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NON-ELECTRICAL USES OF THERMAL ENERGY GENERATED IN THE PRODUCTION OF FISSILE FUEL IN FUSION-FISSION REACTORS: A COMPARATIVE ECONOMIC PARAMETRIC ANALYSIS FOR A HYBRID WITH OR WITHOUT SYNTHETIC FUEL PRODUCTION+

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ABSTRACT

A wide range of neutronic blanket designs indicates that a considerable amount of thermal energy will accompany the generation of fissile fuel in a fusion-fission hybrid reactor. A simple analytic model previously used has been extended to examine the economic constraints of a fission-fussion complex in which a portion of thermal energy is used for producing synthetic fuel (synfuel). Since the values of many quantities are not well-known, a parametric analysis has been carried out for testing the sensitivity of the synfuel production cost in relation to crucial economic and technologic quantities (investment costs of hybrid and synfuel plant, energy multiplication of the fission blanket, recirculating power fraction of the fusion driver, etc.). In addition, a minimum synfuel selling price has been evaluated, from which the fission-fusion-synfuel complex brings about a higher economic benefit than does the fusion-fission hybrid entirely devoted to fissile-fuel and electricity generation. Assuming an electricity cost of 2.7 ¢/kWh, an annual investment cost per power unit of 4.2 to 6 \$/GJ (132 to 189 k\$/MWty) for the fission-fusion complex and 1.5 to 3 \$/GJ (47 to 95 k\$/MWty) for the synfuel plant, the synfuel production net cost (i.e., revenue = cost) varies between 6.5 and 8.6 \$/GJ. These costs can compete with those obtained by other processes (natural gas reforming, resid partial oxidation, coal gasification, nuclear fission, solar electrolysis, etc.). This study points out a potential use of the fusion-fission hybrid other than fissile-fuel and electricity generation.

CONTENTS

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1. INTRODUCTION

A wide range of neutronic blanket designs indicates that a considerable amount of thermal energy will accompany the formation of fissile fuel in a fusion-fission (hybrid) reactor. On the other hand, hydrogen has encountered increasing attention, being apt to become a fuel source (particularly convenient for transport vehicles), an energy carrier and a storage medium. Given that one kilogram of fissile fuel is worth 2.5 MWty, a fissile-fuel-production rate of 0.4 kg/MWty in the hybrid corresponds, when burned, to a quantity of energy equal to that released by the hybrid in supplying this fuel. A hybrid reactor, therefore, can be regarded as a generator of considerable quantities of thermal energy. The economic incentives to utilize this thermal energy have lead to an approach that couples the hybrid system with the production of synthetic fuels.[1] A simple analytic model was used previously to examine the relationship between the principle economic and technical quantities both for fusion-fission hybrid systems[2] and for fusion-driven synthetic-fuel plants.[3] The model has been extended in this study to accommodate the simultaneous production of fissile fuel, electricity (fusion-fission hybrid) and synthetic fuel (synfuel plant). This model has been evaluated within a range of crucial parameters in order to quantify the global economics and plant characteristics. Analysis gives the likely maximum economic investment cost of the fusion-fission complex with or without synfuel production, and indicates that the cost of synfuel can compete with other production methods.

2. MODEL DEVELOPMENT

2.1 Fusion-Fission-Synfuel Concept

The cost of the synfuel produced by a fusion-fission-powered synfuel plant is evaluated by an economic model similar to that developed in two previous works.[2,3] Compared to the previous work,[3] this study takes into account the fission blanket, which increases considerably the energy multiplication and produces fissile fuel. Furthermore, in addition to consuming fissile fuel for electricity generation, a fission burner can supply a synthetic-fuel cycle with process heat at a convenient temperature. The energy flow diagram for the system is shown in Fig. 1; all symbols are defined in the table of nomenclature (Sec.6). It is noted that a hybrid reactor can supply fissile fuel to 5-10 fission burners, depending on the value of the conversion ratios CV^* and CV. In order to emphasize the economic sensitivity of possible synfuel production from the thermal energy generated by the hybrid reactor, only one burner reactor of equal power ($P^* = P$) is explicitly included, and the remaining fissile-fuel users are isolated from the analysis by means of a "fissile-fuel market" (Fig. 1). To include all fissile-fuel users explicitly into the revenue/cost analysis would lead to artificially depressed synfuel prices because of the large effective economic benefits that would be injected by the generation of large quantities of electricity.

The annual fissile-fuel production from the fissile-fuel/fusile-fuel/process-heat generating blanket is described by the specific production rate R(kg/MWty). A fraction f of the blanket thermal power P (available at high temperature, $T_1 \simeq 1500$ K) and another fraction ζ of the remaining blanket power (available at low temperature $T_2 \sim 800$ K) are used to drive a synfuel plant (e.g., thermochemical hydrogen cycle based on a bismuth sulfate/sulfuric acid process[4]).+ The fission burner depicted in Fig. 1 can supply the synfuel process, if necessary, with a fraction ζ^* of its power P^*. The synfuel plant efficiency η' is defined by

$$\eta' \equiv \frac{P_h + \lambda P_e}{fP + \zeta(1-f)\cdot P + \zeta^* P^* + P_c'/\eta} = \frac{\Lambda + \lambda P_e/P}{\Psi} \tag{1}$$

where

$$\Psi \equiv f + \zeta(1-f) + \varepsilon'\bar{\eta}/\eta + \zeta^* P^*/P$$

In addition, assuming that each fusion event would release 20 MeV of energy in an equivalent pure-fusion blanket, the fissile-fuel production rate R, the conversion ratio CV and the energy multiplication M are related by

$$R\ (\mathrm{kg/MWty}) = 3.84\ CV/M \tag{2}$$

Furthermore, if the hybrid blanket alone has to provide the electric power required by the fusion driver and by the synfuel plant,x the energy multiplication M must be sufficiently high. This constraint is reflected in terms of the parameter k', where

$$k' \equiv P_e + \lambda P_e - \varepsilon\bar{\eta}P_F - \varepsilon'\bar{\eta}P \geq 0 \tag{3}$$

\+ In principle, this study is independent of the synfuel process, hydrogen production, coal gasification, ammonia production, etc., being characterized by an appropriate selection of variables displayed in Fig.1.

x For certain thermochemical hydrogen systems, electrical power may be produced by a low-voltage electrolysis step (Ref. 4).

and the following inequality

$$M \geq \varepsilon\bar{\eta}/[\eta(1-\zeta)(1-f)(1+\lambda) - \varepsilon'\bar{\eta}] \tag{4}$$

The equality in Eq. (3) and (4) corresponds to electricity self-sufficiency for the hybrid/synfuel-plant combination. This case is of practical interest, and the constraints embodied in Eq. (3) and (4) are imposed consistently in this study; Eq. (4) essentially gives a constraining relationship between M and f.

