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# THERMAL AND STRUCTURAL DESIGN ASPECTS OF High-TEMPERATURE BLANKETS FOR FUSION SYNFUEL PRODUCTION

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SUMMARY

The decreasing availability of fossil fuels emphasizes the need to develop systems which will produce synthetic fuels to substitute for and supplement the natural supply. A necessary 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.

The most promising process, high temperature electrolysis (HTE) of steam at temperatures of $\gtrsim$1000°C is examined. In HTE, a large fraction (up to ~50%) of the energy input to split water to hydrogen and oxygen comes from thermal energy. For the projected operating conditions achieved by high temperature fusion blankets, overall efficiencies for hydrogen production should be on the order of 60%. The design, thermal-hydraulics, and materials for such blankets are discussed.

DISCLAIMER

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## 1. Introduction

Energy from fusion can help meet United States (U.S.) energy needs through three major applications: 1) electrical generation, 2) synfuels/chemical production, and 3) fissile fuel production.

While electric generation has been the traditional role for fusion energy, the use of fusion in synfuels and chemical production has recently begun to be examined in detail (Fillo, Booth) [1,2,3]. Fusion energy can split water into hydrogen and oxygen. Hydrogen has many potential energy related uses—directly as a fuel for industrial processes, as a feedstock for chemical production (e.g., ammonia) or metal refining (e.g., H-iron), as a blend with natural gas for space heat, or as feedstock for the production of synthetic hydrocarbon fuels. Ultimately, synfuel production may be the most important application of fusion energy.

Of the potential hydrogen production processes using fusion energy, HTE appears attractive. HTE should have the highest fusion to hydrogen efficiency, ~50-65%, depending on operating conditions and power cycle. HTE cells have operated satisfactorily for thousands of hours at ~1000°C; while engineering development of large systems would be necessary, no fundamental problems are foreseen.

Brookhaven National Laboratory (BNL) has been engaged in carrying out a scoping design study called HYFIRE (Fillo) [4]. HYFIRE is similar to the commercial fusion Tokamak reactor, STARFIRE, except that it has an HTE system to produce hydrogen and oxygen and a different blanket and power cycle system.

The electrochemical decomposition of water into hydrogen and oxygen is an endothermic reaction requiring both heat and electricity. In addition to generating high temperature steam which provides the thermal energy for water decomposition, HYFIRE also generates electricity which is used in the HTE cells (and for operation of fusion reactor systems like magnets and RF heating) to make hydrogen. Two blanket types are necessary; the first type heats steam to high temperatures (T~1400°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. The HYFIRE blankets are thus fundamentally different from the STARFIRE blanket.

Fourteen MeV neutrons have a long range in matter and will deposit their energy deep inside reactor blankets. This unique feature of fusion neutrons can be used to generate very high temperatures for high-efficiency hydrogen processes. The interior of the blanket can be kept at much higher temperatures than the first wall and module structure if the latter is thermally insulated from the interior and cooled by a separate coolant circuit.

Studies of such "two-temperature zone" blankets (Powell) [5] indicate that the equivalent of approximately 60% of the total fusion energy can appear as high-grade heat in the blanket interior. Heat leakage from the hot interior will be only a few percent of that deposited in the interior. The energy deposited in the hot interior can then be directly transferred to high temperature process steam which flows to the high temperature electrolysis cells. This avoids the need for high temperature heat exchangers which would be very difficult to develop.

The design aspects of fusion synfuel blankets are examined in this paper. Such blankets (both those supplying steam to electrolyzers and those supplying heat to the power cycle) must meet a number of important criteria:

- o Average tritium breeding ratio for the reactor must exceed one,
- o Reasonable pressure drops,
- o High fraction of fusion energy in insulated hot interior,
- o Low thermal leakage from hot interior,
- o Reasonable electrical generation efficiency (40% or greater), and
- o Good material properties and stresses.

Studies of synfuel blankets indicate that these criteria can be met and that practical blankets can be designed.

