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HYFIRE: A TOKAMAK/HIGH-TEMPERATURE ELECTROLYSIS SYSTEM*

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Summary

The HYFIRE studies to date have investigated a number of technical approaches for using the thermal energy produced in a high-temperature Tokamak blanket to provide the electrical and thermal energy required to drive a high-temperature (>1000°C) water electrolysis process. Current emphasis is on two design points, one consistent with electrolyzer peak inlet temperatures of 1400°C, which is an extrapolation of present experience, and one consistent with a peak electrolyzer temperature of 1100°C. This latter condition is based on current laboratory experience with high-temperature solid electrolyte fuel cells. Our major conclusion to date is that the technical integration of fusion and high-temperature electrolysis appears to be feasible and that overall hydrogen production efficiencies of 50 to 55% seem possible.

Introduction

The ability of the high energy neutrons produced by fusion reactions to deeply penetrate and deposit energy in surrounding structures offers the prospect of developing high temperatures in suitable blanket material, which would enhance the efficiency of thermal-to-electrical power conversion as well as the utilization of high temperature processes (>1000°C) for the production of hydrogen.[1] The objective of the work described in this paper is to investigate the potential merits of coupling a Tokamak fusion reactor with a high temperature blanket to a high-temperature electrolysis process.

In prior work,[2] the STARFIRE commercial Tokamak fusion reactor[3] was directly used as the fusion driver. This paper describes a new design obtained by scaling the basic STARFIRE design to permit the achievement of a blanket power of 6000 MW(th). The guidelines for the current HYFIRE study are essentially similar to those used in the development of the STARFIRE, reference Tokamak reactor design. The final HYFIRE plant embodiment will represent the tenth of a kind first generation plant. STARFIRE technology assumptions and design features are used to the extent possible to permit concentration on high-temperature blanket and balance-of-plant design issues. This approach will permit a direct comparison with the economics of a fusion electric plant.

In addition to the requirement for tritium self-sufficiency, an important ground rule for this initial series of studies was that hydrogen would be the only product produced for sale. Thus, the electrical generation equipment and the overall power conversion process are sized to exactly provide the electrical energy required to operate the Tokamak, electrolysis plant, and balance-of-plant systems. The possible operational and economic advantages of trading off electrical production against hydrogen production is a subject for future optimization studies.

The Fusion Driver

Previous HYFIRE fusion high-temperature electrolysis plant studies[2] used the STARFIRE reactor design directly. These studies indicated significant advantages would be gained by going to somewhat larger device design. The specific scale-up criterion used was the attainment of a blanket thermal power of 6000 MW(th), while maintaining the reference STARFIRE neutron wall loading of 3.6 MW/m.

Key STARFIRE physics assumptions were retained in the scale-up process. These assumptions were: a) hot ion-mode plasma operation with the preferential cooling of electrons; b) rf power for plasma heating and current drive; c) steady-state operation; d) enhanced radiation mode (high Z_{eff}) through the injection of iodine; and e) fueling by recycling and gas puffing.

The COAST[4] Tokamak systems code was used to perform the scale-up computations in a self-consistent fashion, using the above constraints and assumptions. This code will subsequently be used to develop capital cost estimates for the Tokamak system, again using component cost models based on STARFIRE.

Table 1

Summary of HYFIRE and STARFIRE plasma parameters

Parameter (Units)	STARFIRE	HYFIRE
Major radius (m)	7.0	8.5
Minor radius (m)	1.94	2.36
Electron density (m^{-3})	1.17×10^{20}	1.12×10^{20}
D^+ or T^+ density (m^{-3})	0.40×10^{20}	0.36×10^{20}
Z_{aff}	3	3
Burn fraction	0.40	0.33
T_2 fueling rate (g/h)	56	64
Electron kT (keV)	16.8	16.8
Ion kT (keV)	23.5	25.0
Confinement, $\tau_{E,e}$ (s)	3.6	5.1
Confinement, $\tau_{E,i}$ (s)	10.0	16.0
Confinement, τ_p (s)	1.8	2.5
RF power (MW)	90.4	120
RF frequency (10^9 s^{-1})	10.0	9.7
Plasma current (mA)	10.4	12.3
Plasma beta, (%)	6.7	6.7
Field-on-axis (T)	5.85	5.74
Fusion power (MW)	3500	5300

Table 1 summarizes the baseline HYFIRE plasma parameters obtained through the scale-up process and compares them with equivalent STARFIRE parameters. An

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important consequence of the scale-up is the relative improvement in blanket surface area coverage. The overall increase in torus surface area obtained in going from a major radius of 7 m to 8.5 m is proportionately larger than the associated increase in surface area devoted to rf waveguide, vacuum pumping and limiter interfaces.