2.2 Revenue-Cost Formulation

The essential purpose of this formulation is to compute the revenue (REV) and the cost (COST) of the global system (hybrid/fission/synfuel combination), and then the synfuel net cost c_h (called hydrogen production cost) is deduced from the conditon for economic breakeven: REV = COST.

In addition, it is necessary from an economic viewpoint to compare c_h with the minimum synfuel selling price (c_{BE}) that reflects the worth of producing hydrogen instead of electricity from the excess thermal energy generated by the hybrid blanket. The revenue and the cost of the global system (Fig. 1) are first considered. The annual revenue is given by the sale of hydrogen, electricity (if $k > 0$), fissile fuel (if $\phi > 0$) and tritium (if $B > 1$)

$$\text{REV}(\$/y) = \Lambda P c_h + \mu[k] k c_e + \mu[\phi]\phi c_f + \mu[B-1](B-1) t P_F c_t \tag{5}$$

where

$$\mu[x] = \begin{cases} 0 \text{ if } x < 0 \\ 1 \text{ if } x \geq 0 \end{cases}$$

The annual costs are composed of investment costs and operation/maintenance expenses. These costs are gathered into six groups, and, if required, the purchases of electricity, fissile fuel and tritium are added

$$\text{COST}(\$/y) = P^{*}C^{*} + PC_F + \Lambda PC' + (P_e^{*} + P_e + \lambda P_e)C_e + (uCV^{*}P^{*} + RP)C_f + $$
$$+ tBP_F C_t - \mu[-k]kc_e - \mu[-\phi]\phi c_f + \mu[1-B](1-B)tP_F c_t \tag{6}$$

Using the following dimensionless ratios (costs normalized by the electricity market price)

$$\rho_h \equiv \frac{c_h}{\eta c_e} \qquad \rho_f \equiv \frac{uc_f}{\eta c_e} \qquad \rho_t \equiv \frac{tc_t}{\eta c_e} \qquad R^* \equiv \frac{C^*}{\eta c_e} \qquad R_F \equiv \frac{C_F}{\eta c_e}$$
$$R' \equiv \frac{C'}{\eta c_e} \qquad R_f \equiv \frac{C_f}{c_f} \qquad R_t \equiv \frac{tC_t}{\eta c_e} \qquad R_e \equiv \frac{C_e}{c_e} \tag{7}$$

the condition

$$\Delta \equiv REV - COST = 0 \tag{8}$$

gives the relative hydrogen-production cost+

$$\rho_h = R' + [R^* + R_F + \kappa R_e + BRt/M - \kappa + \bar{\varepsilon} + (vR_f+1-v)\rho_f + (1-B)\rho_t]/(\Psi\eta') \tag{9}$$

where

$$\kappa \equiv (1-\zeta)(1-f) + (1-\zeta^*)$$

$$\bar{\varepsilon} \equiv \varepsilon' + \varepsilon/M$$

$$v \equiv CV^* + R/u$$

Equation (9) shows that the hydrogen production cost decreases hyperbolically with the thermochemical plant efficiency and varies linearly with other costs. Eq. (9) is evaluated as a function of crucial parameters, including specifically the case $k' = 0$ (i.e., no net electricity production from the hybrid/synfuel complex). The synfuel cost, c_h or ρ_h, represents the major object function for this analysis, and a specific relationship is assumed to exist between the fissile fuel price and the electricity price.

+ $P^* = P$, $\eta^* = \bar{\eta} = \eta$ and $\lambda = 0$ are assumed hereafter. If $\phi = 0$ were assumed, i.e., tranformation in situ of all bred fissile fuel to electricity through several fission burners, then $P^* = PR/u(1-CV^*)$. Therefore, hydrogen would either become a minor product of the system relative to electricity (if $\zeta^* = 0$), or be produced by a large conglomerate of fission burners (if $\zeta^* = 1$), (see Sec. 3).

2.3 Breakeven Hydrogen Selling Price

The fission burner and the hybrid are first imagined to be disconnected from the synfuel plant, and all thermal energy is devoted solely to electricity generation. The quantity $\Delta_e = REV_e - COST_e$ reflects the economic benefit of this fissile-fuel, electricity-producing system. If the thermal energy generated by such a system is used for synfuel production, from a strictly economic viewpoint, the synfuel production will be more attractive than the electricity generation only if it brings about a higher benefit. The selling price of the synfuel produced, therefore, will have to satisfy the obvious condition $REV - COST \geqslant REV_e - COST_e$, or

$$\Delta \geqslant \Delta_e \tag{10}$$

Assuming that incorporation of the thermochemical plant does not alter the hybrid cost (possible incremental costs may be added to the synfuel plant cost), the minimum synfuel (hydrogen) selling price, c_{BE}, reflecting the incentive or worth for producing hydrogen instead of electricity, can be derived from Eq. (5) and (6), taking into account the constraint $\Delta = \Delta_e$. The normalized ratio h can be written

$$h = c_{BE}/\eta c_e = R' + [1 - (1 - \varepsilon'/\Psi)R_e]/\eta' \tag{11}$$

As expected, c_{BE} or h is independent of the fissile-fuel price and the burner and hybrid-investment costs. On the basis of this formalism, the sale of synfuel brings about more benefit (or less deficit) than does the sale of electricity without hydrogen production; c_{BE} will be called the "breakeven hydrogen selling price".

