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HYDROGEN PRODUCTION FROM FUSION REACTORS COUPLED WITH HIGH TEMPERATURE ELECTROLYSIS*

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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 complement 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. Processes which may be considered for this purpose include electrolysis, thermochemical decomposition or thermochemical-electrochemical hybrid cycles. Preliminary studies at Brookhaven indicate that high temperature electrolysis has the highest potential efficiency for production of hydrogen from fusion. Depending on design electric generation efficiencies of ∿40-60% and hydrogen production efficiences of ∿50-70% are projected for fusion reactors using high temperature blankets.

INTRODUCTION - FUSION AS A SYNTHETIC FUEL PRODUCER

Need for Synthetic Fuels Using Some Type of Inexhaustible Resource

World reserves of oil and gas are being rapidly depleted and the general consensus is that they will be essentially gone in a short period of time. Many of the industrialized nations, the United States for example, are now importing a large fraction of their petroleum needs, with consequent worries about sources of supply to maintain continued growth patterns, future prices, and effects on the balance of payments.

It is generally believed that future energy demands which have in the past relied on oil and gas will in the future have to be supplied by alternate sources. This will mean an increased reliance on established energy sources such as coal and nuclear (LWR) to meet the projected energy deficit.

Coal can supply both electricity and synthetic portable fuels, but there appear to be concerns about the degree to which it can meet future demands, in terms of production rates, total available resources, and possible harmful environmental effects. For example, the potential long-range climatological effects of large additions of CO_2 to the atmosphere are being studied.

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Nuclear (LWR) sources, though, will supply energy primarily to generate electric power. This will help to abate some of the demands for oil and gas. However, for a number of demand sectors, practical technology has not yet been developed (and may never be) for direct electrical use. Also, nuclear (LWR) may be found wanting as an energy source in a few decades due to heavy pressure on uranium reserves. The long-range prospects for nuclear energy deployment also depend upon demonstration of terminal waste disposal technology and resolution of broader energy policy questions.

These conditions have led to an increased interest in identifying a way to produce substitute fuels from the inexhaustible energy sources, that is, solar, geothermal, fission (breeder), and fusion. Thermonuclear fusion as a future inexhaustible energy source appears to have the advantage of relatively high power density as compared to alternate inexhaustible energy sources such as solar or geothermal, with the potential of favorable economics. Further, it has no apparent geographic or climatological constraints. The supply of deuterium and lithium fuels for fusion reactors appears to offer no significant resource concern. If the synthetic fuel derived from fusion energy is hydrogen, it can serve multiple functions; as a chemical feedstock for much more efficient coal liquefaction and gasification; ammonia production and metal-ore reduction; as an efficient source of electricity by using fuel cells; and ultimately, as a primary transportable fuel. The supply of hydrogen would be virtually unlimited since it is obtained from water.

Inexhaustible fission technologies, such as the LMFBR or GCFR can also be considered as a source for the production of synthetic fuels based on hydrogen. Here, however, the primary product is expected to be electricity, and production of synthetic fuels will probably have to follow the route of conventional electrolysis, at a relatively low efficiency compared to the potential for fusion reactors.

In contrast, fusion reactors have the potential to supply unique energy forms (e.g., radiation and very high temperature heat) that may lead to significantly increased efficiency for the production of synthetic fuels. An evaluative study of the application of fusion energy to synthetic fuel production has been recently carried out [1] which identifies a number of promising approaches.

Basic Options of Hydrogen Production from Fusion

Three basic candidate methods of hydrogen production from neutron energy have been identified: a) direct decomposition including high temperature electrolysis; b) thermochemical cycles including partial radiolysis; and c) direct radiolysis. While comparision of these methods are difficult to make, engineering judgment can be exercised so that expected relative efficiencies of the processes and relative engineering feasibility, i.e., complexity, materials compatibility and temperature limitations, mechanical design requirements, etc., can be made. Based on these subjective comparisons, preferential ranking of the above methods is possible and is discussed in some detail in the panel study [1] on fusion synfuels production. One of the most promising is high temperature electrolysis which is expected to have the highest efficiency [∿50-55% based on a conventional power cycle (40% efficient) and as high as 70% with an advanced power cycle (60% efficient)]. Its technology is also more near at hand compared, for example, with thermochemical or radiolysis.

The preliminary evaluations developed in Ref. [1] were the basis for choosing high temperature electrolysis for the fusion synfuels conceptual design [2] reported here.

Synthetic Fuels Using Fusion

The high energy neutrons from DT fusion reactions can penetrate very deeply into materials before their kinetic energy is transformed to heat. This unique feature of fusion energy, and the fact that ∿80% of the energy released per DT fusion reaction is carried by 14 MeV neutrons, can dramatically increase the efficiency of electric power generation, as well as produce H_2 and H_2 based synthetic fuels at high efficiency.

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, operates at very high temperatures. Separate coolant circuits are required for the two temperature regions, as well as a thermal insulator between them.

Materials for the hot interior are capable of much higher temperatures than HTGR type conditions (800°C). Further, the coolant for the hot interior need not be helium, but can be a process fluid like steam or CO_2. This direct heating feature eliminates the transfer of high temperature heat across a metallic primary heat exchanger, which could severely limit the maximum temperature and choice of coolant.

Table I shows the melting points of some candidate high temperature refractory materials for the hot interior. All appear compatible with helium or argon coolant. Only the oxide refractories, and perhaps some carbides (e.g., SiC), would be compatible with steam or CO_2 coolant. The hot interior probably would be a packed bed of small diameter (1-2 cm) rods or balls. The low peak power densities (∿10 MW/m^3) and the large surface area in the blanket should result in relatively low temperature differences (on the order of 100°C) between the coolant and the packed bed.

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 characteristic time for release into the inert gas coolant is only a few minutes, 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 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.

Direct heating of steam by neutron energy to high temperatures in refractory oxide fusion blankets appears practical, and is the mode of generating process heat for the high temperature electrolysis process. Circulating high-temperature steam through the blanket poses some engineering design problems, but these are not deemed insurmountable. A high temperature electrolysis process should generate H_2 from water at an overall efficiency of ∿50-70 percent depending on design. Since hydrogen production cost by electrolysis is primarily determined by electric power cost, the fact that high temperature process blanket steam is used for directly decomposing water to H_2 and that high overall efficiency (50 percent compared with 30-35 percent by conventional electrolysis) can be achieved, implies significant potential economic advantages of a fusion-HTE system.

The previously noted unique ability of fusion neutrons to directly heat the interior of a blanket to very high temperatures, offers great potential for the high efficiency power cycles using fusion heat. The FAST (Fusion Augmented Steam Turbine) power cycle (discussed in Section 4) can admit steam, superheated directly in the blanket, to the turbine inlet at temperatures of ∿2000°F. Power cycle efficiencies of ∿60 percent appear possible under these conditions with a power cycle efficiency of 60 percent and HTE units operating at 1800°C. The potential efficiency for generation of H_2 from fusion energy is very high, on the order of 70 percent.

FUSION-HTE SYSTEM

The hydrogen production process couples fusion, the primary inexhaustible energy source, with high temperature electrolysis, i.e., the direct decomposition of water at temperatures where a significant fraction of the decomposition energy is provided by thermal energy. Steam is transported from the blanket system and distributed to the electrolyzers, the balance of energy being made up by electrical work supplied to the electrolytic cells. The latter source of work is a result of converting a fraction of the fusion energy to thermal energy which is then converted to electricity in a standard thermal cycle. A simplified process flow sheet which couples the three basic elements of the system with hydrogen and oxygen as products is shown in Fig. 1.

A conceptual design depicting the system is shown in Fig. 2. The electrolyzers are contained in pressure vessels which surround the Tokamak fusion reactor and are housed outside the reactor assembly in separate compartments. They are fed steam directly from the high temperature blankets.

The last compartment contains the heat exchangers for H_2 separation as well as the hydrogen storage vessels. To maintain a high steam/H_2 mixture temperature, the mixture is sent back to the blankets for reheat. The number of electrolyzers is a function of temperature drop across the electrolyzers and hydrogen production requirements. Electrical requirements for the electrolysis process are served by the power conversion unit. The electrical generating plant houses the turbines and steam generators as well as auxiliary systems. Power conversion is based on a helium-steam loop. Not shown are the tritium facilities which must also be considered for plasma fueling.

Blanket

With reference to Fig. 1 the high and low temperature regions refer to the fusion blanket, the high temperature region being further subdivided into two regions. The blanket must satisfy three basic functions: 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. The latter two functions are carried out in a helium cooled blanket, the tritium diffusing into the helium stream to be trapped out by absorption or conversion to gas and then trapped out by absorption. It may also be possible to breed tritium on the surface of the process heat (steam) module.

The low temperature region is common to both types of blankets while the subdivision of the high temperature region refers to either the process heat or electric production modules.

In either blanket design the structural shell is stainless steel. The process heat (steam) modules contain a high temperature oxide such as MgO, ZrO_2, Al_2O_3, or SiC. The shell is thermally insulated from the high-temperature refractory material and is independently cooled by a bank of coolant tubes. The insulator may be a fibrous material, compatible with the high temperature oxide.

The shell structure, ∿0.75 cm thick, is maintained at ∿350 to 400°C. Typically, 30 percent of the fusion energy is deposited in this region assuming no thermal leakage from the high temperature zone. The coolant tubes are compatible with the shell structural material, and in the stainless steel design, the tubes are typically ∿0.5 cm ID, 0.2 cm wall thickness. Low temperature steam and/or water mixture is the coolant. Operating conditions are ∿2000 psi. The high temperature refractory zone is either a packed ball bed or rods through which steam, ∿1500 to 2000°C, is passed. If tritium breeding is required in the high temperature blanket, $LiAlO_2$ may be placed between the coolant tubes and shell with tritium diffusing into the plasma chamber. Preliminary calculations indicate that breeding ratios of ∿0.5 to 0.7 may be achieved. The deficit in tritium is provided by high breeding blankets designed for electric power production. Actually, calculations indicate that the high breeding blankets would provide sufficient tritium so that additional make-up would not be required.

