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HYFIRE: A TOKAMAK--HIGH-TEMPERATURE ELECTROLYSIS SYSTEM*†

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ABSTRACT

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. 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 (HTE) system. The purpose of the study is to provide a mechanism 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 [1], the primary difference residing in the type of blanket between the two reactors as well as power cycle design. In addition to exploring a range of blanket and power cycle options to determine those best suited for H_2 production, 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

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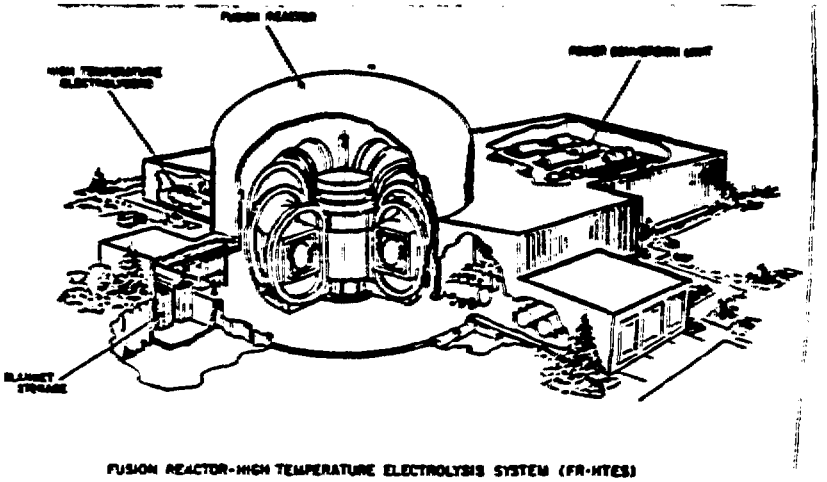


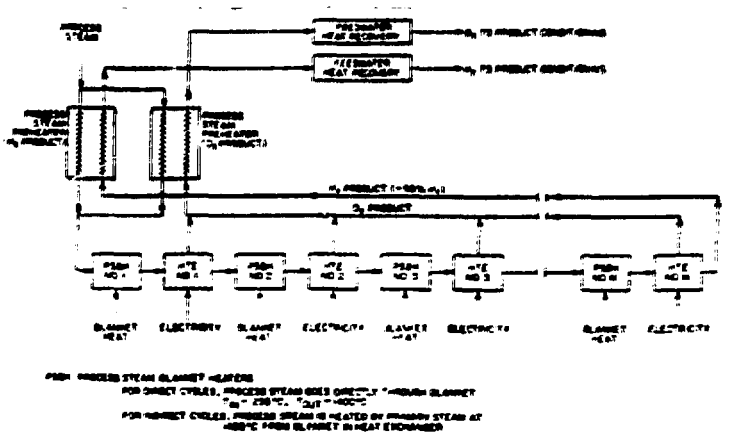
FUSION REACTOR-HIGH TEMPERATURE ELECTROLYSIS SYSTEM (FR-HTES)

Fig. 2.

All superconducting equilibrium field coils are located outside the 12 toroidal-field coils and four 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.



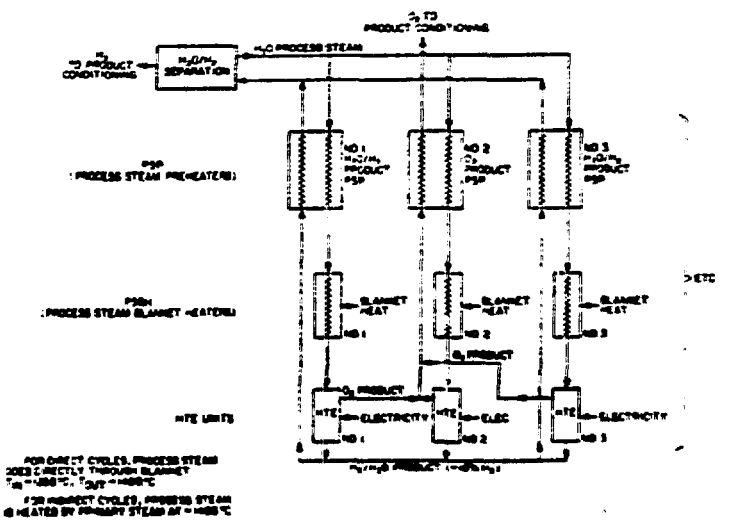
FLOW ARRANGEMENT FOR HTE PROCESS WITH HIGH (~90%) FRACTIONAL CONVERSION OF STEAM TO H_2 IN HTE UNITS

Fig. 3.