Since c_h (or ρ_h) is deduced from the condition $\Delta = 0$ and c_{BE} (or h) from the conditon $\Delta = \Delta_e$, $c_h < c_{BE}$ (or $\rho_h < h$), therefore, implies $\Delta_e > 0$; similarly, $c_h > c_{BE}$ implies $\Delta_e < 0$. The benefit (or deficit) Δ naturally depends on the selling price c_h relative to the production cost c_h and c_{BE}. These various economic situations are depicted schematically in Fig. 2. The following expression summarizes the economic condition that must prevail before hydrogen is worth being produced

$$c_h \leqslant c_{BE} \leqslant c_h' \tag{12}$$

3. MODEL EVALUATION

3.1 Parameter Study for Fixed Values of Less Sensitive Parameters

In order to focus onto the influence of crucial variables (i.e., the most uncertain quantities at present state of knowledge), lesser important quantities have been given constant values throughout the numerical analysis. In particular

$$R = 0.4\text{kg/MWty};\ B = 1;\ \varepsilon = 1;\ \varepsilon' = 0.2;\ \zeta = 0.3$$
$$\eta^* = \bar{\eta} = \eta = 0.4;\ \eta' = 0.5;\ \lambda = 0;\ P^* = P$$
$$R_e = 0.2;\ R_f = 0.3;\ R_t = 0.05;\ \rho_f = 0.0913$$

Given that the energy worth of a kilogram of fissile fuel is 2.5 MWty, the value R = 0.4 kg /MWty corresponds to the typical condition where the burning of the fissile fuel bred by the hybrid will release a quantity of energy equal to that released by the hybrid in supplying this fuel. For most hybrid blankets studied,[5] R falls in the range 0.4 - 1.0 kg/MWty. The fusion driver is assumed to be self-sufficient in tritium (B = 1) and to operate at a breakeven condition ($\varepsilon = 1/Q = 1$). The synfuel effeciency $\eta' = 0.5$, because high efficiency is regarded as an essential incentive for the synfuel development.[x] Electricity generation cost (R_e), fissile-fuel processing cost (R_f) and tritium processing cost (R_t) are assigned prudent values, but their influence is weak relatively to that of investment costs. Finally, $\rho_f = 0.0913$ corresponds to a convenient relationship $c_f(\$/g) = 8c_e(¢/kWh)$, approximately verified for $c_e \simeq 2\text{-}3$ ¢/kWh. Generally, ρ_h is not sensitive to variations in ρ_f; the use of other fissile-fuel/electricity cost relationships (e.g., Ref. 7) give essentially the same results as presented herein.

3.2 Results and Discussions

Figure 3 shows that ζ^* and CV^* have a very weak influence on ρ_h. For instance, for M values up to 30, ρ_h increases less than 7 % with ζ^* increasing from 0 to 0.5; the ρ_h variation is even less (4.4 %) with CV^* varying from 0.6 (light-water converter reactors) to 1.2 (fast breeders). Therefore, the values $\zeta^* \simeq 0$ and $CV^* = 0.8$ (advanced converter reactors) are selected for use throughout this study. Note that $\rho_h < h$ in Fig. 3 and, therefore, $\Delta_e > 0$.

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x Publications exist which state possible constraints for economic synfuel

Figure 4 shows the relationship between M and CV for a given ρ_h, as well as giving the constraint for no net electricity production ($k' = 0$); M and CV increase or decrease with increasing f, for a given ρ_h, according to ρ_h being greater or smaller than h (equal to 2.20 for this case). The curve for $k' = 0$ (Eq. 4) delimits the minimum values of M and CV for realizing the electricity self-sufficiency for the hybrid-thermochemical complex. Curves in Fig. 4 are drawn for $\varepsilon = 1$; being pratically proportional to ε (i.e., Eq. (9)), M can be easily deduced for other values of ε. Figure 4 points out that for obtaining "low" synfuel production costs, M and CV must be large and f must be small; on the other hand, a low-multiplication hybrid will be sufficient for achieving the breakeven synfuel selling price. The particular points A and A" shown in Fig. 4 represent reference cases and will reappear in following figures.

Figure 5 shows the investment-cost influences on the hydrogen production cost and the breakeven selling price for the case of $k' = 0$ and a moderate M value. In this example, $\rho_h \geq h$ for $R^* + R_F \geq 1.52$; $\rho_h > h$ implies $\Delta_e < 0$ (refer to Fig. 2), that is, an economic deficit for the burner and the hybrid without hydrogen production is predicted. In another example not shown, M = 50, f = 0.4 ($k' > 0$), ρ_h and h increase with R' with the same slope $\partial\rho_h/\partial R' = 1$, but $\rho_h = h$ for $R^* + R_F = 1.60$.

Figure 6 represents a summary of these results and shows h for several values of R' and $R^* + R_F$ for $\rho_h = h$ (breakeven). Every straight line, for a given ρ_f, corresponds to $\Delta_e = 0$. For instance, if the device has the characteristic $\varepsilon/M = 0.213$ without hydrogen production, the investment cost $R^* + R_F$ must be less than 1.4 (point A) for realizing some benefit, unless ρ_f is increased. Similarly, if $\varepsilon/M = 0.1$, $R^* + R_F$ corresponds to 1.52 (point A'). In both examples, the breakeven synfuel selling price h (independent of M) remains around 2.2.

Up to this point all results have been presented in dimensionless form, from which actual selling and production costs can easily be derived. It would be instructive to give a specific example based on absolute rather than normalized costs. Figure 7 shows, for example, that as the electricity price c_e increases from 2 to 3 ¢/kWh, the hydrogen production cost c_h varies from 5 to 7.4 \$/GJ (for the $k' = 0$ case) and from 3.8 to 5.7 \$/GJ for M = 50. Curves are drawn for $c_f(\$/g) = 8c_e(¢/kWh)$, i.e., $\rho_f = 0.0913$; if $c_f(\$/g) = 50c_e(¢/kWh) - 100$ is used,[7] which corresponds to $\rho_f = 0.114$ for $c_e = 2.5$ ¢/kWh and to $\rho_f = 0.342$ for $c_e = 5$ ¢/kWh, calculation shows that c_h only changes by 0.7 to 7 % for $c_e = 2.5$ to 5 ¢/kWh (for k' = 0). Consequently, the relationship assumed between the electricity price and the fissile-fuel price has a negligible influence on the synfuel production cost within the range examined.

If the investment costs prove to be very high, for example, the case corresponds in Fig. 5 to point X (ρ_h = 2.87). Since X > A''', a deficit (Δ_e < 0) will exist without hydrogen production, as seen in Fig. 2. Assuming c_e = 2.7 ¢/kWh, calculation gives C^* = 1.8 \$/GJ, C_F = C' = 3 \$/GJ and c_h = 8.61 \$/GJ.

Figure 8 gathers results of some recent costing/economic studies for an absolute comparison with this study. Combined with an efficient thermochemical plant, a fusion reactor or (even better) a fusion-fission hybrid reactor could produce hydrogen at a cost comparable to that given by other processes.