2. HTE Synfuel 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.

As temperature increases, the reaction enthalpy remains virtually constant. The electrical energy input, however, decreases with increasing temperature while the thermal energy input increases. The increasing fraction of thermal energy as electrolysis temperature increases results in a higher process efficiency, so that more hydrogen can be produced for a given fusion energy input. At the projected HTE temperature of 1400°C in HYFIRE, hydrogen efficiencies of 55% (fusion energy to hydrogen chemical energy can be achieved.

For the HTE operating conditions ($T \sim 1400$°C, 10% conversion of steam to hydrogen) in HYFIRE, approximately half of the input energy to the HTE cells comes as thermal energy from the sensible heat of the steam and half as electricity.

Conventional electrolysis of water is carried out at near ambient temperatures with liquid water as the electrolyte. In HTE, steam is electrolyzed using a solid ceramic electrolyte. The electrodes can be high-temperature metallic or ceramic materials.

Extensive work has been done on the use of solid electrolytes for the 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 Development Laboratories (Isenberg) [6]. The Westinghouse fuel cell design is based on a thin layer electrochemical cell supported on a thick ceramic porous base. This approach permits significant reductions in electrolyte thickness. In earlier designs where the electrolyte was self-supporting, electrolyte thicknesses were large and performance relatively poor. A schematic of the Westinghouse fuel cell is shown in Figure 1. This design also serves as the basis for the high temperature electrolyzer since an electrolyzer is a fuel cell in reverse.

For 1000°C operation, the cells are composed of a porous nickel cermet hydrogen electrode, a doped indium oxide oxygen electrode, and a $ZrO_2$-$Y_2O_3$ electrolyte which is vapor grown to a thickness of several tens of microns. Typically, current densities in the electrolyte are on the order of 500 mA/cm$^2$. The cell is adaptable to mass production, with each component laid down successively in a manner similar to the production of integrated semiconductor circuits.

In order to keep electrode currents within acceptable limits, successive cells along each electrolyzer tube are connected in series. A large number of electrolyzer tubes are then connected in parallel in a large pressure vessel.

Brown Boveri, in the Federal Republic of Germany, has tested solid oxide fuel cells for extended periods of time. Single cells have operated for over 34,000 hours (Rohr) [7], and lifetimes of more than five years are expected. This cell uses nickel anodes, a lanthanum-nickel oxide cathode, and a 1.2 mm thick electrolyte.

## 3. HTE Synfuel Blanket Design

Synfuel applications are dependent on blanket and materials development. The fusion blanket provides three functions: 1) convert neutron energy to high-temperature process heat, e.g., steam for electrolysis, 2) convert neutron energy to high-temperature thermal energy for input to an electrical power cycle, and 3) breed tritium. The latter two functions have been extensively studied in fusion electric generation designs (Badger) [8].

Figure 2 illustrates a "two-temperature zone" blanket module that supplies high-temperature process steam to the electrolyzers. This type of blanket was first proposed as a way of using an aluminum structure in fusion blankets to achieve extremely low radioactive inventories. The low-temperature structural shell of the module has a separate coolant circuit and is thermally insulated from the hot interior. The neutron and gamma energy deposited in the hot interior ceramic bed heats the high-temperature steam flowing through it.

For a fusion/HTE reactor, the blanket would be divided into two regions—the first would supply steam and process heat to the electrolyzers while the second would provide heat for the power cycle that generated electricity for the electrolyzers. Because of the necessary very high internal temperatures, e.g., 1400°C in the steam-cooled process heat modules, the blanket modules in the first region must be of the two temperature zone type. They would have water-cooled metal shells (e.g., of stainless steel) at a relatively low temperature, e.g., ~300°C. The interior of each module would have steam-cooled refractory oxide rods operating at a much higher temperature, e.g., ~1400°C.

Approximately 40% of the reactor would be covered by process heat modules; modules in the remaining 60% of the blanket would provide heat for the electrical power cycle and would breed tritium. Of the fusion energy captured by the HTE process heat modules, most (~50-60%) would appear in the high-temperature steam coolant. The remainder would be removed by the coolant for the low temperature shell and used for electrical power generation.