A promising fabrication approach to the design of the process heat modules is shown in Fig. 3. 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. Fig. 4 shows a typical access port arrangement for a Tokamak reactor.

Structurally the electric production and high breeding blankets are essentially the same as the high temperature blankets, the outside shell being cooled by a bank of coolant tubes which operate at the same process conditions as noted before. A neutron multiplier, Be or PbO, and a solid lithium compound, $LiAlO_2$ and neutron moderator replace the high temperature refractory. These materials are thermally insulated from the structural shell by a fibrous graphite cloth. The multiplier-breeder-moderator zone is cooled by helium at 700 to 800°C and 30 atm.

In these designs tritium breeding occurs in the hot interior of the module with the bred tritium rapidly diffusing out of the solid lithium compound (e.g., $LiAlO_2$) into the He coolant from which it is trapped by absorption in a metal hydride or by conversion to T_2O and absorption in molecular sieve material. The neutron multiplier (e.g., PbO, Be) is used in the portion of the module near the first wall in order to maximize the tritium breeding ratio. The breeding ratios are relatively high with a PbO neutron multiplier (1.3) and very high with the Be multiplier (1.8).

The fabrication approach to the design of the electric production modules (Fig. 5) is essentially the same as the process heat modules. Insertion and/or removal is through small access ports in the plasma chamber.

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 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 the HTE process. The materials effort now underway in the fusion program should lead to the development of satisfactory structural materials for these applications. More specialized material problems related to the HTE applications appear, however. These are conceptual with the stability of oxides such as MgO and Al_2O_3 in the high temperature steam under radiation and thermal cycling conditions. Such materials will be used both in the form of solid rods or balls, as well as a low density solid block or fibrous thermal insulation. The principal requirement is that these materials not crumble or inject excessive amounts of fines to the coolant system and that thermal insulation capability be maintained during the life of the module. Because of the more specialized aspects of these materials, it may be advisable to ensure that they will also be considered in the fusion materials development program.

The general design concepts involved in such high temperature blankets appear feasible. Given satisfactory materials, there appear to be no bars to the development of high temperature blankets for fusion reactors using the HTE process to produce synfuels.

Design of High Temperature Electrolyzers

High temperature steam leaving the high temperature refractory zone of the blanket is distributed to the electrolyzers in ceramic-lined ducts. The high temperature solid oxide electrolyzer consists of a cooled steel symmetrical pressure vessel, internally insulated, which operates at 10 atmospheres. Steam or mixture of steam and hydrogen is fed to the electrolyzer where water is reduced to hydrogen on one side of the electrolyte and oxygen is liberated on the other. The existing H_2/H_2O mixtures are recycled back to the blanket system for reheating so that steam can be electrolyzed at a high temperature. When the hydrogen concentration reaches the design value at the highest temperature, the gas mixture passes into a series of lower temperature electrolyzers. The endothermic electrolysis reaction cools the gases to a temperature where conventional heat exchangers can be used.

The oxygen generated in the first series of high temperature electrolyzers passes directly to the low temperature electrolyzers without reheating. The low temperature electrolyzers, have oxygen inlet and outlet ports, while the high temperature vessels require only an oxygen exit port for the oxygen produced in the electrolyzer.

A schematic diagram of the HTE is shown in Fig. 6. The diameter of the vessel is 3.5 m and the length is 6.8 m. The central plenum receives the high temperature steam entering the HTE. Two adjacent plenums collect the gas after electrolysis in the tubes. These are next to the large regions in which the oxygen is produced. The two end sections of the HTE unit are at low temperature, and house electrial connections at the end of the electrolyte tubes.

A major factor in the design of the electrolyzers is the minimization of thermal stresses due to heating and cooling and temperature cycling during operation. The outer cooled region of the containment vessel is held at virtually constant temperature at all times and will not experience any significant problem. Internal components, on the other hand, will experience temperature changes of over 1400°C and large dimensional changes when the HTE unit starts up from or shuts down to room temperature. The tubes, for example, are designed so that one end is fixed, with the other free to move, to accommodate the dimensional changes.

The gas entering the HTE is H_2O in the first electrolyzer and a mixture of H_2O and H_2 in subsequent electrolyzers. This gas is distributed from the central plenum through feed tubes. The feed tubes are 2.4 m long and 5 mm in diameter, and can be joined tubes that are sealed together. The feed tube has spacers to center it in the electrolyte tube and can support the outer tube at high temperatures if required. The feed tubes are centered within the electrolyte support tubes as shown in Fig. 7. The gas passes through the feed tube to the base of the electrolyte support tube. It then passes between the tube and feed tubes to the second plenum. During passage the gas diffuses across the porous support tube to the cathode where it is electrolyzed to hydrogen and cooled by the endothermic reaction.

The two tube sheets which hold the feed tubes are both constructed as interconnecting sections which are sealed together with a ceramic braze. Each section is 0.5 m square with 46 tube rows of 45 each. The shapes of the sections are designed to conform with the ceramic insulation and support around the walls.

The electrolyte support tubes are constructed as shown by the schematic in Fig. 7. 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 tubes are closed at one end. Each end has a conduction oxide layer. At the closed end the conducting surface oxide is in electrical contact with an oxide cap which passes through the insulation. The end of the cap is at a temperature where metal can be used in the oxidizing atmosphere. The metal continues the electrical path to a conducting plate at each end of the vessel. The plate in turn is connected to an insulated terminal through the pressure vessel. These components are shown schematically in Fig. 7. The open end of the electrolyte support tube with its conducting oxide is sealed into the tube sheet section with a conducting seal. The seal in turn makes contact with a conducting oxide facing the tube sheet sections which are also sealed together with a conducting ceramic seal. These details of the electrolyte support tube are also shown in Fig. 7.

The high temperature solid oxide electrolyzer is supported on a porous zirconia tube as shown in Fig. 8. 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 IR losses or overvoltages. At temperatures close to 1650°K a thickness of ∿ 1.0 mm is acceptable whereas at 1000°K a 10 μ electrolyte layer would be required. The materials of construction are, for example, $ZrO_2 - Y_2O_3$ 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.

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.

There are losses due to excess voltage that may occur during the flow of current. These include electrochemical polarization losses and resistance losses. The resistance losses arise because of the resistivity of the electrodes, electrolyte, and interconnection materials. These can be reduced by proper cell design and geometry. The polarization losses are related to the electrochemical reaction kinetics. They may be due to the intrinsic activation energy of the reaction which at high temperature may be negligible but which will have to be checked experimentally. The second polarization loss arises due to concentration gradients or slow migration of reactants to the interface. The latter have been considered and discussed by Tedmon, et. al. [3] and are not expected to be a problem at the temperatures of interest.

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 out 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.

There are alternative methods to recover heat from the oxygen and steam/hydrogen streams. For example, one can take saturated steam from the turbine as make-up steam and send it to the O_2 heat exchanger and hydrogen/steam heat exchanger to recover the heat. The remaining heat of oxygen and steam/hydrogen streams would be recovered from water in a hydrogen separation unit where hydrogen is separated out from steam by condensation. The coolant water from the hydrogen separation unit would be returned to the boiler feed water of the power cycle loop.

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 ∿ 60 percent with a FAST (Fusion Augmented Steam Turbine) cycle (discussed in the next section). This implies that the overall hydrogen process efficiencies would be high, ∿ 65 to 70 percent, for high temperature electrolysis as well as low temperature electrolysis, ∿ 60 percent.

FAST(FUSION AUGMENTED STEAM TURBINE) CYCLE

For the FAST cycle steam is superheated directly in the hot interior of the blanket module. Open cycle gas turbines presently operate at much higher inlet temperatures than the conventional steam turbine. The latter has been held at an inlet temperature of ∿ 1100°F for many years because of material temperature limitations in the steam generator/superheater. The present inlet temperature for gas turbines is ∿ 2000°F (1090°C) with a projection of ∿ 2400°F (1320°C) by the early 1980's [4]. With direct superheating of steam in fusion blankets, overall cycle efficiency can be raised from the ∿ 38% level achieved in fossil fuel steam plants to a level of ∿ 60% assuming that the turbine inlet temperature is 2000°F (1090°C).

High temperature turbine cycles based on the combustion of hydrogen and oxygen have been extensively investigated [5,6] with projected turbine inlet temperatures up to 3000°F. Operation at these temperatures will require development of water cooled or ceramic blades. This would increase the efficiency of the FAST cycle to ∿ 70%; however, the increase may not warrant the major turbine development program that would be required.

Figure 9 shows a flow sheet for the FAST cycle. Approximately 30-50% of the steam in the turbine circuit flows through the blanket, emerging at a high temperature, typically 1500-1800°C. It then mixes with the main steam flow; the resultant mixed temperature is controlled to the desired turbine inlet temperature by the relative flow proportions. Bypassing most of the steam flow around the blanket reduces blanket pressure drop, flow velocity, piping dimensions, and the carry over of blanket fines. Fig. 10 shows the efficiency of the FAST cycle as a function of turbine inlet temperature from 1600°F (870°C) to 2400°F (1320°C), for the case of three reheats and the limiting case with continuous reheat, turbine inlet pressure of 2000 psia, and exhaust pressure of 1 psia. The FAST cycle efficiency of ∿ 60% which could be achieved with essentially developed turbine technology, can be very important for fusion. It will greatly reduce unit $/KW(e) capital costs for a fusion power plant, as well as reduce the thermal pollution levels per KWH by a factor of 3, as compared to LWR.