All the results presented above are for the conditions where P^* = P and ζ^* = 0, with sale of fissile fuel (ϕ > 0) and electricity (k > 0). Another computational option, however, can be considered: the entire bred fissile fuel could be transformed to heat through fission burners for synfuel production (ϕ = 0 and ζ^* = 1), and the global system could be exactly self-sufficient in electricity (k = 0); synfuel is, therefore, the only product delivered to the market. In this case, with all parameters having the values shown in Fig. 4, except P^* = 5P, ζ^* = 1, f = 0.4, and M = 4.55, calculation gives (for c_e = 2.7 ¢/kWh) c_h = 5.63 \$/GJ and c_h = 7.34 \$/GJ if R_F = R' = 1 (i.e., C_F = C' = 3 \$/GJ). This case can be viewed as a large conglomerate formed by one fusion-fission unit (of power P) and five units of fission burners-converters, all powering several synfuel plants (with a total equivalent output thermal power P_h = 2.89P). This enormous production can, of course, reduce the synfuel production cost, but is not likely realizable.

4. CONCLUSIONS

a) Although simplified, the analysis method presented can provide considerable information on the dependence between economic and technical quantities. The model is versatile, with appropriate constraints, the system can be regarded as a pure-fu ion-driven synfuel plant or, in the other extreme, as an enormous conglomerate of hybrid, fission burners and synfuel plants.

b) If all the thermal energy generated by the fission-fusion complex is devoted to electricity generation, the maximum allowable investment cost (R^* + R_F) is around 1.52 ηc_e (for ε/M = 0.1); beyond this value a net deficit may be expected. If, however, a portion of the thermal energy is used for synfuel production, the economically acceptable investment cost $(R^* + R_F)$ may be increased ($1.6 - 1.7 \pi c_e$, for instance) provided that the synfuel market price is sufficiently lucrative (8-10 \$/GJ, for instance).

c) The synfuel production cost (approximately equal to the breakeven selling price) evaluated by this study is likely to fall between 6.5 and 8.6 \$/GJ. The production cost may be even lower if all the bred fissile fuel is transformed to heat for producing synfuel.

d) Compared to other processes of hydrogen production (natural gas reforming, resid partial oxidation, coal gasification, and electrolysis), the fission-fusion-synfuel concept can be economically competitive and appears cheaper than a pure-fission or a pure-fusion process.

e) Though the cost of the synfuel produced by a fusion-fission-driven synfuel plant appears to be among the cheapest ones, it is still much too high when compared to the current market price of the natural gas ($\simeq$ 2 \$/GJ). This fact can discourage the use of the nuclear energy (fission or fusion) for the synfuel production. Since other processes give a cost even higher, the shift to a widespread use of synfuel likely will not occur until the price of the natural gas increases to a comparable level.

This study points out a potential non-electric use for the fusion-fission energy. Economic usage may occur especially for the case where the hybrid reactor might prove to be too expensive for generating fissile fuel and electricity at competitive price.

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6. NOMENCLATURE

Symbol	Definition
P_F	Total fusion power (neutrons, alpha particles, radiation)
$P = MP_F$	Thermal power of fusion-fission hybrid
P^*	Thermal power of fission burner
P_6	Thermal power rejected by synfuel plant
P_c	Circulating power for fusion driver
P_c'	Electrical power required by synfuel cycle
P_h	Hydrogen-production rate, expressed as equivalent thermal power
C_F	Fusion-driver cost (including fission blanket, operation and maintenance (O & M) costs)
C^*	Fission-burner cost (including O & M)
C'	Thermochemical-plant cost (including O & M)
C_f	Fissile-fuel-processing cost (including O & M)
C_t	Tritium-processing cost (including O & M)
C_e	Electricity generation cost (including O & M)
c_f	Fissile-fuel market price
c_t	Tritium market price
c_e	Electricity market price

c_h	Hydrogen-production cost (net cost: $\Delta = 0$)
c'_h	Hydrogen market price
$R_F = C_F/\eta c_e$	Normalized fusion-driver cost
$R' = C'/\eta c_e$	Normalized synfuel-plant cost
$R^* = C^*/\eta c_e$	Normalized fission-burner cost
$R_e = C_e/c_e$	Normalized electricity-generation cost
$R_t = tC_t/\eta c_e$	Normalized tritium-processing cost
$R_f = C_f/c_f$	Normalized fissile-fuel processing cost
$\rho_f = uc_f/\eta c_e$	Normalized fissile-fuel price
$\rho_h = c_h/\eta c_e$	Normalized hydrogen-production cost
$h = c_{BE}/\eta c_e$	Normalized breakeven hydrogen selling price
η	Thermal-to-electric conversion efficiency of hybrid (at temperature T_2)
$\bar{\eta}$	Equivalent thermal-to-electric conversion efficiency of hybrid (at mean temperature of T_1 and T_2)
η^*	Thermal-to-electric conversion efficiency of fission burner
f	Fraction of high-temperature heat needed for the synfuel cycle
M	Total energy multiplication of blanket
CV	Fissile atoms produced in hybrid blanket per fusion neutron
CV^*	Fissile atoms produced in fission burner per fission
R	Fissile fuel production rate per unit of hybrid power
c_{BE}	Breakeven hydrogen selling price, i.e., if $c'_h = c_{BE}$, $\Delta = \Delta_e$
B	Tritium breeding ratio
t	Quantity of tritium per energy unit (t = 0.049 kg/MWty)
u	Quantity of uranium per energy unit (u = 0.4 kg/MWty)
ε	Recirculating power fraction for fusion driver
ε'	Recirculating power fraction for the synfuel plant (e.g., a low-voltage electrolysis step in a thermochemical hydrogen cycle)
λ	Fraction of electricity transformed from power rejected by the cycle
ζ	Fraction of low-temperature heat from hybrid needed for the synfuel cycle
ζ^*	Fraction of heat from fission burner for the synfuel cycle
Δ	Return-on-investment, or profit, of global system
Δ_e	Profit of fission burner-hybrid devoted to electricity and fissile fuel generation only