The modules for the electric generation cycle can be of the single-temperature or two-temperature type. In the BNL HTE designs, they have generally be of the latter type however, with a He cooled interior (SiC, Be, and $LiAlO_2$) at ~800°C and water cooled module shells stainless steel) at ~300°C. The two-temperature zone construction permits one to achieve good thermal cycle efficiencies, on the order of 40%, while keeping the stainless structure at temperatures which enhance its resistance to radiation damage.

The breeding blanket uses Be as a neutron multiplier in the front of the hot interior, followed by a neutron moderating region (ZrC or SiC) in the rear. $LiAlO_2$ is the absorbing material for tritium breeding. About 70% of the total fusion energy (~24 MeV/fusion) is deposited as heat in the hot interior.

The breeding ratio achieved in the breeding blanket must be high, >1.5, in order to have the average breeding ratio for the fusion reactor as a whole exceed one. In fact, it appears necessary that some partial breeding be carried out in a back breeding zine behind the process steam modules. In order to allow sufficient margin for neutron losses to penetrations (for example, pumping and beam lines) as well as errors in neutron cross sections, the average of T/n for the reactor should be on the order of 1.1. For a breeding ratio of 1.55 in the breeding modules, this requires that the breeding zone behind the process steam modules achieve a breeding ratio of 0.4 or greater.

Neutronic analyses of process steam modules have also been carried out. For optimized designs, a breeding ratio of 0.50 can be achieved while retaining a high fraction (∿45%) of fusion energy deposited in the steam cooled interior and reasonably good Q values (22 MeV/fusion).

4. HTE Synfuel Blanket Thermal Hydraulics

Thermal hydraulic analyses have been carried out for a wide range of conditions, with numerical values for the parameters chosen to determine the dominant effects on blanket design from a thermal hydraulics point of view. Both HTE and power/tritium modules have been analyzed. The pressure of the helium coolant for the hot interior is typically on the order of 30 atm, $\Delta T$ on the order of 400°C, and the pumping power on the order of 1-2% of the blanket thermal power. In effect, the helium coolant circuit conditions are roughly comparable to that in the HTGR, with the principal difference being the somewhat lower pressure for the primary circuit than the HTGR.

The water coolant conditions for the tubes in the module shells will approximate those in PWR's with a pressure of ∿2000 psi, a top temperature of ∿300°C, and peak heating fluxes of ∿1 $MW/m^2$. The Bremstrahlung surface heating on the sides of the tubes facing the plasma (Figure 2) is of the same order as the heating in the module shell. This tends to flatten the azimuthal heat flux distribution around each tube. The pressure drop in the water circuit can be kept to less than one atm.

Depending on the HTE process design, the thermal hydraulic conditions in the steam-cooled portion of the HTE process heat modules can be more limiting than those in the He or $H_2O$ coolant circuits for several reasons: 1) the coolant is a gas (steam) at a relatively low pressure, e.g., 10-20 atm (compared with He at ∿40 atm), 2) the temperature rise of the coolant in the blanket can be as low as 1150°C (compared with the He circuit where $\Delta T$ is ∿400°C) if it is pegged to the temperature drop in the electrolyzer unit, and 3) the coolant can make a large number of passes, on the order of 10, through the blanket if it passes in series through a corresponding number of process heat modules.

Typical results for thermal hydraulic analyses for the HTE process heat modules are summarized in Figure 3. The interior of the hot steam module is composed of a packed bed of zirconia rods, 1 cm in diameter, with the rod length varying from a minimum of 3 m to a maximum of 5 m.