3. HIGH TEMPERATURE ELECTROLYSIS PROCESS DESIGN

Two HTE process options have been identified during the scoping design study. In the first case, high-fractional conversion of steam to hydrogen (~90% H_2 at the exit of the last HTE) is considered, Figure 3. Transport of thermal energy to the electrolyzers is either through a direct or indirect process, as well as variations on these processes. In the direct process, steam/H_2 is recycled through the blanket to the electrolyzers in series. For the indirect process electrolyzers are heated in the entrance section by recycled steam from the blanket.

In the second case, low-fractional conversion of steam to hydrogen (~10% H_2 at the exit of the HTE) is considered, Figure 4. Transport of thermal energy



FLOW ARRANGEMENT FOR HTE PROCESS WITH LOW (~10%) FRACTIONAL CONVERSION OF STEAM TO H_2 IN HTE UNITS

Fig. 4.

to the electrolyzers is again either a direct or indirect process. In the direct process, process steam from the blanket passes through one or two electrolyzers in series but with no recycle through the blanket. The indirect process is similar to that in high-fractional conversion.

The choice of either HTE process option and transport thermal energy to the electrolyzer is significant for it impacts not only the plumbing but also the coupling to the power cycle and mode of final hydrogen extraction. This will be discussed in more detail in later sections.

4. 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 from the HTE's and high-temperature heat for the thermal power cycle, differentiates the HYFIRE and STARFIRE blanket system.

Setting the requirements 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. As in STARFIRE, the first wall/blanket structure or shell is PCA stainless steel.

Three blanket options are under way for HYFIRE. Each option has a 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 refractory oxides, e.g., ZrO_2 or Al_2O_3, from 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, although the latter may be mitigrated due to the steady-state performance by HYFIRE. 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

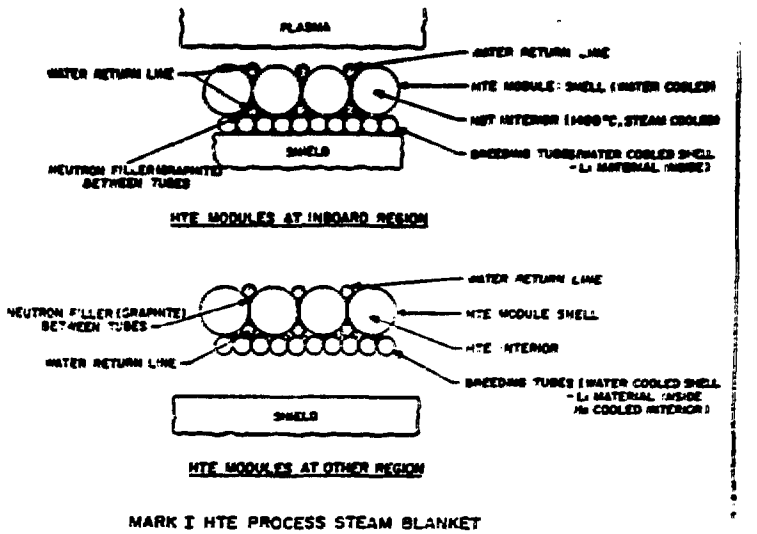
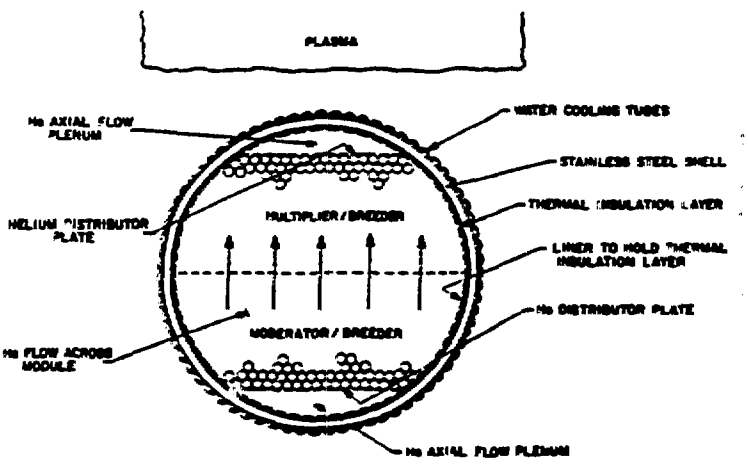