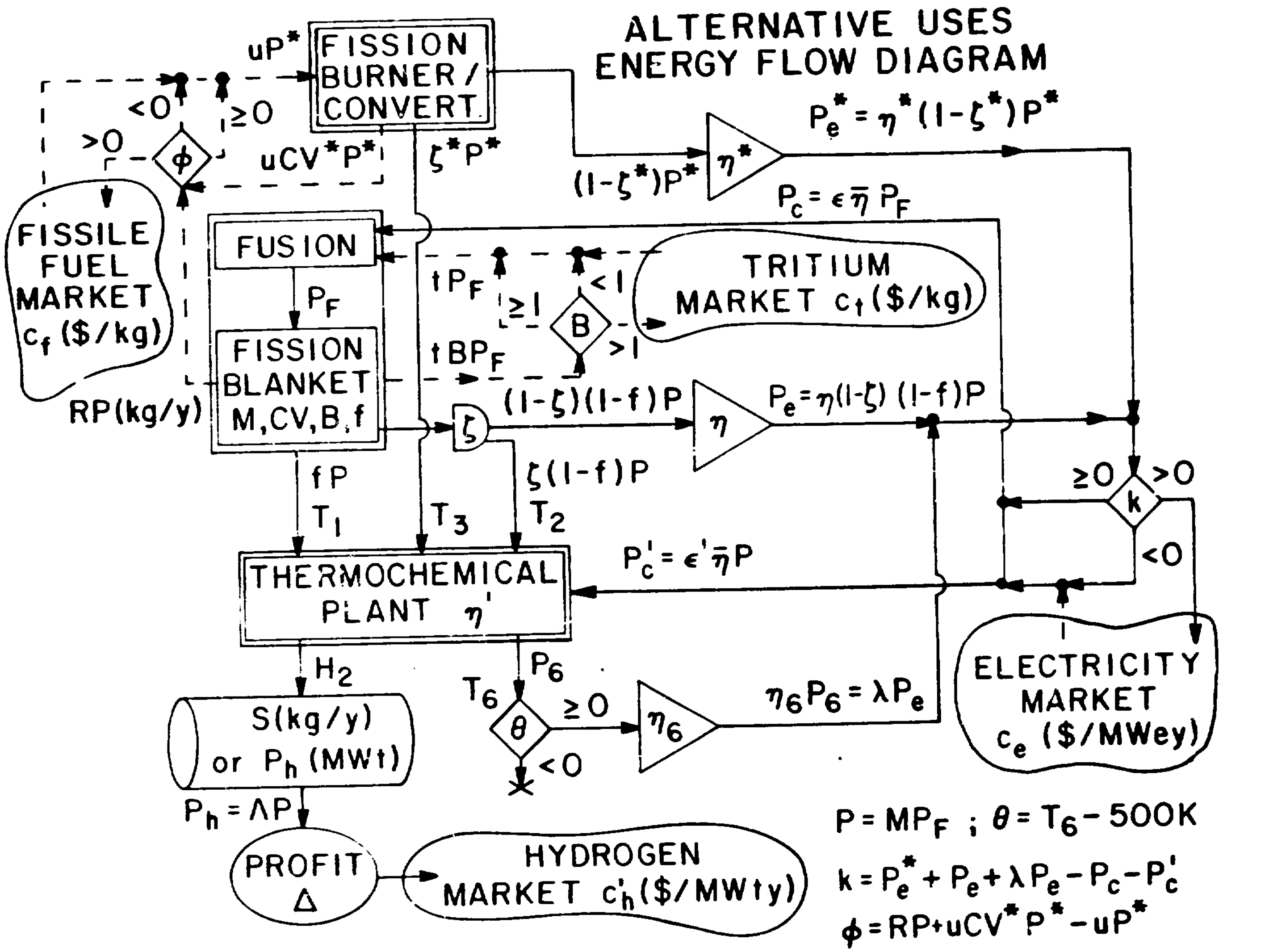

Fig. 1 Schematic energy flow diagram of fusion-fission-synfuel concept. Refer to Nomenclature (Sec. 6) for definitions of symbols.

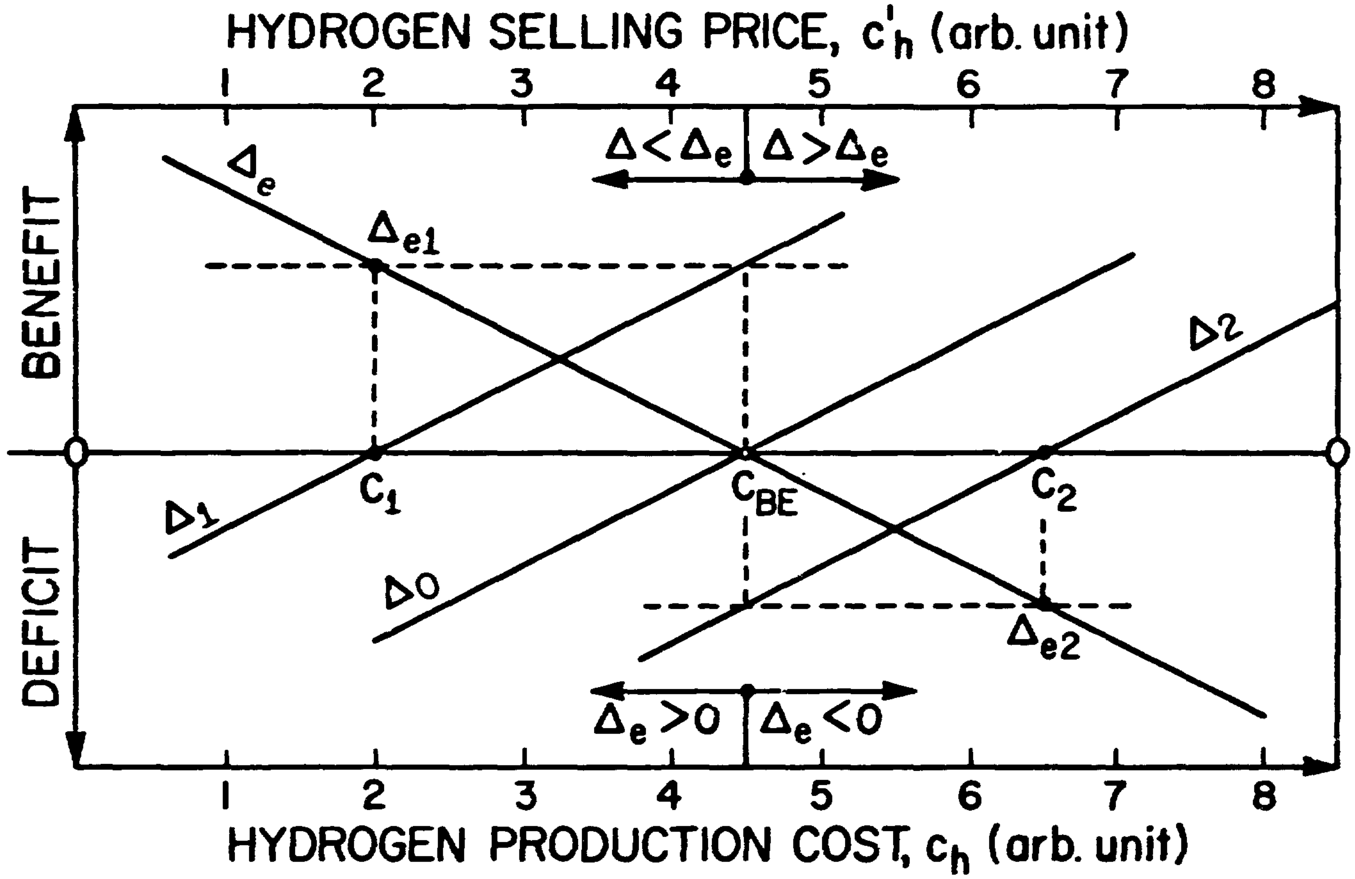

Fig. 2 Benefit/deficit vs production costs c_h and selling price c'_h of the hydrogen (same arbitrary unit), relatively to breakeven selling price c_{BE}.