In the pressure drop plot of Figure 3, the effects of varying independent parameters such as maximum steam temperature, steam pressure, and so on, are shown in a unique way. Lower, average, and higher on the abcissa refer to the independent parameters at the specific values indicated on the plots. For example, the plenum height is varied from 3 cm (lower), 5 cm (average), to 7 cm (higher). To calculate the pressure drop for plenum heights of 3 cm and 7 cm, average values of all other parameters are used. This will also be the case when the steam temperature and other parameters are varied. Values of the pressure drop at intermediate values may be found by interpolation as well as extrapolation. The pressure drop increases by increasing the module diameter for the same set of independent parameters. Except for a 3 cm plenum height, the pressure drop may be kept to less than 1 atm throughout the blanket module. The parameter values are representative of expected blanket design figures so that the range of pressure drops are, indeed, a good cross section of blanket performance.

Changing the maximum steam temperature, rod length, and heating fraction of the hot interior bed have little effect on the pressure drop. On the other hand, changing the plenum height, void fraction in the hot interior, temperature increase in the bed, and steam pressure have a more pronounced effect on the pressure drop. Flow—in these uses—has been across the blanket bed, resulting in lower pressure drops since the flow path is less than a meter compared with 3-5 m for longitudinal flow.

Eight passes in series would result in a total pressure drop of ~1.2 atm for the 25 cm diameter module which is probably acceptable. For larger diameter modules, e.g., 40 cm, the pressure drop is ~2.4 atm. This is probably somewhat too high. These results are based on average values. There are ways, though, to reduce the pressure drop as indicated in Figure 3, although some options may result in other adverse effects. For example, increasing the steam pressure to 40 atm reduces the pressure drop ~30%, but the wall structure thickness would have to increase. More neutron energy is then deposited in the thicker structure rather than in the high-temperature interior. Consequently, any design change to reduce pressure drop must be carefully examined for its effects on neutronics and structral aspects.

The ball bed or rods will be somewhat hotter than the local steam temperature. The total surface area in the bed is very large, however, so that even with a relatively low film coefficient, the peak temperature difference between the bed and steam is estimated to be only ~50-100°C.

In summary, both pressure drop and film temperature drop appear reasonable with steam coolant for the HTE blanket modules. Optimum parameters and/or designs may be somewhat different than shown here, but not significantly so.

5. HTE Synfuel Blanket Materials

The feasibility of any fusion blanket primarily relates to materials. The modular blanket structure must maintain vacuum integrity in the highly damaging neutron environment for years. Thermal cycling and sputtering effects will also be important. Most designs postulate periodic blanket replacement, but a lifetime of several years or more is needed for practical reactors. This problem will be common to all blankets, regardless of whether they are used to generate synfuels or electricity. Materials research and development efforts in the fusion program are expected to lead to satisfactory materials for first walls and blanket structural shells.

Questions related to the special interior materials for an HTE blanket, however, need to be investigated. The stability of refractory oxides, such as $ZrO_2$ or $Al_2O_3$, in the interior region of the blanket is crucial. These materials will be exposed to high-temperature steam or steam/hydrogen process streams and will be subject to neutron damage, radiation, and cycling. The oxide refractories in the HTE blanket interior will be in the form of rods or balls, with the thermal insulation between the high-temperature interior and the structural shell being a low-density block or fibrous mat.

These materials must not crumble and inject large amounts of fines into the process stream and must maintain thermal insulation capability during the life of the blanket. Materials compatibility tests in the steam and steam/hydrogen mixtures have been carried out at BNL (Horn) [9]. These indicate that $ZrO_2$ and $Al_2O_3$ have negligible weight loss up to the maximum temperatures studied, ~1500°C (Figure 4). The effects of radiation exposure have not been investigated, however, and should be examined as part of the fusion materials development program.

Critical to the successful operation of the BNL two temperature zone blanket is the performance of the insulator separating the two temperature zones. In addition to low thermal conductivity, the insulating material should have high resistance to radiation damage, should maintain its structural integrity in the coolant/radiation environment, and should have low density to minimize total internal heat generation within it. It should also be compatible with its gaseous environment—steam for the process heat modules, helium for the electric generation modules.

