thermal energy storage is not required; (5) the need for an intermediate coolant loop is reduced; (6) electrical energy storage is significantly reduced or eliminated; and (7) an ohmic heating solenoid is not needed, and external placement of the equilibrium-field coils is simplified. It has been estimated that the combined benefits of steady state can result in a saving in the cost of energy as large as 25 to 30%.

All fusion applications will probably require reasonably high plant availabilities (fraction of the time the plant is on-line), on the order of 0.5 to 0.8, due to the high capital investment for the reactor. As with any electric generation system, fusion reactors connected to the grid will have to have high reliability, with relatively few outages per year. Reliability requirements for a synfuel plant will be less demanding, though, since the product can readily be stored off-line. Fluctuations in plant output can thus be readily smoothed out by using available storage to meet demand requirements if the plant shuts down. While high capital cost reactors will have to have high plant factors for economic reasons, they could be allowed to shut down unexpectedly fairly often for short periods (i.e., to start up the plasma), if they were not connected to an electrical grid.

3. Blanket Design

The HYFIRE blanket must perform three functions: a) provide high-temperature (≥1000°C) process steam at moderate pressures (in the range of 10 to 30 atm) to the high-temperature electrolysis 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 D-T 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 to allow for doubling time requirements, perturbations, etc., for HYFIRE places a premium on space, i.e., it will probably be necessary to breed tritium in regions of the process steam blanket modules. Tritium from the power cycle part of the blanket must make up the tritium deficiency.

The two-temperature zone blanket[3] approach is mandatory for the process steam portion of the energy supply. The modules will have relatively cool shells (~300°C) with thermal insulation between the shell 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 has an HTE steam module region and a power cycle module region with tritium breeding in each region. Tritium breeding is to be accomplished with solid breeders, and tritium inventory in the blanket should be minimized. A possible problem with tritium holdup in Li_2O has been raised by the STARFIRE study. This can be circumvented either by using neutron multipliers (Be, Pb) and a solid breeder (either Li_2O or $LiAlO_2$), by scavenging with D_2 or H_2 in the He purge circuit, or by using a liquid breeder material (e.g., PbBiLi mixture). Tritium will be released to He purge streams, and not to the main 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.

For the HTE modules the refractory oxides (ZrO_2 and Al_2O_3) in the high-temperature region of the blanket must be stable under exposure to the steam or steam/hydrogen process stream under radiation and thermal cycling conditions. Such materials will fill the interior of the blanket as solid rods or balls, and will also be used as a low density solid block or fibrous thermal insulation between the high-temperature interior and the structural shell. Materials compatibility tests[4] in steam and steam/hydrogen indicate that ZrO_2 and Al_2O_3 are suitable for long-term service up to ~1500°C (the present testing limit at BNL). Tests with SiC and MgO indicate these materials are restricted to somewhat lower temperatures.

Figure 3, the MARK II blanket, is representative of one of the blanket options. All of the larger modules are of the two-temperature-zone type, with steam cooling of the hot interiors and water cooling of the module shells. A row or smaller diameter modules (e.g., diam ~15 cm) are placed in front of

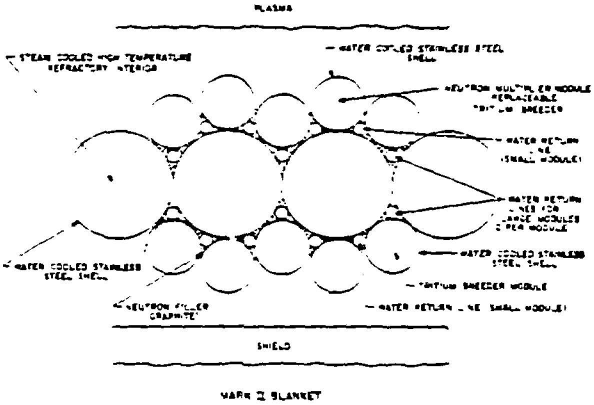


Figure 3

the row of main modules for neutron multiplication/tritium breeding. Several smaller modules would be mounted on a grid so that they could be removed as a unit when appropriate. The remainder of the blanket (i.e., the main modules and the tritium breeder modules behind them) could be left in place for further use, since their radiation damage would be considerably less.

Cylinders are attractive since they are easier to fabricate and have the most structural strength for a given thickness of the module wall. Spaces between the cylinders are filled by water return lines and some solid neutron moderating material (e.g., graphite). Surprisingly little plugging is necessary to fill the gaps between the modules. Each of the main modules have two water return lines, with one water return line per smaller module. (It may be desirable to have an additional water line between the smaller modules immediately facing the plasma, to reduce neutron streaming to parts of the main module shells.) The return line arrangement allows all headering to be on one side of the blanket sector. Coolant flows down the module shell to its end, with flow back through the return lines. Steam flow can also be headered from one side of the blanket sector. Flow would go down one plenum in the main module, cross flow through the module interior, and return through the other plenum.