An additional feature of the FAST cycle is the efficient use of the hot/cool energy splits in the blanket. The fusion energy from the cool structure produces high pressure saturated steam, and the high temperature heat from the interior superheats it. Alternate advanced power cycles that only use the high temperature need very high efficiency to match the FAST cycle, since the low temperature heat from the structure only produces ∿ 33% efficiency in a separate conventional steam cycle. For a 70/30 hot/cool split, an alternate cycle would require an efficiency of 70% to achieve an overall average efficiency of 60% for the reactor.

RESULTS OF DESIGN STUDY

Efficiency Considerations

The basis for the energetics of a high temperature electrolysis process for hydrogen production is the thermodynamics of the decomposition of water.

$$H_2O_{(\ell)} = H_2O_{(g)} \tag{1}$$

$$H_2O_{(g)} = H_{2(g)} + 1/2\ O_{2(g)} \tag{2}$$

ℓ refers to liquid state

g refers to gaseous state

The free energy change in an isothermal process is expressed by

$$\Delta G = \Delta H - T\Delta S \tag{3}$$

where

ΔG = free energy change for reaction (2), Kcal/mol

ΔH = enthalpy change for reaction (2), Kcal/mol

T = absolute temperature, °K

ΔS = entropy change for reaction (2), Kcal/mol °K

The electrolytic decomposition of water is controlled by the relationship

$$\Delta G = nfE \tag{4}$$

n = number of gram equivalents per atom, n = 2

f = Faraday's constant 96,500 Coulomb/gm equiv.

E = emf or voltage potential of cell, volts

In an electrolyzer, the electrical energy supplied to the cell is related to ΔG, the non-work energy needed for the decomposition is expressed by the $T\Delta S$ term, and the total energy is related to the total enthalpy change for the system, ΔH.

The thermodynamic values for the water decomposition reaction, (2), as a function of temperature, are given in Fig. 11. This information is well known and readily available from many sources; the best thermodynamic compilation dating back to the NBS Circular 500 (1952). It is noted that for this system, ΔH remains almost constant with temperature, increasing only very slightly up to temperatures as high as 4200°K. The $T\Delta S$ term steadily rises and as a result the ΔG term steadily decreases until it reaches zero at a temperature on the order of 4200°K. The quantity ΔG relates to the amount of electricity fed to the cell and $T\Delta S$ the thermal energy. What is important is that as the temperature of the cell is raised, the $T\Delta S$ term increases. The fraction of the thermal energy input required increases and the electrical energy needed decreases. Fig. 11 shows the fraction of thermal energy input and indicates that at 2160°K (1886.8°C) 50 percent of the energy input for water decomposition would be thermal energy and 50 percent electrical energy. Theoretically, at 4200°K all the energy can be put in as thermal energy for water decomposition and no electrical energy would be required. This would be a true thermal splitting of water. However, this temperature cannot be reached because other dissociative chemical reactions take place, forming the free radicals, H, O, and OH which are energy absorbing and limit the upper temperature.

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. Depending on the temperature that can be achieved in the high temperature region of the fusion reactor blanket, the ratio of thermal energy to electrical energy is fixed by the thermodynamic conditions established in Fig. 11. This means that not all the energy in the high temperature region can be used in the HTE so that the remainder must be used in the conventional power cycle to generate electrical power for the HTE. This provides the rationale for subdividing the high temperature region into two regions; one marked HTRE for the electrolyzer circuit and the other HTRP for the power cycle, the latter incorporating the helium cooled tritium breeding blanket.

To gain some estimate of the effect of temperature, a simplified energy analysis is considered to determine the efficiency of the conversion of the total fusion energy to hydrogen fuel gas energy. The analysis assumes that:

1) 100 units of thermal energy total is generated by the fusion reactor,

   70 units of thermal energy generated in the HTR,
   30 units of thermal energy generated in the LTR (x-rays, etc.)

   let x = fraction of the 70 units in HTR which can be used in HTE; this is the fraction absorbed in HTE,

   then 1 - x = fraction of the 70 units in HTR which is used in the HTRP part of the conventional power cycle.

2) The conventional power cycle operates at a maximum of 40 percent efficiency (conversion of thermal energy to DC electrical energy).

3) The high temperature electrolyzer operates at close to 100 percent current efficiency which is a fairly reasonable assumption at elevated temperatures.

For a balanced system:

$$\frac{\text{Thermal energy}}{\text{Electrical energy}} = \frac{T\Delta S}{\Delta G} = \frac{70x}{0.4\ [30 + (1-x)\ 70]} \qquad (5)$$

Assuming an average temperature for the HTE, the ratio of $T\Delta S/\Delta G$ can be obtained from Fig. 11. From Eq. (5) x can be computed. The cycle efficiency of the entire system defined as conversion of total fusion energy to hydrogen fuel gas energy is then:

$$\%\ \text{Cycle efficiency (LHV)} = \frac{0.4\ [30 + (1-x)\ 70] + 70x}{100} \times 100 \qquad (6)$$

Cycle efficiency is based on the lower heating value (LHV) of hydrogen since the thermodynamics are based on Eq. (2) for water in the gaseous state. The convention for the sale of fuel is based on the higher heating value (HHV).

The HHV efficiency is given in Table II along with the LHV and a plot of both LHV and HHV efficiency for both conventional (40%) and advanced (60%) power cycles are shown in Fig. 12. There is approximately 7 to 8 percentage points improvement in HHV over LHV. It is also noted that based on the assumptions made, ideally the highest efficiency that can be obtained is at an HTE temperature of 3600°K when x = 1 and all the HTR heat (70%) goes to the HTR and the LTR heat (30%) goes to providing the electricity. 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°K) material temperature limitations may impose practical operating limits. Below a 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 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°K (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 and would seem to justify a development program for HTE.

In addition to the H_2 efficiency gains as a consequence of high temperature, a substantially higher H_2 efficiency can be achieved with the inclusion of an advanced power cycle (60% efficiency) in the system. For example, at 1700°K 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 and would seem to justify a development program for advanced power cycles based on high temperature blankets.

Results of the conceptual design study are summarized in Table III for two maximum steam temperatures, 1377°C and 1827°C. The power cycle efficiency is found to be $\sim$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 $\sim$1400°C and 1800°C as born out by the theoretical calculations as well. Overall conversion from steam to hydrogen is 89.4% and 94.3%.

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 relies on cost estimate assumptions for individual components, such as the fusion reactor, coal-synthetic fuel plant, etc. These results are summarized in Tables IV through VI.

Before any costing can be done, some idea as to the fuel production capacity for a given fusion reactor size is necessary. Table IV includes a summary of the hydrogen fuel production capacity of the reference design HTE system based on a 2000 MW(th) fusion reactor with a conventional power cycle (CP) efficiency of ∿40 percent. These results are compared with a system operating with an advanced high efficiency power cycle (AP) operating at ∿60 percent efficiency. The maximum HTE temperature was fixed at 1600°K in both cases.

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 H_2 production would produce the energy equivalent of 20,000 bbl/day, which would fuel ∿500,000 autos with average driving patterns. A factor of three reductions 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.

Table V summarizes estimates on capital investment costs. Note that the syngas production rate is three times that reported in Table IV and is based on a 6000 MW(th) fusion reactor. 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 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.

Table VI is an evaluation of fuel production costs. 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 an 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 reserve for a grid system.

REFERENCES

1. "Fusion Energy Applied to Synthetic Fuel Production", DOE Report, CONF-770593, October, 1977.

2. "Fusion Reactors-High Temperature Electrolysis (HTE)", DOE Report, HCP/T0016-01, January, 1978.

3. Spacil, H. S., and Tedmon, Jr., C. S., Electrochemical Dissociation of Water Vapor in Solid Oxide Electrolyte Cells", J. Electrochem. Soc., 116, 1618, 1627 (1969).

4. Armstrong, C. H., "Effect of Recent Advancements in Gas Turbine Technology on Combined Cycle Efficiency", ASME Paper 74-PWR-8, Joint Power Generation Conference, Miami Beach, California (Sept. 15-19, 1974).

5. Kelley, J., "Hydrogen Tomorrow - Demands and Technology Requirements", Jet Propulsion Laboratory, Pasadena, Calofirnia (Dec., 1975).

6. Hausz, W., "Hydrogen Systems for Electric Energy", 72-TMP-15, General Electric Company - TEMPO Center for Advanced Studies, Santa Barbara (1972).