Table I summarizes the results of the materials tested in air, argon, helium, and steam in a non-radiation environment. The thermal conductivity tests in helium were limited to temperatures on the order of 800°C due to the power requirements of the heater, so that the data shown at 1000°C are extrapolated values. At this temperature there appears to be not much difference between the five insulations tested. The zirconia felt has the lowest conductivity (0.40 W/m-K) and the alumina-silica mat the highest (0.54 W/m-K).

In summary, the zirconia felt has the lowest thermal conductivity at 1000°C but its density is three times that of the carbon felt and two times the alumina-silica mat density. The graphite felt would have equal insulating performance in helium as that of zirconia felt but 25% thicker. The increase in weight would still make it one of the lightest of the insulations; therefore, at this point, graphite felt would be the preferred insulation for the helium-cooled electric generation modules. Of the materials tested, though, all have approximately the same thermal conductivity values in the temperature range of interest; are all compatible with helium; and all would be acceptable for the electric generation blanket modules.

The choice is not so clear for insulating the steam-cooled modules. Graphite has been tested in steam at ~900°C and appears satisfactory up to this temperature; however, it does not appear likely that it would be suitable all the way up to 1400°C. The best insulator from the standpoint of compatibility with $ZrO_2$ hot interiors would be $ZrO_2$ felt, perhaps with some graphite felt in the cooler regions adjacent to the first wall and structural shell.

## 6. Summary and Conclusions

Fusion is a promising source for synthetic fuels. The unique ability of fusion energy to generate very high process temperatures should result in efficient processes for the generation of hydrogen from water decomposition. Hydrogen can be directly used as a fuel or combined with carbon to produce portable liquid or gaseous carbonaceous fuels.

Of the many potential processes for hydrogen production, HTE of steam appears to be the most promising. HTE cells have operated at high temperatures for long periods. The process steam would be supplied from high-temperature, two zone fusion blankets. The overall efficiency, fusion-to-hydrogen chemical energy, is projected to be in the range of 50-70%, depending on the process conditions and type of power cycle. Large-scale HTE technology can probably be developed by the time that the first commercial fusion reactors would be operating.

Blankets for HTE fusion reactors appear practical: tritium breeding is adequate, thermal mal-hydraulic performance is good, and the required material performance achievable.

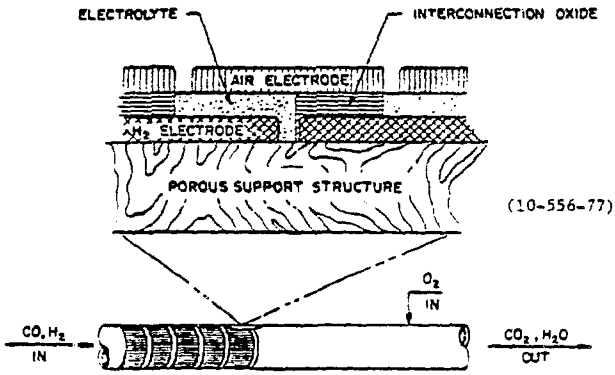


FIGURE 1 HTE Cell for high temperature electrolysis (Westinghouse Design).

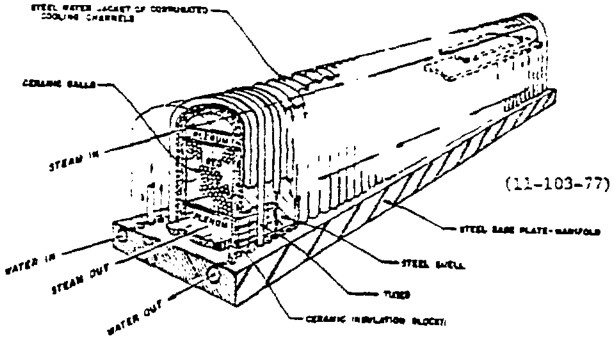


FIGURE 2 HTE process module, 5000 MW reactor.