Fig. 5a.

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.

Representative process (HTE) and power/tritium blanket modules are shown in Figures 5a and 5b. All of the larger modules (~40 to 50 cm diameter) are of the two-temperature type with steam cooling of the hot interior for HTE modules, primary He cooling (~20 atm) of the hot interior for tritium breeding modules with heat exchange to a secondary He (~70 atm) stream in small heat exchangers directly behind the blanket and water cooling of the module shells.

Representative tritium breeding ratios for the three blanket options are shown in Table I. All options are viable from the standpoint of neutronics



CROSS SECTION OF MARK I BREEDING BLANKET MODULE

Fig. 5b.

TABLE I

Representative Tritium Breeding Results

MARK I	MARK III	MARK II
Breeding blanket		Breeding blanket
1.2 to 1.6	1.0 to 1.4	1.1 to 1.3
HTE breeding		HTE blanket
.3 to .5 (no front breeding)		.3 to .5 (no front breeding)

and thermal hydraulics. There is not adequate energy deposition in the hot blanket interior for the HTE's and power cycle in MARK II. MARK I is a preferred design since tritium is radioactively isolated from the main He coolant stream, stress on the module structure is low due to low primary coolant presure, and no leakage of steam from the steam generator into the blanket is possible because of the intermediate He-to-He heat exchanger.

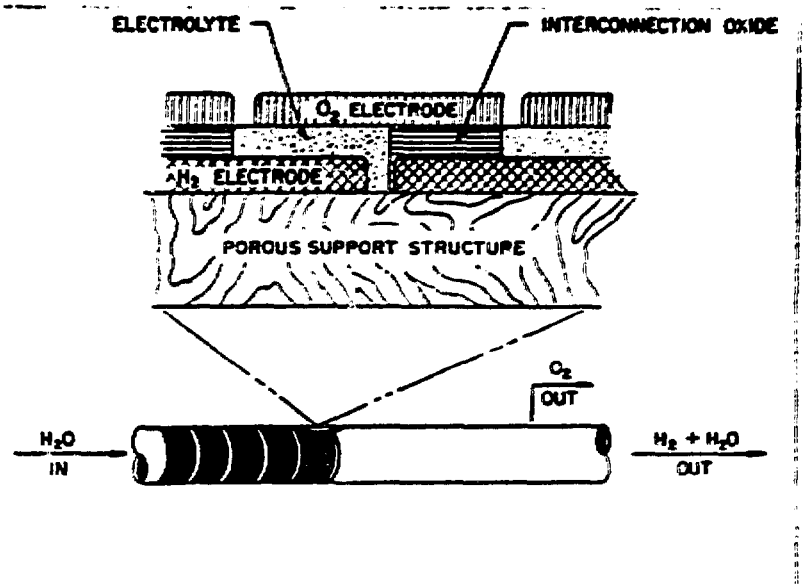
5. HIGH-TEMPERATURE ELECTROLYSIS PROCESS

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 $T\Delta S$, 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.

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, $T\Delta S$, increases. The ratio of thermal energy ($T\Delta S$) 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, $T\Delta S$, 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.