TABLE I

MELTING POINTS OF SOME HIGH TEMPERATURE REFRACTORIES

Carbides	M.P. (°K)	Oxides	M.P. (°K)	Nitrides	M.P. (°K)
HfC	4161	ThO_2	3573	TaN	3361
TaC	4148	MgO	3098	BN	3273
NbC	3773	HfO_2	3085	TiN	3205
ZrC	3533	ZrO_2	2973	ZrN	3203
TiC	3523	CaO	2843		
SiC	3100	BeO	2725		
VC	3083	Al_2O_3	2323		

TABLE II

FUSION ENERGY-HIGH TEMPERATURE ELECTROLYSIS WITH CONVENTIONAL POWER CYCLE FOR PRODUCTION OF HYDROGEN FUEL GAS

100% HTE efficiency
40% Conventional power cycle efficiency
70% of fusion energy generated in high temperature region
30% of fusion energy generated on low temperature region

Temperature °K	°C	Hi-Temp. Ht. to total energy ratio TΔS/ΔH	Hi-Temp. Ht. to elec. energy ratio, TΔS/ΔG	Fraction of HTR for HTE, x	Overall Cycle Efficiency LHV, %	HHV, %
1000	726.8	0.298	0.295	0.1508	47.0	54.8
1460	1186.8	0.333	0.500	0.238	50.0	57.3
1700	1426.8	0.390	0.639	0.292	53.0	59.9
2000	1726.8	0.464	0.866	0.355	55.5	62.0
2160	1886.8	0.500	1.000	0.408	57.2	63.5
2600	2326.8	0.605	1.530	0.542	62.7	69.0
3000	2726.8	0.712	2.470	0.710	69.8	74.6
3600	3326.8	0.854	5.830	1.000	82.0	84.6
Conv. cells						
353	80 Lurgi-80% cell eff.				32.0	45.2
398.2	125 GE/SPE-90% cell eff.				36.0	45.4

LHV=% efficiency based on lower heating values of hydrogen

HHV=% efficiency based onhigh heating value of hydrogen

TABLE III

SYNTHETIC FUELS FROM FUSION REACTORS
TABLE OF PROCESS FLOW PARAMETERS

<u>Electrolytic Cells</u>	<u>Max. Inlet Temp. to Electrolyzers</u>	
	1650°K	2100°K
ΔT/Cell	150°C	150°C
Electrical Input to Cells	598.4 MW(e)	573.7 MW(e)
Thermal Energy to Cells	392.9 MW(t)	459.8 MW(t)
Output Temp. of Steam + H_2 (last HTE)	727°C	727°C
Overall Steam Conversion to H_2	94.3%	89.4%
<u>H_2 Separation</u>		
H_2 Quality - at 9 atm and 50°C (water impurity)	98.65%	98.6%
<u>Power Conversion</u>		
High Temp. Region - T&P of Helium	800°C, 30 atm	800°C, 30 atm
Low Temp. Region - T&P of Steam (sat.)	350°C, 2400 psia	350°C, 2400 psia
Energy Split (high temp. region)	1007.1 MW(t)	940.2 MW(t)
(low temp. region)	600 MW(t)	600 MW(t)
Power Conversion Eff.	38%	38%
<u>Total Plant Efficiency</u> (HHV H_2)	49.3%	51.2%
Hydrogen Production	23.5 MT/HR	25.9

TABLE IV

HIGH TEMPERATURE ELECTROLYSIS WITH CONVENTIONAL AND ADVANCED POWER CYCLE FUEL PRODUCTION CAPACITY FOR 2000 MW(t) FUSION REACTOR

	HTE-CP	HTE-AP (FAST)
High Temperature Region - °K	1600°K	1600°K
Cycle Efficiency - %	52.5%	71.5%
Hydrogen Production - SCF/D	267×10^6	364×10^6
Hydrogen Production - MT/D	638	868
Equiv. SNG. (Methane) - SCF/D	86×10^6	117×10^6
Coal Hydrogenation with HTE H_2 - T/D	1,914	2,600
SNG. Production with HTE H_2 - SCF/D	134×10^6	182×10^6
Conventional SNG Plant Equiv. - Coal Feed T/D	5,960	8,100
HHV Equiv. Gasoline - BBL/D	14,800	20,130

TABLE V

CAPITAL INVESTMENT COST FOR A FUSION-SYNTHETIC FUEL PRODUCTION PLANT

[Basis: Hydrogen Production Rate has Fuel Equivalent Value to a 250 x 10^6 SCF/D SNG Plant]

Efficiency: Output H_2 Fuel Energy/Input Fusion Energy	Capital Cost of Plant
50%	\$2.4 x 10^9
70%	\$1.7 x 10^9

Cost Assumption: Fusion Reactor + Electrolyzers = \$400/KW(th) [\$1000/KW(e) Equivalent]

Efficiency: Output H_2 Fuel Energy/Input Fusion Energy	Capital Cost of Plant
50%	\$4.8 x 10^9
70%	\$3.3 x 10^9

Cost Assumption: Fusion Reactor = Electrolyzers = \$800/KW(th) [\$2000/KW(e) Equivalent]

Coal Synthetic Fuel - SNG Plant	Capital Cost of Plant
Conventional SNG	\$1.0 x 10^9 *

* Coal Feed Cost Equivalent to Additional \$1.0 x 10^9 Investment at \$25/Ton

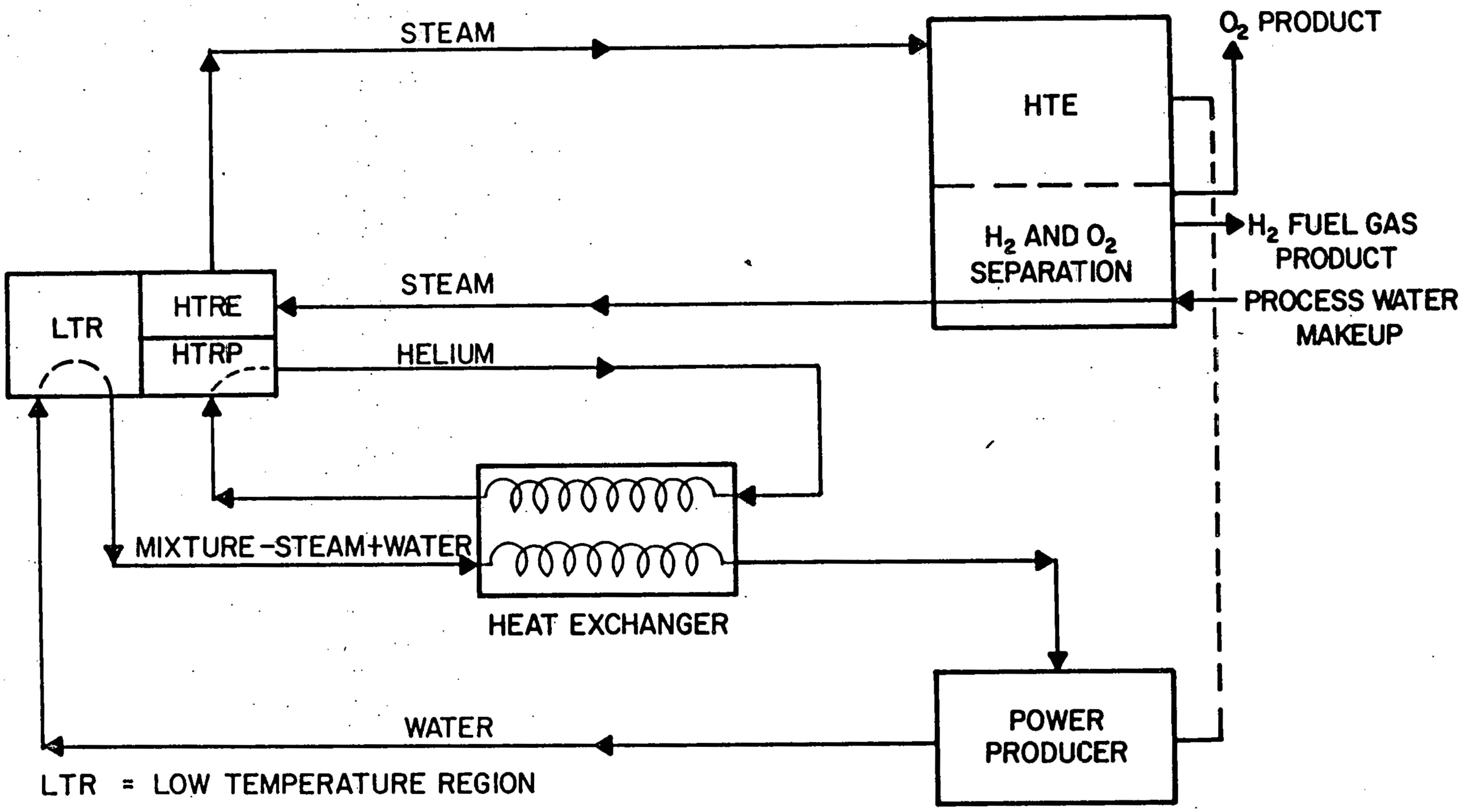
TABLE VI

PRODUCTION COST EVALUATION

	Fuel Cost ($\$/10^6$ BTU)
Fusion-Synthetic Fuel Production Plant	
Assumption: 15% Fixed Charge - Fusion Reactor + Electrolyzers = $400/KW(th) [$1000/KW(e) Equivalent]	
Efficiency: Output H_2 Fuel Energy/Input Fusion Energy	
50%	4.70
70%	3.40
Assumption: 15% Fixed Charge - Fusion Reactor + Electrolyzers = $800/KW(th) [$2000/KW(e) Equivalent]	
Efficiency: Output H_2 Fuel Energy/Input Fusion Energy	
50%	9.40
70%	6.80
Coal Synthetic Fuel Plant (based on $25/ton coal)	
Syncrude ($24/BBL)	4.00
SNG	3.00-4.00
Fission - Electrolytic Synfuel Plant	
Assumption: Reactor + Electrolyzers - $1000/KW(e)	
30% Efficient System	7.85

Fig. 1 FUSION REACTOR-HTE-CONVENTIONAL POWER CYCLE FOR SYNTHETIC FUEL(H_2) PRODUCTION

SIMPLIFIED SYSTEM DIAGRAM



LTR = LOW TEMPERATURE REGION
HTRE = HIGH TEMPERATURE REGION FOR HTE
HTRP = HIGH TEMPERATURE REGION FOR POWER
HTE = HIGH TEMPERATURE ELECTROLYZER