The High-Temperature Reactor Blanket

The key technological development required for the consideration of fusion as a heat source for hydrogen production is a high-temperature blanket. The two-temperature approach, first proposed by BNL[5] for minimum activity blankets, provides for the deposition of the bulk of the neutron energy in a hot interior region which is thermally insulated from a cooler structural shell. Heat is extracted at two different temperature levels by two different coolant streams. This blanket design approach is the key difference between the STARFIRE and HYFIRE concepts, with the exception of relative size.

The HYFIRE blanket is required to provide high-temperature steam for the electrolysis process, thermal energy for efficient generation of electricity to operate the plant, and to breed sufficient tritium to compensate for burnup and process losses. Two types of blanket modules have been designed to meet these requirements, a steam-cooled "HTE" module with a tritium breeding zone and a He-cooled tritium breeding "power" module. The relative numbers of each type of module is an important design variable which can be adjusted to trade tritium production off against high-temperature steam and electrical power production. In each case, the first wall and blanket structural material is PCA (Prime Candidate Alloy) stainless steel as in STARFIRE; however, in HYFIRE, the steel shell is cooled by pressurized water. The modules are arranged along toroidal field lines since this minimizes differences in overall blanket configuration and associated maintenance procedures between STARFIRE and HYFIRE.

The interior of the HTE steam modules, shown in Fig. 1, consists of rods of ZrO_2 which are thermally insulated from the steel shell. Materials compatibility tests[5] in steam and steam/hydrogen indicate

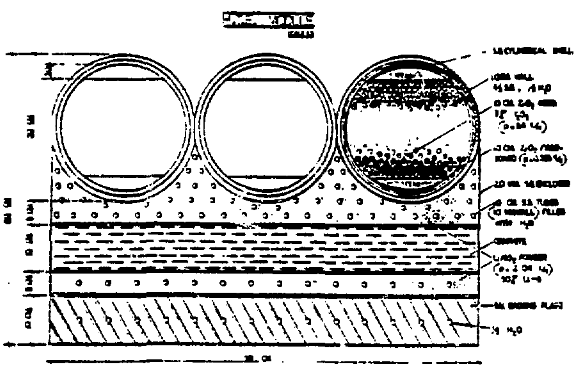

Fig. 1 Steam-cooled blanket module.

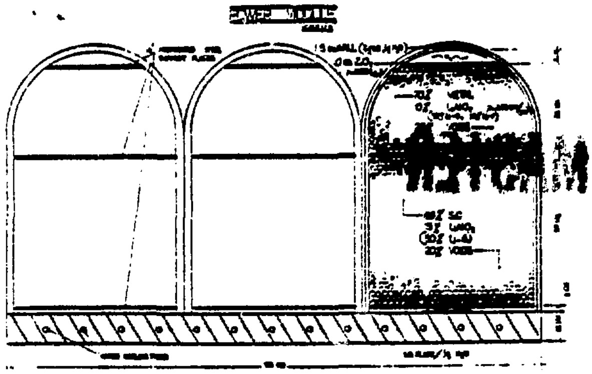

Fig. 2 Helium-cooled blanket module

that ZrO_2 is suitable for long-term service up to at least 1500°C. As with all blanket materials at this time, the integrity of this material with respect to long-term irradiation by high energy neutrons is uncertain.

The HTE module utilizes a relatively thin tritium breeding layer outboard of the steam-cooled HTE zone. Consistent with the STARFIRE design, the tritium breeding medium is $LiAlO_2$. The design employs at least two structural steel boundaries to minimize the potential of tritium leakage into the HTE steam circuit.

The tritium breeding/power production module, shown in Fig. 2 also employs a low-temperature water-cooled shell. The interior region is He-cooled and contains two distinct zones. The inboard zone contains a beryllium multiplier as well as $LiAlO_2$; the outboard zone consists of SiC and $LiAlO_2$. Since interior structural materials are minimized, the blanket may operate at relatively high temperatures, which promotes tritium removal as well as efficient power conversion. The primary He steam (at ~20 atm) exchanges heat with a secondary He power conversion steam (at ~70 atm) in small heat exchangers outboard of the blanket.