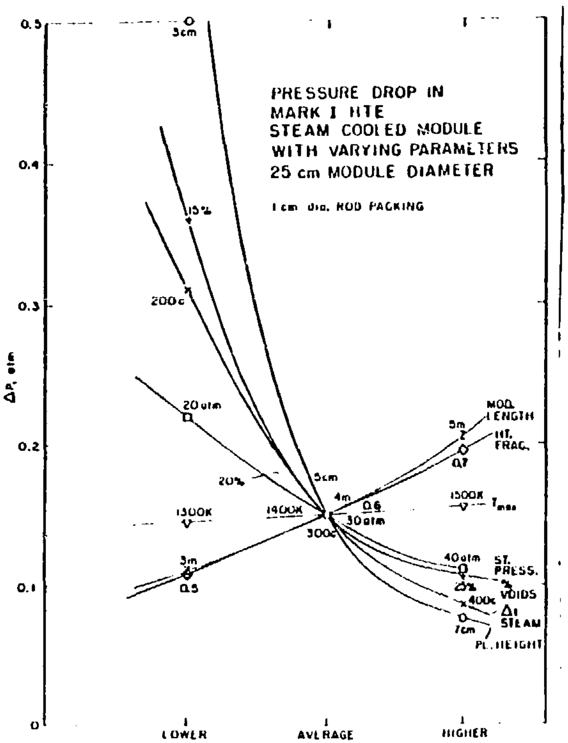


FIGURE 3 Pressure drop in Mark I HTE steam cooled module, varying parameters.

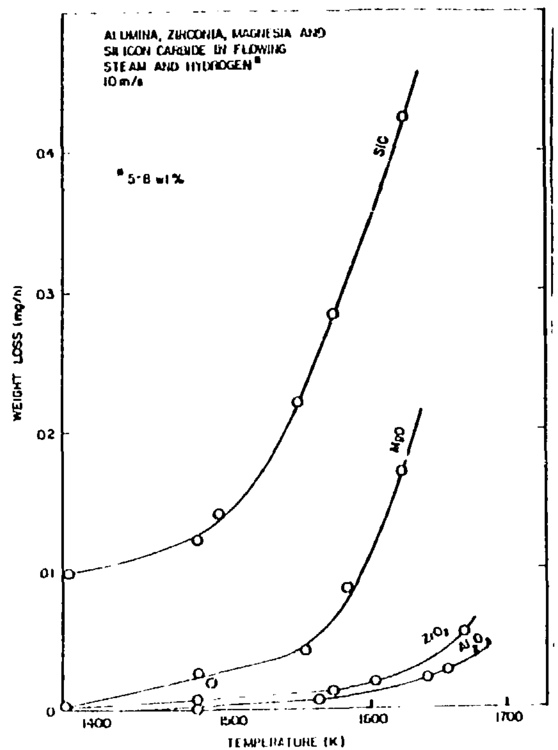


FIGURE 4 Alumina, zirconia, magnesia, and silicon carbide in flowing steam and hydrogen.

TABLE I

SUMMARY OF MATERIALS TESTED

**Thermal Conductivity of Insulators in the Temperature Range of 300-1000°C**

| | Watts/m-K | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Air | | Argon | | Helium | | Steam | |
| | 300°C | 1000°C | 300°C | 1000°C | 300°C | 1000°C | 500°C | 1000°C |
| Alumina-silica mat, 8 lb/ft$^3$ | .06 | .22 | .07 | .28 | .24 | .54 | — | — |
| Carbon felt, 5 lb/ft$^3$ | — | NA | .11 | .29 | .24 | .51 | .11 | .25 |
| Graphite felt, 4 lb/ft$^3$ | — | NA | .11 | .27 | .26 | .51 | .25 | .45 |
| Zirconia fibrous board, 24 lb/ft$^3$ | .07 | .14 | .07 | .14 | .15 | .49 | .14 | .16 |
| Zirconia felt, 14 lb/ft$^3$ | .08 | .17 | .08 | .17 | .18 | .40 | .07 | .26 |

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