a) $c_h = c_1 < c_{BE} \rightarrow \Delta_e = \Delta_{e1} > 0$, and $\Delta_1 \leq$ or $> \Delta_{e1}$ according to $c'_h \leq$ or $> c_{BE}$

b) $c_h = c_2 > c_{BE} \rightarrow \Delta_e = \Delta_{e2} < 0$, and $\Delta_2 \leq$ or $> \Delta_{e2}$ according to $c'_h \leq$ or $> c_{BE}$

c) $c_h = c_{BE} \rightarrow \Delta_e = 0$, and $\Delta_0 \leq$ or > 0 according to $c'_h \leq$ or $> c_{BE}$

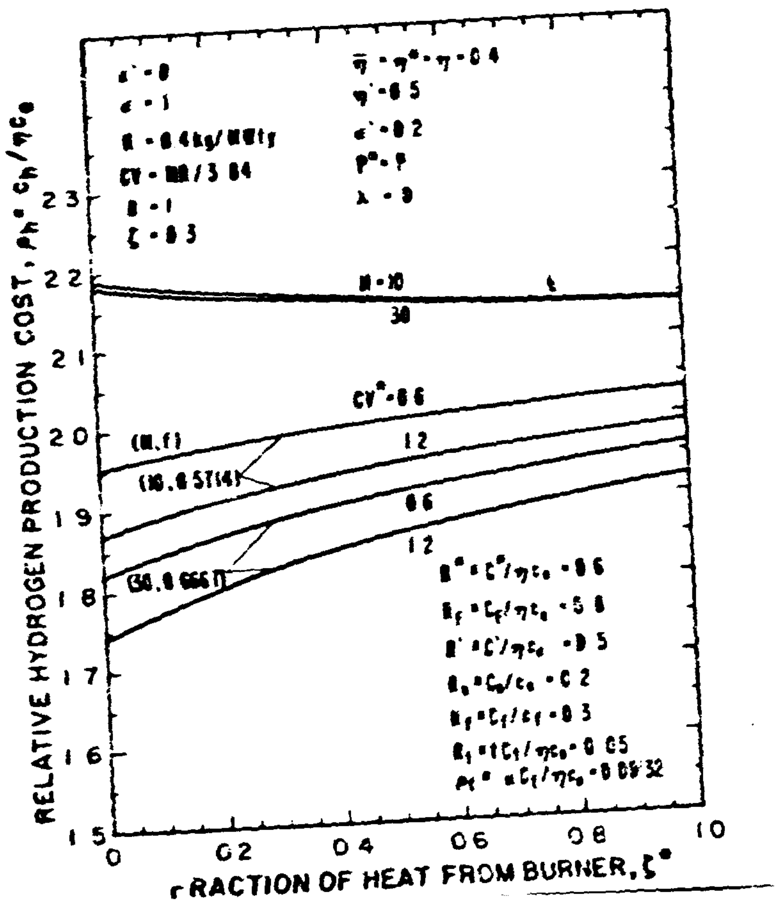

Fig. 3 Dependence of hydrogen production cost (ρ_h) and breakeven selling price (h) (relative to electricity price) on fraction ζ^* of heat generated by the fission burner. Hybrid-synfuel complex is electricity self-sufficient ($k' = 0$), values of M and f are, therefore, related. Curves drawn for CV* equal to 0.6 (LWR) and 1.2 (fast breeder) and M in the range 10-30.

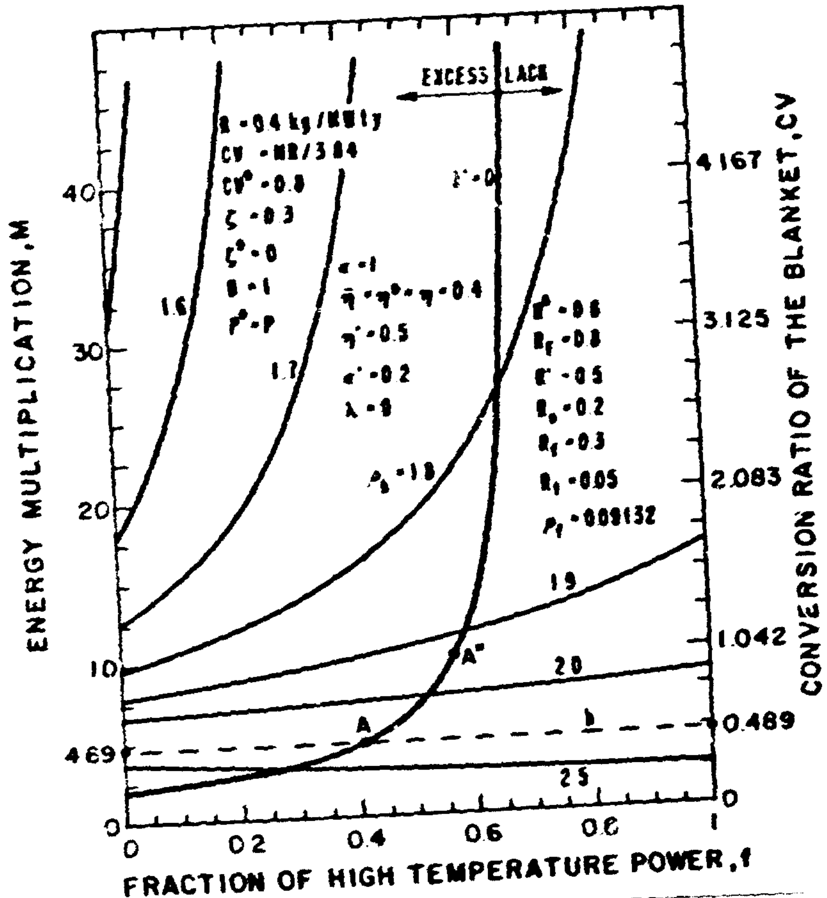

Fig. 4 Dependence of energy multiplication M and conversion ratio CV of the blanket on fraction f of high-temperature heat and for several hydrogen production costs ρ_h. Case of electrici self-sufficiency for hybrid-synfuel complex ($k' = 0$) is also shown.