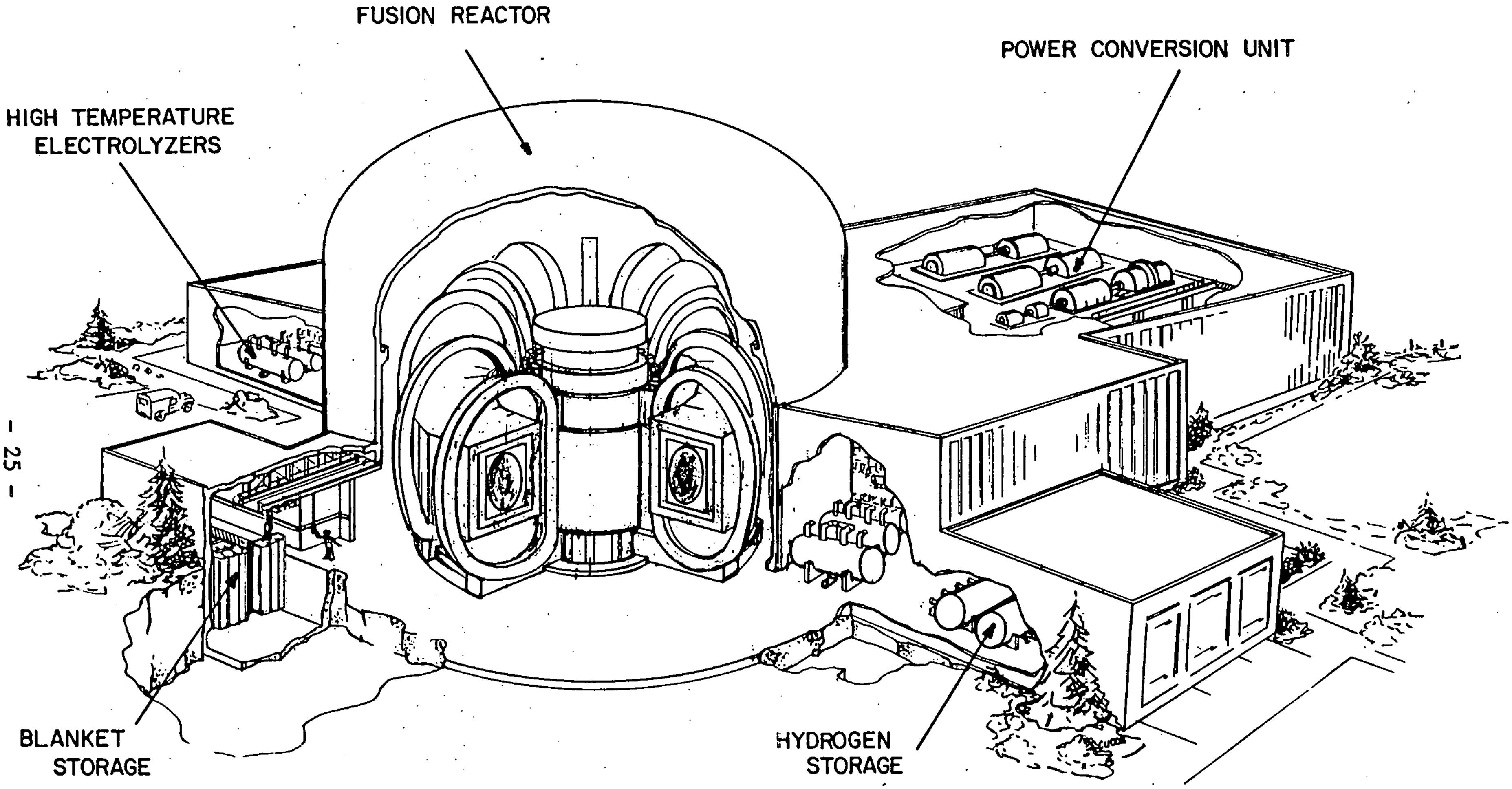


Fig. 2 FUSION REACTOR-HIGH TEMPERATURE ELECTROLYSIS SYSTEM (FR-HTES)