Representative tritium breeding ratios for the three blanket options studied are shown in Table 1. All options are viable from the standpoint of neutronics and thermal hydraulics. A preferred design would be MARK II, since it would offer one type of blanket in the reactor chamber. It also has the potential for highest electrical to hydrogen production efficiency provided that there is adequate energy deposition in the hot blanket interior.

4. 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 making 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.

Table 1 Representative tritium breeding results

MARK I	MARK II	MARK III
Breeding blanket		Breeding blanket
1.2 to 1.6	1.0 to 1.4	1.1 to 1.3
HTE breeding		HTE breeding
.3 to .4 (no front breeding)		.3 to .4 (no front breeding)

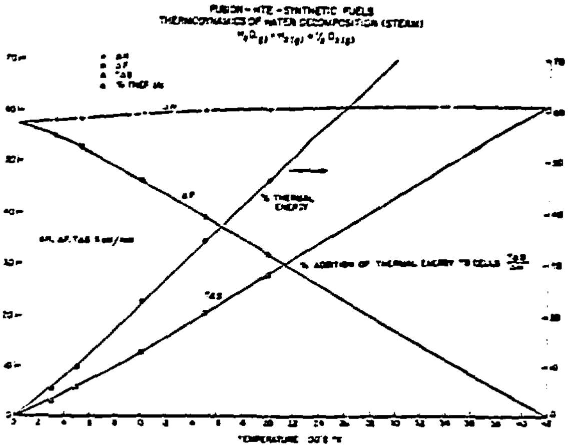


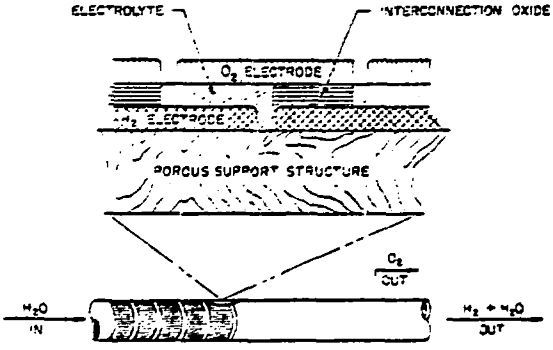
Figure 4

The energy splits are shown, as a function of temperature, in Figure 4. 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. For HYFIRE, the design temperature of interest is 1400°C.

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/H_2 stream will cool by 100° to 200°C as it proceeds through the electrolyzer.

Extensive work has been done on the use of solid electrolytes for high-temperature electrolysis of steam. Major developments in high-temperature solid oxide electrochemical cells have resulted from studies of solid oxide fuel cells at Westinghouse Research and Development Laboratories. The Westinghouse fuel cell design is based on a thin layer electrochemical cell supported on a thick ceramic porous base. This approach permits significant reduction in electrolyte thickness. A schematic of the Westinghouse fuel cell is shown in Figure 5. This design also serves as the basis for the high-temperature electrolyzer since an electrolyzer is a fuel cell in reverse.

High-temperature electrolysis uses 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 (several mils) electrolyte layer of yttria-stabilized ZrO_2. Electrodes are electrically connected in series along each tube to minimize IR losses. A large number (~10^5) of electrolyzer tubes are then connected in parallel in a large pressure vessel, Figure 6. Typical steam pressures in a high-temperature electrolyzer are on the order of 10 to 20 atm.



HTE CELL DESIGN
(WESTINGHOUSE FUEL CELL)

Figure 5

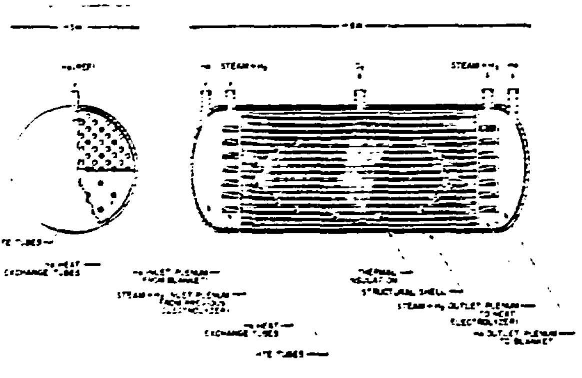


Figure 6

Previous studies[5] of HTE processes have assumed that steam is directly heated in the hot interior of the HTE process heat modules, and then passes into the HTE electrolyzer. The steam is cooled as it passes through the electrolyzer by the endothermic electrolysis process. In order to keep the electrolyzer temperature at a high average value, it is necessary to electrolyze only a small fraction (~10%) of the steam during its passage and return the steam-H_2 mixture for reheat to another section of the blanket. The optimum number of series of reheats and electrolyzers depend on various parameters. 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.