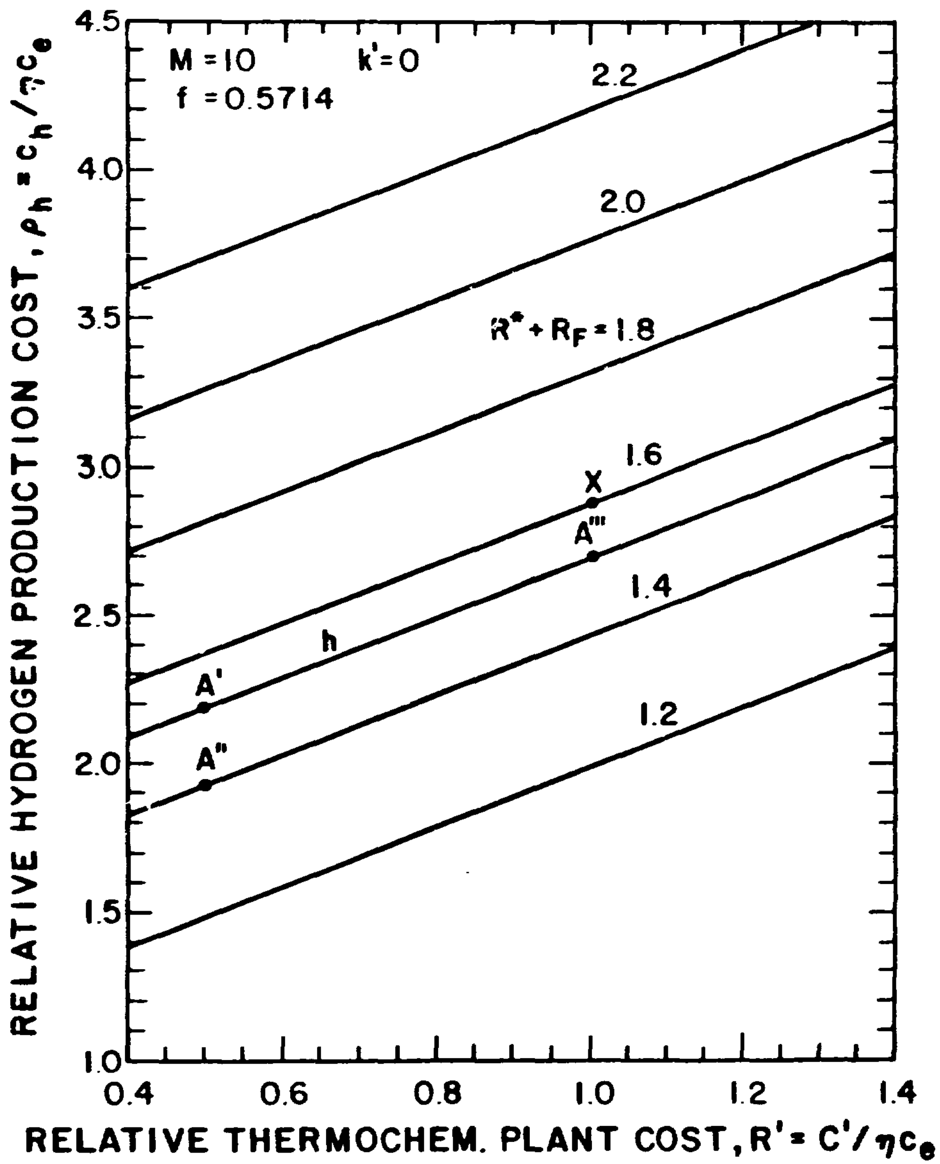

Fig. 5 Dependence of hydrogen production cost (ρ_h) and breakeven selling price (h) on synfuel plant cost (R'), for several fission-burner and hybrid investment cost ($R^* + R_F$). Electricity self-sufficiency (k' = 0) for hybrid-synfuel plant, with M = 10 and f = 0.5714. Values of all other parameters are shown in Fig. 4.