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10-585-77

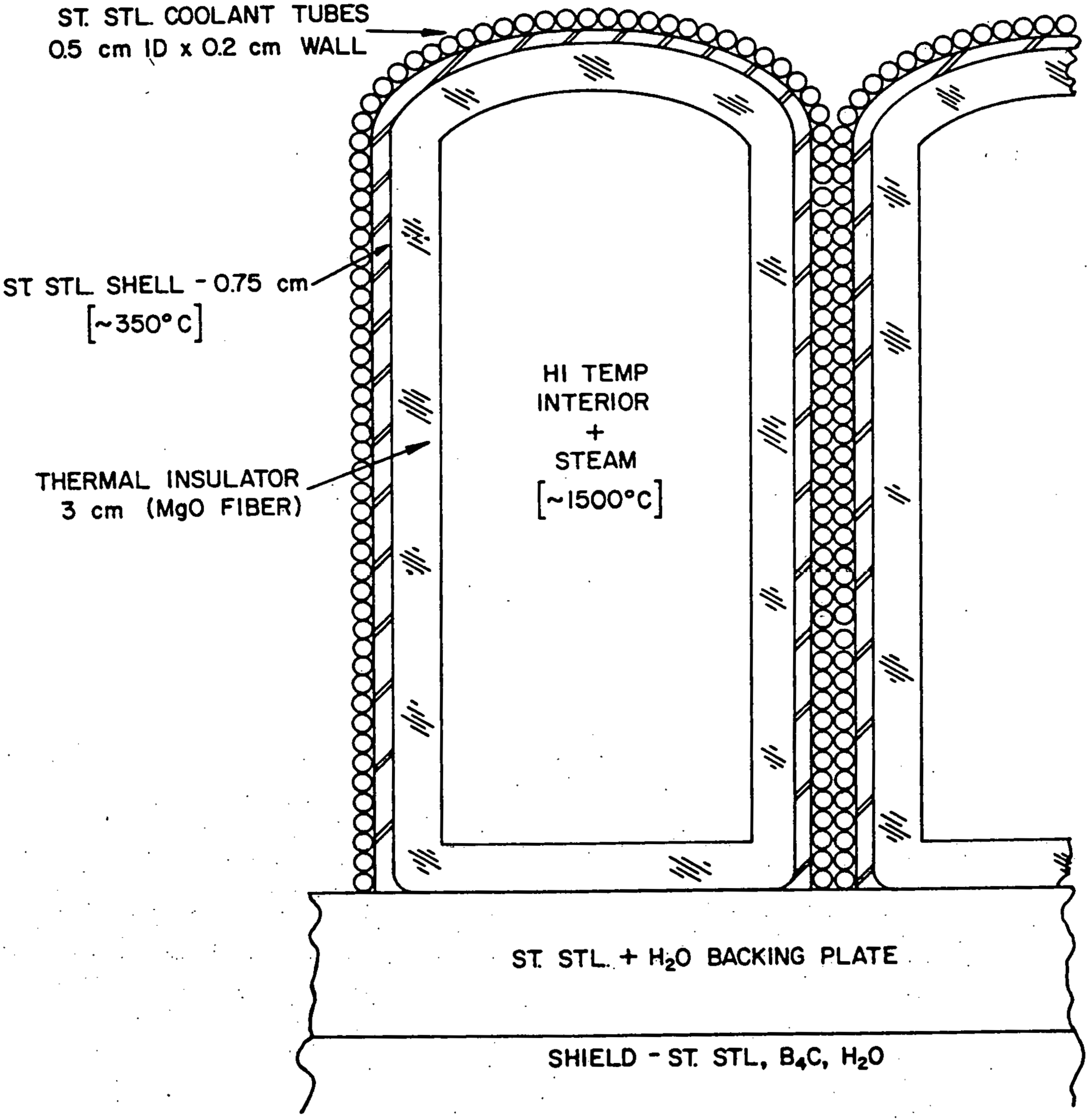

Fig. 3

BLANKET CROSS SECTION
HTE PROCESS HEAT MODULE

JAF

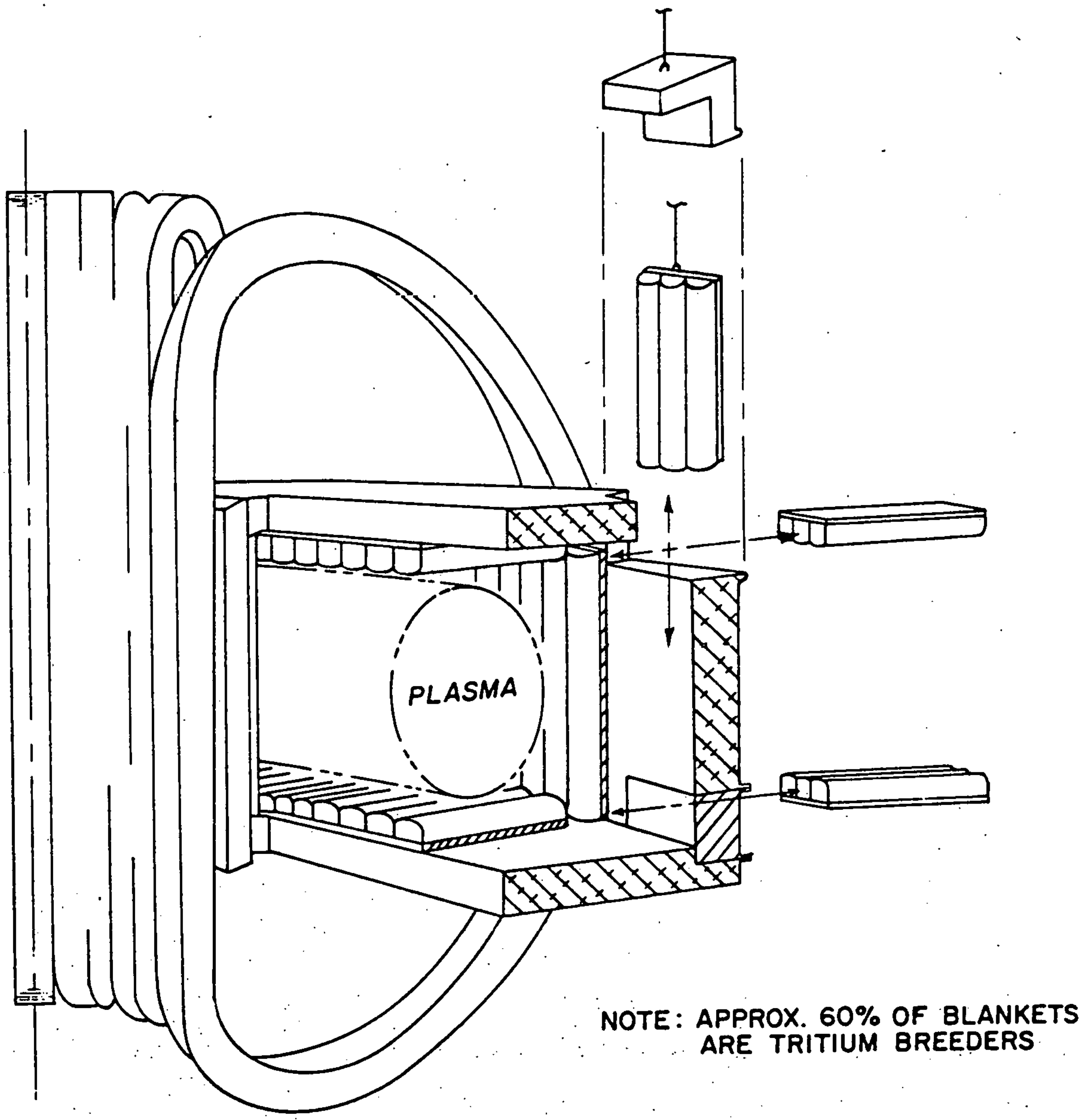

Fig. 4 SCHEMATIC SHOWING MODULE REMOVAL

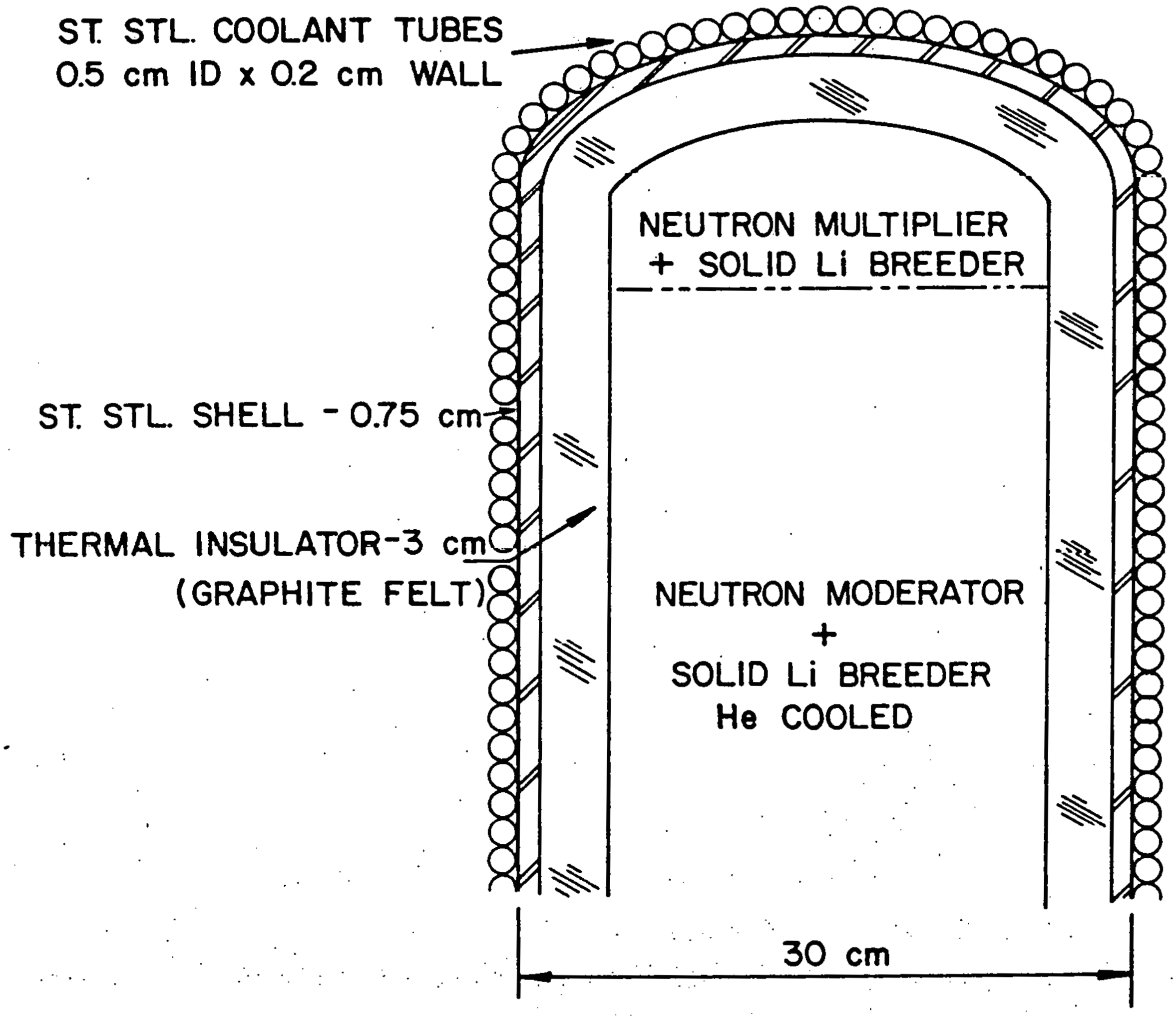

Fig. 5 ELECTRIC PRODUCTION MODULE-T BREEDING