A schematic of the Westinghouse fuel cell is shown in Figure 6. 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



HTE CELL DESIGN
(WESTINGHOUSE FUEL CELL)

Fig. 6

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 ($\sim 10^5$) of electrolyzer tubes are then connected in parallel in a large pressure vessel. Typical steam pressures in a high-temperature electrolyzer are on the order of 10 to 20 atm.

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 ($\sim$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 $\sim$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 $\sim$1400°C, and 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.

5.1 Hydrogen Recovery

If the conversion of steam to 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.

Since the conversion per pass is so low, the recycle ratio is quite high, i.e., it takes 10 passes through the HTE system before a mole of steam is completely converted to hydrogen, and since that steam must be brought up to process conditions then completely condensed in each pass through the system, much attention must be paid to energy conservation if the process is to be a viable one. One way to conserve energy would be to use the high-temperature steam leaving the HTE system to drive a turbine thereby producing electricity which can be recycled to the process. In this scheme, the process stream leaving the HTE would first be cooled recouperatively to about 538°C, a temperature compatible with steam turbine blade materials. It would then pass through the turbine (which would not have any extraction streams) exiting at about 1.5 psia and approximately saturated. Based on a turbine efficiency of 81%, 19 kWh of electricity can be recovered per lb-mole of hydrogen. Only about 70% of the steam can be condensed out of this stream using cooling tower water. The resulting low pressure wet hydrogen steam must be compressed to some suitable product discharge pressure (the actual pressure will depend on the end use intended for the hydrogen). This compression would be done in several stages with intercooling between stages. Each intercooler will remove some of the remaining water vapor thus making a product stream of 98 to 99% dry hydrogen possible. Based on assumed compressor efficiencies of 80% and a final discharge pressure slightly above 1 atm, approximately 3 kWh of compressor work are required leaving a net of about 16 kWh/mole of hydrogen product. It should be noted that the above is based on a reasonable selection of process parameters with virtually no effort as yet to optimize these process conditions.

6. BLANKET/POWER CYCLE/PROCESS COUPLING

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.

As an example of a directly heated electrolyzer, the blanket (already discussed) has three distinctly different heat generation zones, each with its own process fluid and with different process parameters.

One zone which involves the front wall of all modules operates at the relatively modest temperature of 320°C and is kept cool by the circulation of high pressure (1000 to 2000 psi) water. The heat generation in this zone is about 43.5% of the total reactor heat output which amounts to 1740 MW(th). The pressurized water coolant from this zone is circulated through a steam generator in which 1000 psia saturated steam is generated on the secondary side.

Another zone, which will lie behind the front wall of about 50% of all blanket modules, is optimized for tritium breeding. This zone will operate at 800°C and is cooled by pressurized (70 atm) He gas which will be used to superheat the steam referred to above. The heat generated in this zone is about 35% of the total reactor heat output which amounts to 1400 MW(th).

The third and final zone, which will lie behind the front wall of the remaining 50% of all blanket modules, is designed with the needs of the high-temperature electrolyzers in mind. This zone will operate in excess of 1400°C and serves to resuperheat relatively low pressure (10 atm) steam to 1400°C before it goes on to the electrolyzers. The heat generation in this zone is 21.5% of the total reactor heat output which amounts to 860 MW(th).

Looking at the steam circuit, make-up water is added to recycle water and together they enter a steam boiler not unlike that of a PWR-type fission reactor. The 1000 psia saturated steam produced is superheated to about 760°C, by means of the hot helium mentioned above, at which condition it enters the high-pressure steam turbine, exiting at 10 atm and about 482°C at which conditions it enters the third zone of the blanket mentioned above. It leaves the blanket at 1400°C and goes directly to the high-temperature electrolyzers where ~10% is converted to hydrogen and oxygen. The oxygen is wasted after passing through heat exchangers to recover its heat content. The hydrogen together with the unreacted steam is passed on to the hydrogen recovery portion of the flow sheet which is described in Section 4.

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 with the potential of reaching 60%.

6. CONCLUSIONS

Based on HYFIRE studies to date, the following observations are made: a) the MARK I blanket appears more attractive (simultaneously meets global tritium breeding requirements and required energy splits between process steam and helium, potential 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.

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