The High-Temperature Electrolysis Process

In view of thermodynamic efficiency limits on thermal-to-electrical power conversion cycles, it is clearly desirable to operate water decomposition processes such that the ratio of thermal energy input to electrical energy input is maximized, consistent with practical technological constraints. The ratio of thermal-to-electrical energy increases linearly with electrolysis temperature. The successful development on a laboratory scale, of high-temperature fuel cells[7] offers the opportunity to consider the use of this technology for efficient high-temperature electrolysis.

The solid oxide electrolyte fuel cell technology, developed by Westinghouse, has been tested satisfactorily for thousands of hours at operating temperatures of 1000°C. By operating in reverse, with dc power applied, these cells have the potential for very high fusion to hydrogen energy conversion efficiencies.

The basic electrolyzer cell stack configuration is shown in Fig. 3. A succession of this electrode layers of suitably doped ceramics are deposited on a thick-

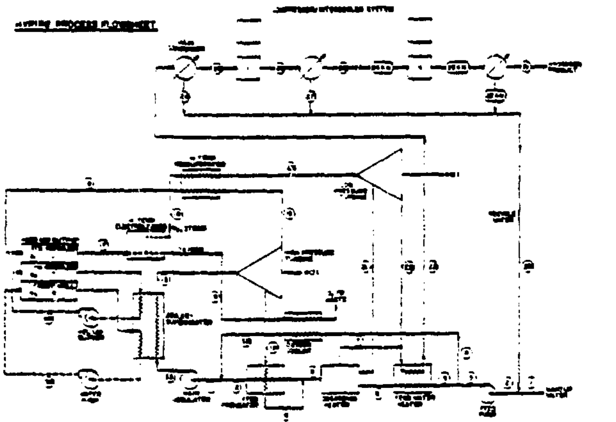

Fig. 3. Sectional view of the high-temperature electrolyzer cell stack based on the Westinghouse solid electrolyte fuel cell.

walled porous ceramic tube of yttria-stabilized zirconia. These thin layers comprise the hydrogen electrode, the electrolyte (yttria-stabilized zirconia) that permits ion transport (but not free electron transport), the oxygen electrode, and the interconnection layer between cells. The electrodes are electrically connected in series along each tube to minimize I^2R losses.

Arrays of electrolyzer tubes connected in parallel within a large pressure vessel comprise an HTE process module.[9] The diameter of the vessel is of the order of 4 m and the length is about 7 m. The central plenum receives the high-temperature steam generated in the HTE modules. The steam flows through the center of each electrolyzer tube and the exit steam consists of a lower temperature steam and hydrogen mixture which is collected in adjacent plenums.

Either high- or low-fractional conversion of steam is possible, which has a bearing on the degree of recycling of the H_2/H_2O exit streams back through the blanket system for reheat. The selected approach provides for the electrolysis of only about 10% of the steam during its transit through the electrolyzer to keep the electrolyzer temperature at a high average value.

An important issue in the application of the solid oxide electrolyte technology is the suitability of electrolyzer operation at peak inlet temperatures of 1000° to 1100°C, which is consistent with present experience,[7] versus operation at ~1400°C which will yield improved cycle efficiency at the expense of development risk. As a consequence, two point designs are being pursued. The first design, nearing completion, is directed at the high-temperature regime of blanket and electrolyzer operation. During the next twelve months, emphasis will be placed on the lower temperature design point.

Fusion-High Temperature Electrolysis System

A complete process flowsheet, shown in Fig. 4, has been developed for the system coupling the high-temperature blanket to the high-temperature electrolysis and electrical power generation subsystems, and material flow and energy balances accomplished through the development of a digital computer code to represent the overall cycle.

The overall plant can be thought of as having four principle process circuits; a) the low temperature water loop which extracts heat from the front wall of the blanket elements; b) the helium loop; c) the steam-hydrogen loop which provides the dual function of electricity generation and hydrogen production; and d) the waste oxygen circuit. The steam-hydrogen loop is by far the most involved.

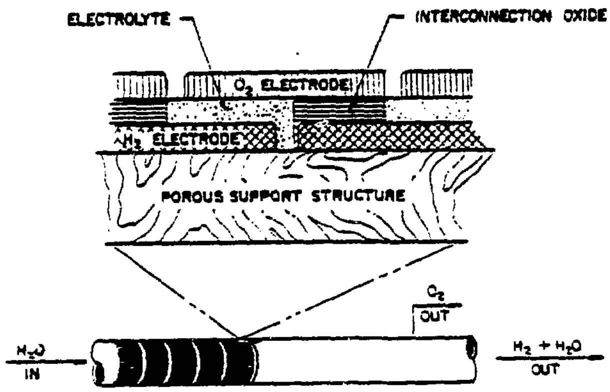

Fig. 4 HTE cell design (Westinghouse fuel cell).