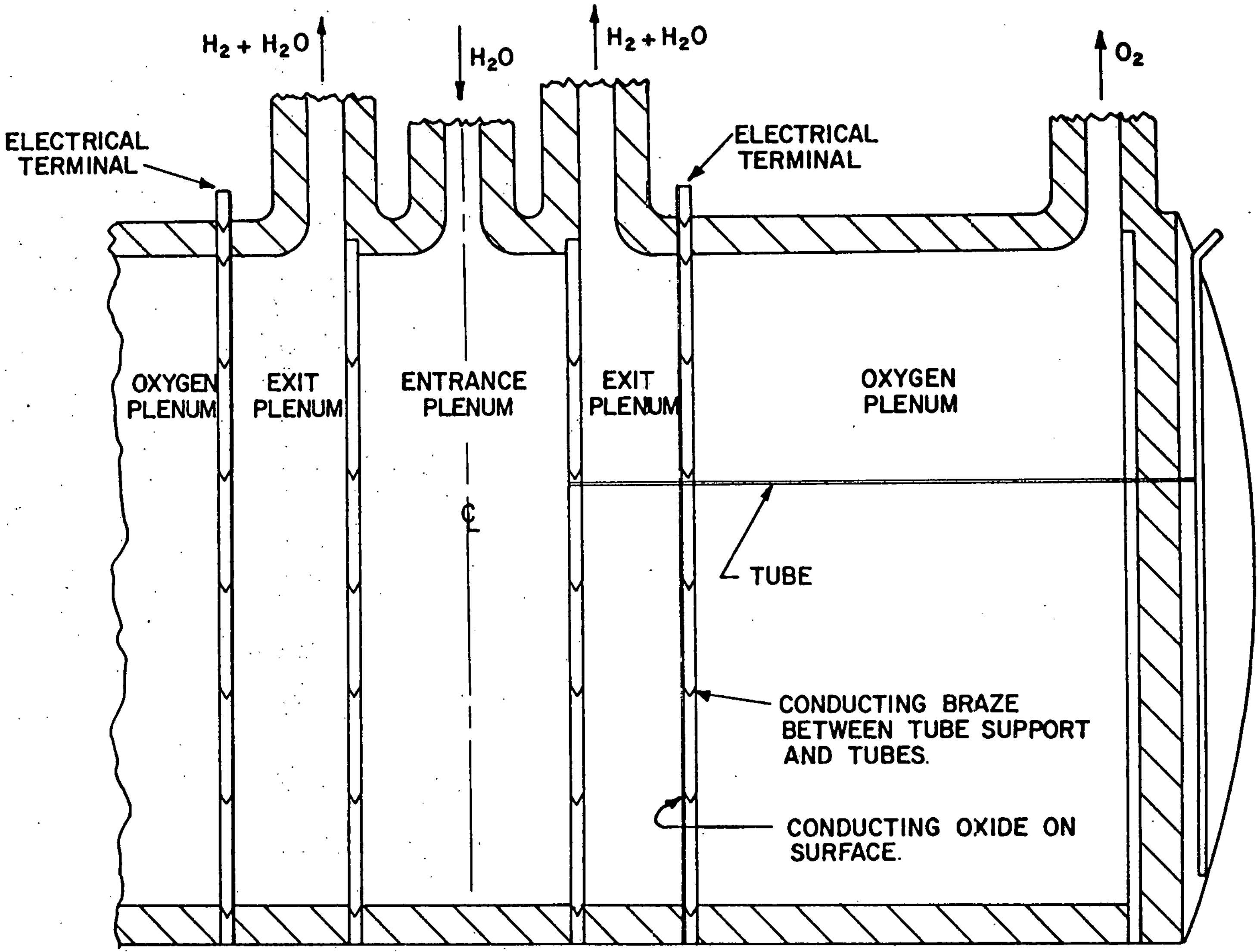

Fig. 6 HTE VESSEL

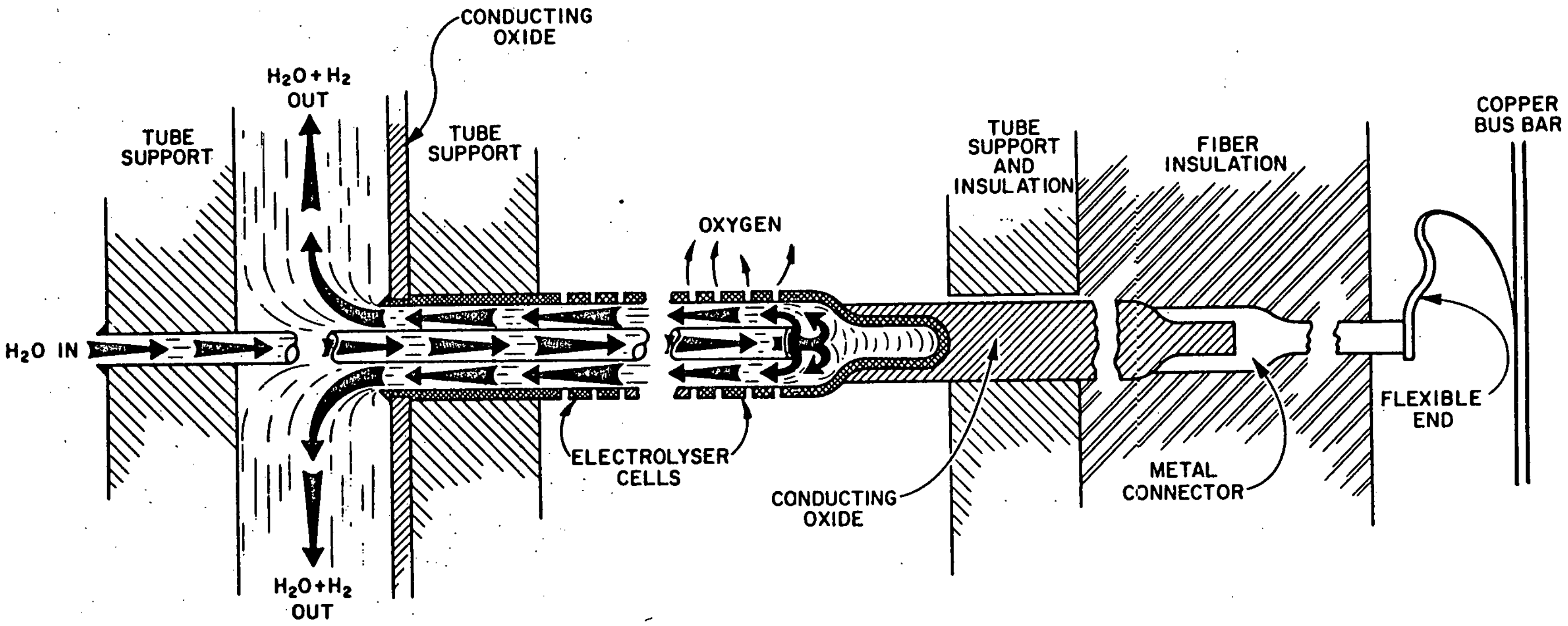

Fig. 7 DETAILED CROSS-SECTION OF HTE CELL

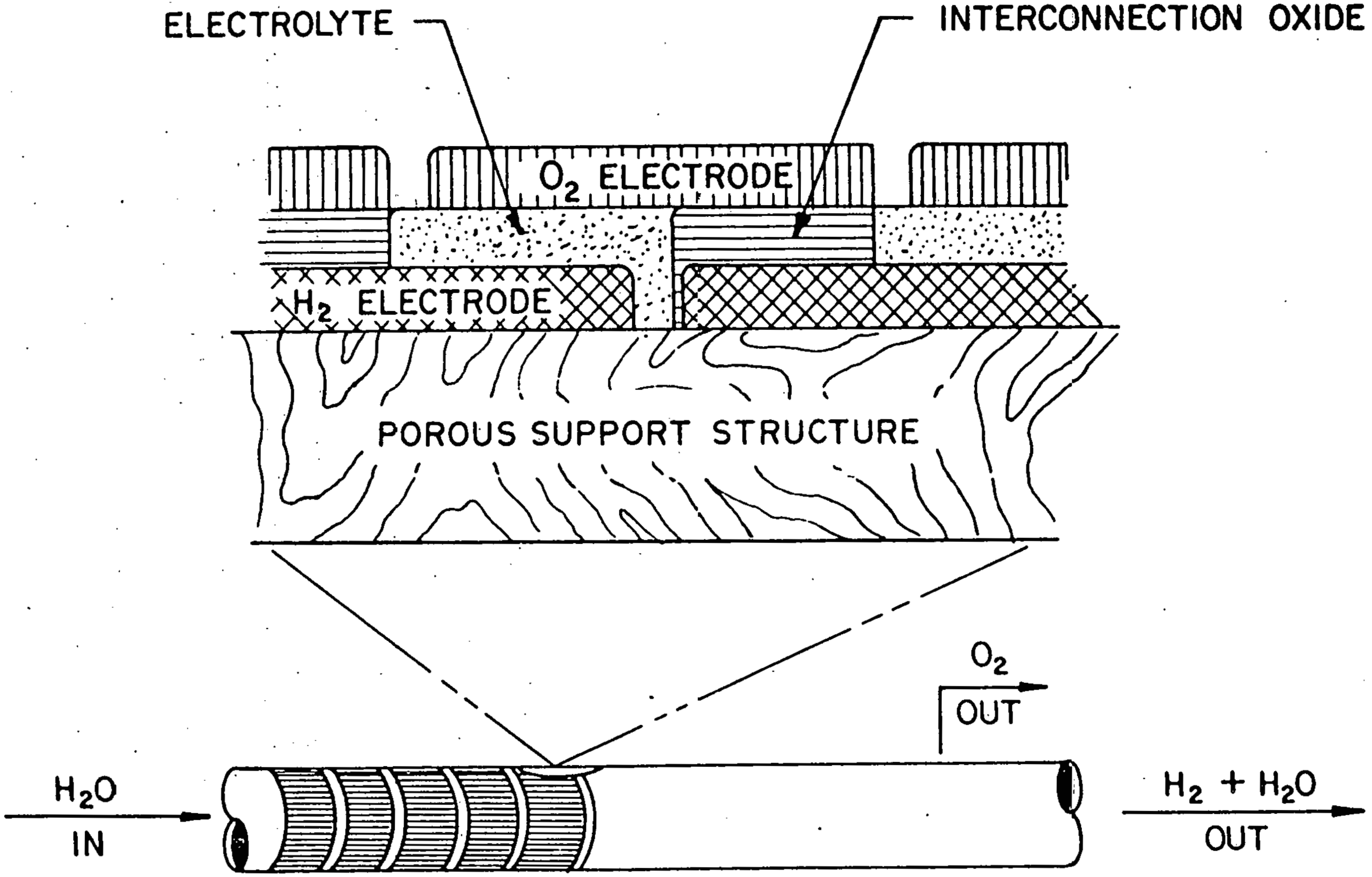

Fig. 8

HTE CELL DESIGN
(WESTINGHOUSE FUEL CELL)

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FAST POWER CYCLE
(FUSION HEAT SOURCE)