This type of electrolysis process arrangement is characterized by: 1. Steam-H_2 mixtures flow through the blanket, with the H_2/steam ratio varying from 0 for the first electrolyzers to ~10/1 at the exit of the electrolyzer string. The refractory in the hot blanket interior must thus withstand steam/H_2 mixtures at temperatures of ~1400°C. 2. Radioactive isotopes picked up by the steam-H_2 stream will go along with the H_2 product, necessitating cleanup by filtration or absorption (e.g., in ion exchange resins).

Other types of HTE process arrangements are possible to mitigate activation of the H_2 product. Rather than circulating steam through the blanket to remove heat, instead, it passes straight through the electrolyzers, either in series or parallel flow, exiting as almost pure H_2. Heat is provided to the electrolyzers (and removed from the blanket) by circulating O_2 plus inert gas (e.g., He) from the shell side of the electrolyzer. Oxygen would be separated from the inert gas at the end of the process and discharged to the atmosphere or whatever market was available.

Another design approach would be to make the HTE electrolyzer slightly longer (e.g., about 10% longer), with a separate shell side zone to transfer heat from the He blanket coolant to the steam-H_2 mixture flowing inside the nonporous ZrO_2 HTE tube. A separation partition between the O_2 shell side zone and the He shell side zone is required, with a flowing gas sweep to prevent slight mixing of gases in the two zones.

5. Thermal Power Cycle/Process Design

For the HTE process, only about 20% of total fusion energy needs to be extracted at the HTE process conditions (steam at 1400°C), and it seems likely that this should be easily achieved with the MARK II blanket, even when deposition in the multiplier/breeder front modules is accounted for. However, for an efficient power cycle, it is necessary to have a substantial amount of superheat energy at temperatures above 300°C. This requires an additional 15% in the temperature range of 300° to 500°C, and would be provided by steam from the main modules, which either could heat the power cycle steam indirectly in a steam-to-steam heat exchanger, or could heat it by direct injection. Accordingly, about 35% of the total fusion energy needs to be deposited in the hot interior of the main modules, with an accompanying breeding ratio, T/n, of ≥ 1.1. This may or may not be possible, depending on module materials and design. If insufficient energy is deposited in the main modules, it would be necessary to have some fraction of the multiplier/breeder modules cooled by high-temperature He to get sufficient superheat for the steam cycle.

In general, drivers on power cycle design include: a) the two-temperature zone blanket; b) superheated steam power cycle; and c) STARFIRE recirculation. 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 H_2 production efficiency (total fusion energy to the chemical energy of the hydrogen produced) is in the 50 to 55% range. Direct steam superheat in MARK II blankets was the potential for significant increase in power cycle efficiency. The turbine would have to operate above 1200°F, though, which would imply advancement in turbine technology.

6. Conclusions

Based on HYFIRE studies to date, the following observations are made. a) the MARK II blanket appears more attractive (single type of blanket in reactor chamber, potential for high thermal efficiency); b) attractive tritium breeders such as $LiAlO_2$ and liquid lead with dissolved lithium have been identified; c) gross power cycle efficiencies in the 40 to 45% range appear achievable; and d) high H_2 production efficiencies in the 50 to 55% range appear achievable.

7. References

1. C.C. Baker et al., STARFIRE—Commercial Tokamak power plant overview, in *Proc. 8th Symp. Engr. Problems of Fusion Res.*, November 1979.

2. C.C. Baker et al., A commercial Tokamak power plant design—Final Report, Argonne National Laboratory, Argonne, IL, to be published.

3. J. Powell et al., High temperature blankets for the production of synthetic fuels, in *Proc. 7th Symp. Engr. Problems of Fusion Res.*, Knoxville, TN, 1977, Vol. II, pp. [illegible]-5, IEEE, New York, 1977.

4. F.L. Horn et al., Performance of ceramic materials in high temperature steam and hydrogen, in *Proc. 1st Topical Meeting Fusion Reactor Materials*, Miami, FL, 1979, Part A, pp. 439-43, North-Holland Publishing Co., Amsterdam, 1979.

5. Fusion reactors—High temperature electrolysis (HTE), J.A. Fillo, Editor, Department of Energy, Washington, D.C., DOE Report HCP/T0016-01, Jan. 1978.