If the conversion of steam of hydrogen in the high temperature electrolyzers is to be limited to 10% (to minimize electrical requirements), steps must be taken to separate the product hydrogen from the waste steam. One way to accomplish this separation is to cool the process stream and condense out the water. A product hydrogen stream in excess of 99% purity can be achieved in this way, based on recouperative heat exchange at the high-temperature end of the process and normal cooling tower water at the low-temperature end of the process.

Table 2 summarizes key cycle parameters associated with the high-temperature design point. These parameters are not final, and are subject to minor iteration.

Table 2

Summary of HYFIRE plant parameters

Gross blanket thermal power, MW(th)	6000 blanket
Steam exit temperature, °C	1420 blanket
Helium exit temperature	800 high
Pressure turbine inlet temperature, °C	621 high
Pressure turbine inlet pressure, MPa	7.59 low
Pressure turbine inlet temperature, °C	533 low
Pressure turbine inlet pressure, MPa	3.43 total
Electrical power to electrolyzers, MW(e)	1540 total
Thermal power to electrolyzers, MW(th)	906
Production Mt/day	1702
kg/hr	70,909
Fusion power to hydrogen conversion efficiency, %	50

Summary and Conclusions

The HYFIRE studies to date have investigated a number of technical approaches for using the thermal energy produced in a high-temperature Tokamak blanket to provide the electrical and thermal energy required to drive a high-temperature water electrolysis process. Current emphasis is on two design points, one consistent with electrolyzer peak inlet temperatures of 1400°C, which is an extrapolation of present experience, and one consistent with a peak electrolyzer temperature of 1100°C. This latter condition is based on current laboratory experience with high-temperature solid electrolyte fuel cells.

The Tokamak driver for HYFIRE is based on the STARFIRE reference commercial fusion power plant design. A reference blanket design has been selected, incorporating modules designed to produce high-temperature steam and modules designed to breed tritium and provide process heat. An initial process design and plant layout has been completed; component cost and plant economics studies are now underway to develop estimates of hydrogen production costs and to determine the sensitivity of this cost to changes in major design parameters. Our major conclusion to date is that the technical integration of fusion and high-temperature electrolysis appears to be feasible and that overall hydrogen production efficiencies of 50 to 55% seem possible.

References

1. J.A. Fillo, Review of fusion synfuels, in Proc. 4th Topical Meeting Technology Controlled Fusion Res., King of Prussia, PA, 1980, Vol. II, pp. 1601-13, DOE, Washington, D.C., 1981.

2. O. Lazareth, J. Fillo, J.R. Powell, M. Steinberg, R. Benenati, V-D. Dang, F. Horn, D. Hsieh, H. Issacs, H. Makowitz, and J. Usher, HYFIRE: A Tokamak--high-temperature electrolysis system, in Proc. 4th Topical Meeting Technology Controlled Fusion Res., King of Prussia, PA, 1980, Vol. II, pp. 1639-42, DOE, Washington, D.C., 1981.

3. STARFIRE--A commercial Tokamak fusion power plant study, Argonne National Laboratory, Argonne, IL, ANL/FPP-80-1, Sept. 1980.

4. D.A. Sink et al., User's manual for COAST-4, a code for costing and sizing Tokamaks, Westinghouse Electric Corporation, Pittsburg, PA, WFPS-TME: 79-023, 1979.

5. J.R. Powell, Editor, Preliminary reference design of a fusion reactor blanket exhibiting very low residual radioactivity, Brookhaven National Laboratory, Informal Report, BNL-19565, 1974.

6. F.L. Horn, J.A. Fillo, J.R. Powell, Performance of ceramic materials in high-temperature steam and hydrogen, in Proc. 1st Topical Meeting on Fusion Reactor Materials, Miami, FLA., 1979, Part A, pp. 439-43, North-Holland Publishing Co., Amsterdam, 1979.

7. W. Feduska et al., Thin film cell/battery power generating system, Westinghouse Electric Corporation, Pittsburg, PA, Report to DOE, CO-1197-9, 1978.

8. E.F. Sverdrup et al., Design of high temperature solid electrolyte fuel cell batteries of maximum power output per unit volume, Energy Conversion, 13, pp. 129-141, Pergamon Press, NY, 1973.