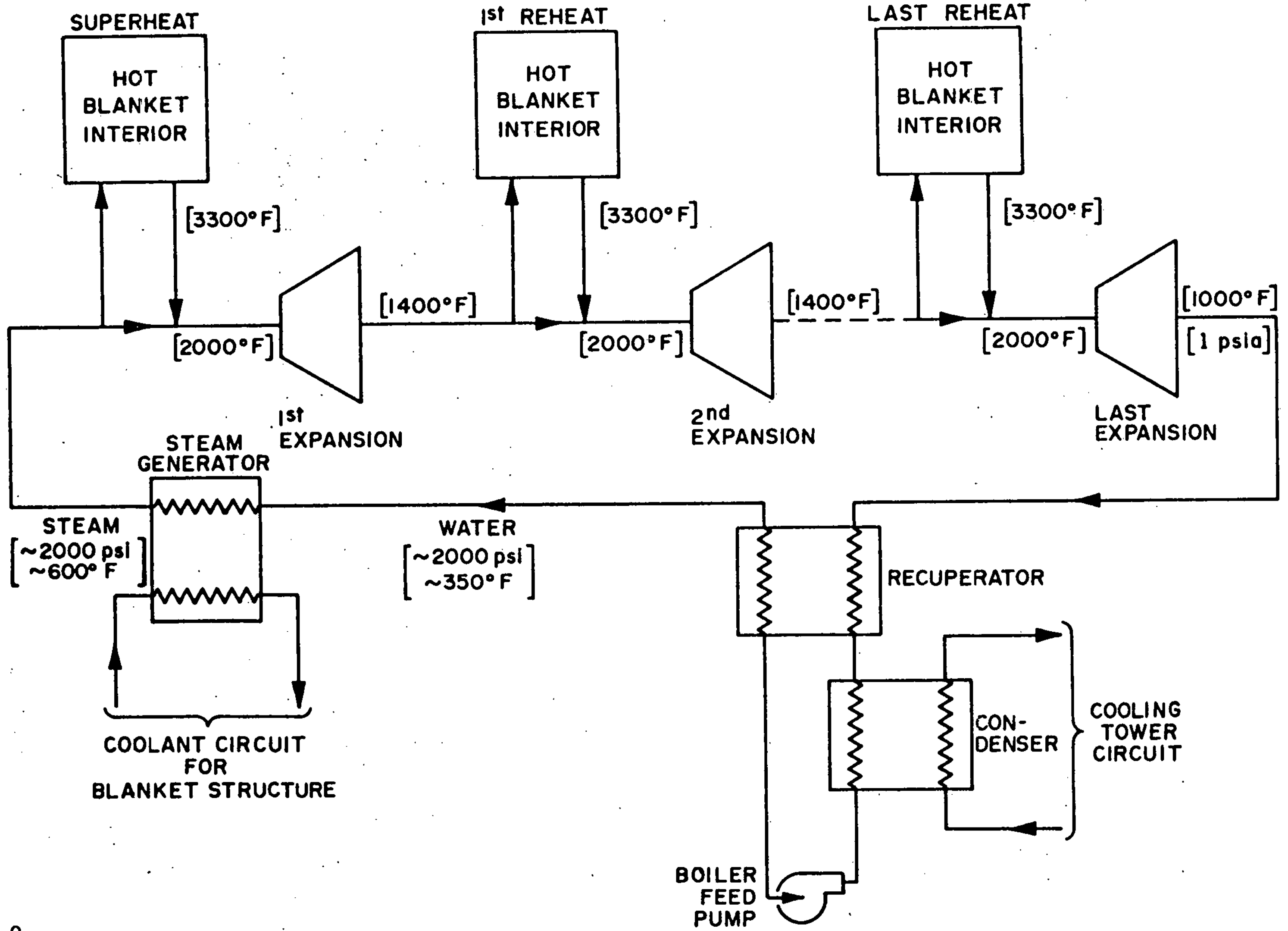

Fig. 9

10-550-77

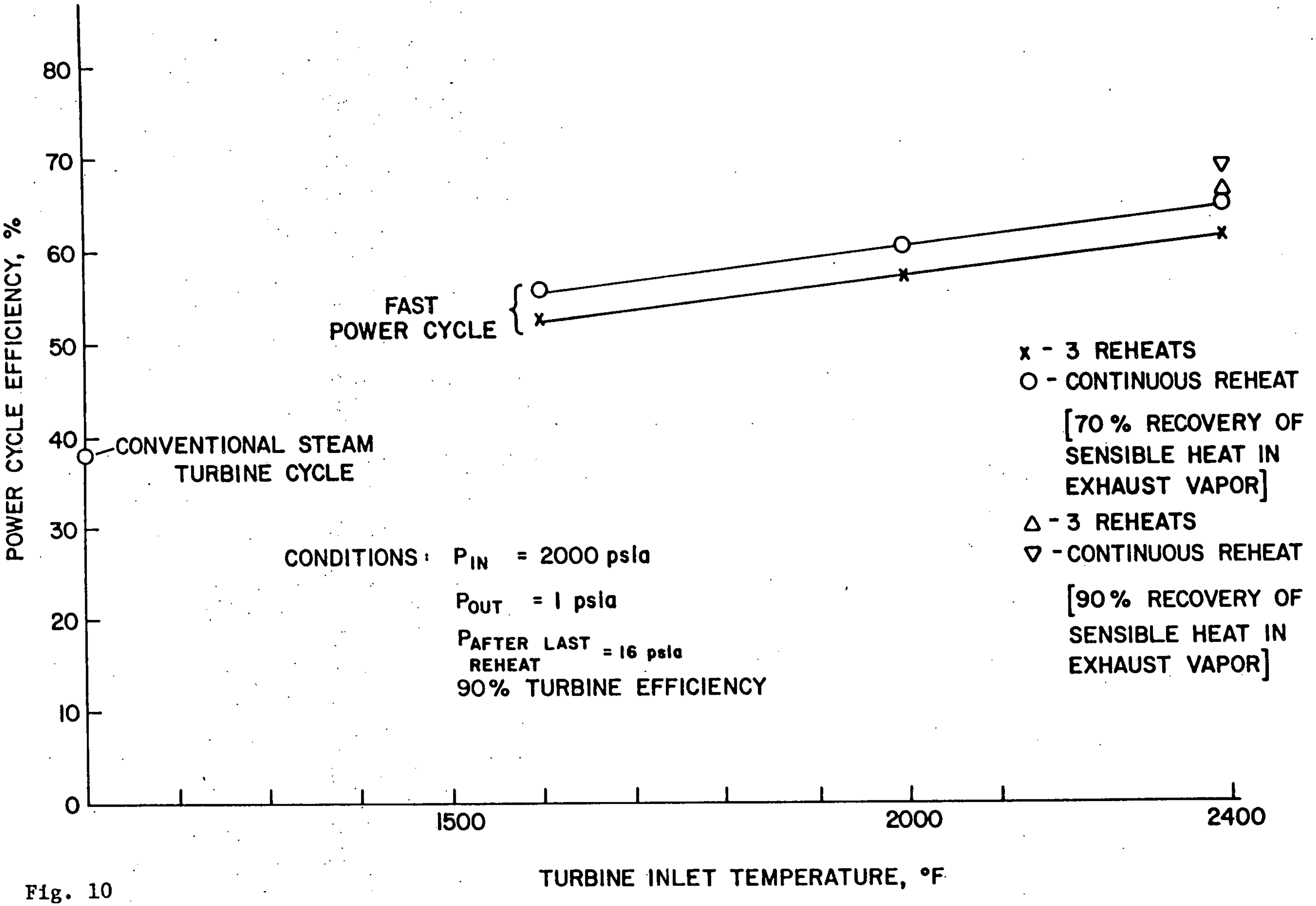
POWER CYCLE EFFICIENCY, %
0
10
20
30
40
50
60
70
80
1500
2000
2400
TURBINE INLET TEMPERATURE, °F
CONVENTIONAL STEAM TURBINE CYCLE
FAST POWER CYCLE
x - 3 REHEATS
O - CONTINUOUS REHEAT
[70 % RECOVERY OF SENSIBLE HEAT IN EXHAUST VAPOR]
△ - 3 REHEATS
▽ - CONTINUOUS REHEAT
[90 % RECOVERY OF SENSIBLE HEAT IN EXHAUST VAPOR]
CONDITIONS: P_IN = 2000 psia
P_OUT = 1 psia
P_AFTER LAST REHEAT = 16 psia
90% TURBINE EFFICIENCY

Fig. 10

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FUSION - HTE - SYNTHETIC FUELS
THERMODYNAMICS OF WATER DECOMPOSITION (STEAM)
$H_2O_{(g)} = H_{2\,(g)} + \frac{1}{2}\,O_{2\,(g)}$

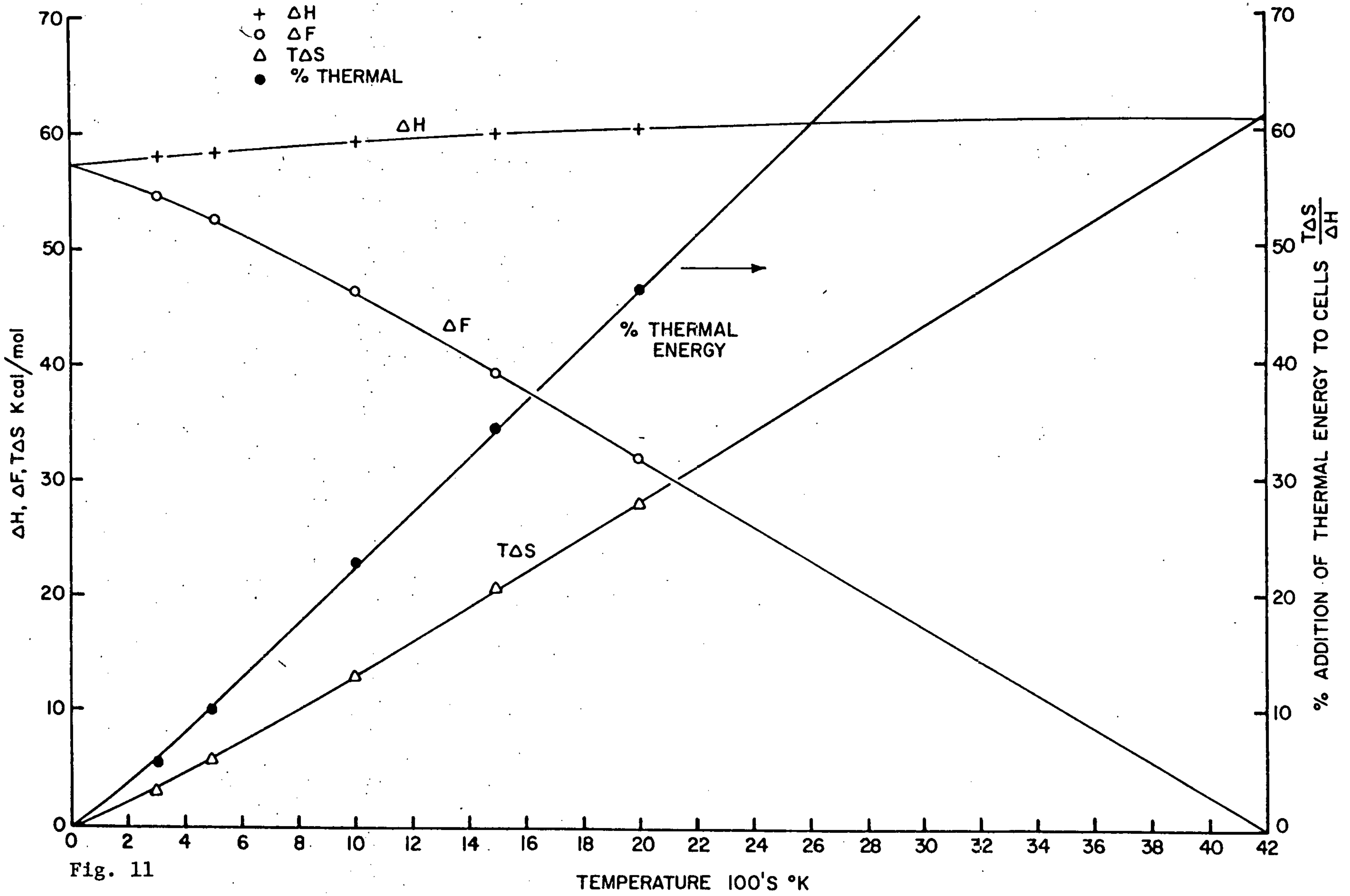

Fig. 11

Fig. 12

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