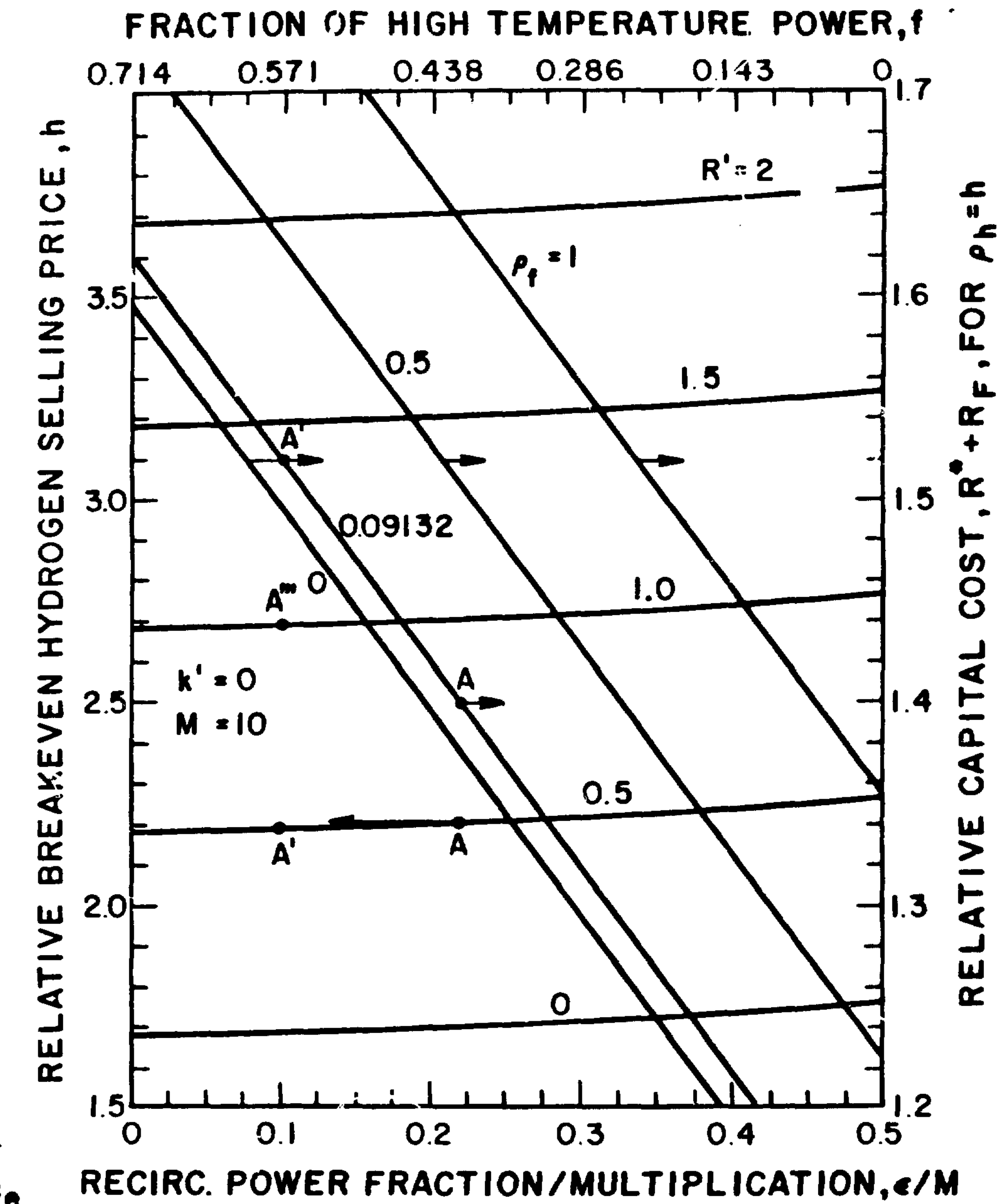

Fig. 6 Dependence of breakeven hydrogen selling price (h), for several synfuel-plant cost (R'), and dependence of investment cost ($R^* = R_F$) for $\rho_h = h$, for several fissile-fuel price (ρ_f), on recirculating-power-fraction-to-energy-multiplication ratio (ϵ/M). Hybrid-synfuel plant is electricity self-sufficient (k' = 0). Values of all other parameters are shown in Fig. 4.

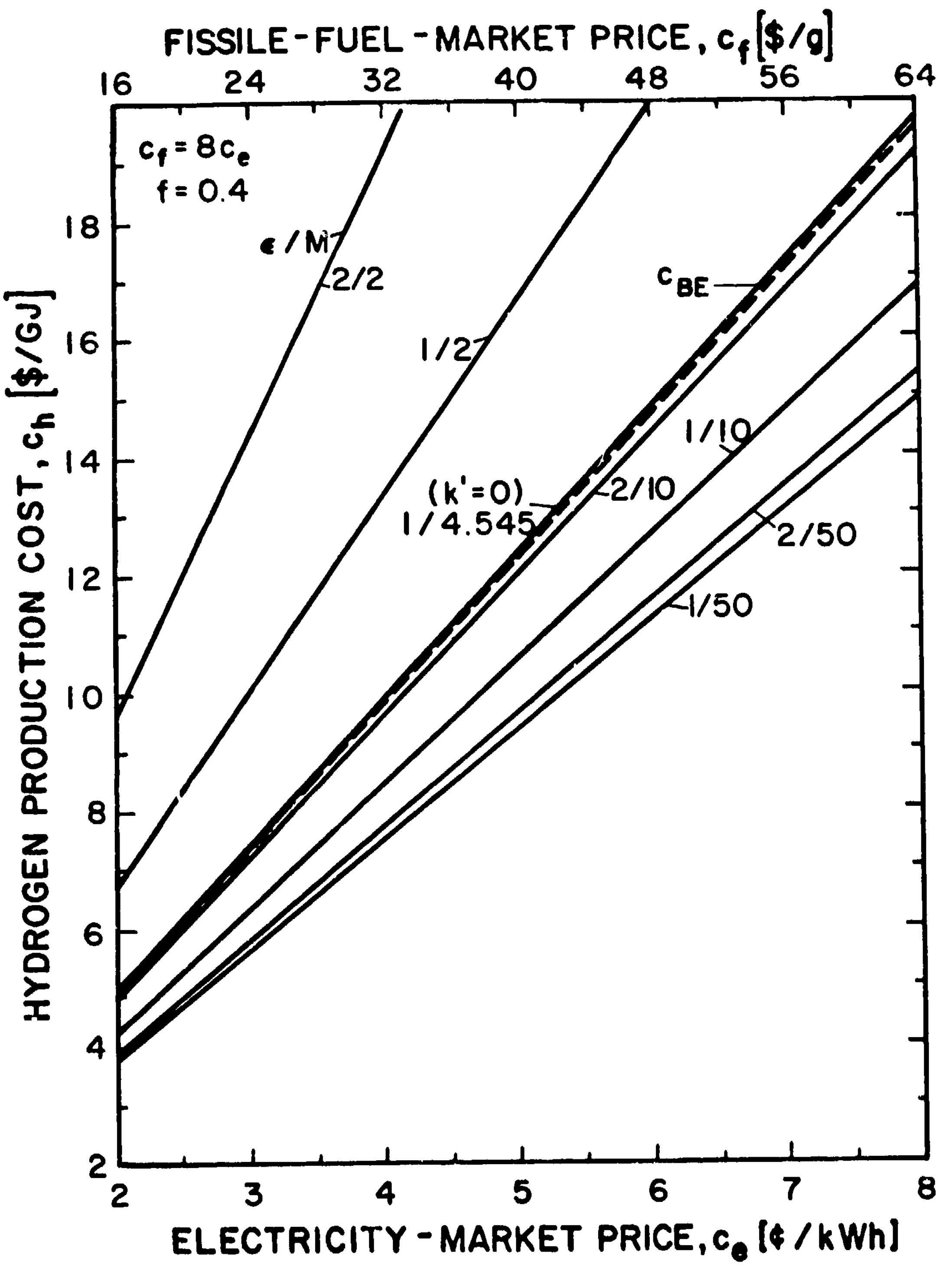

Fig. 7 Hydrogen production cost (c_h) and breakeven hydrogen selling price (c_{BE}) vs electricity price (c_e) for several couples of ε/M values, f = 0.4. For the k' = 0 case, ε/M = 1/4.545. Values of all other parameters are shown in Fig. 4.

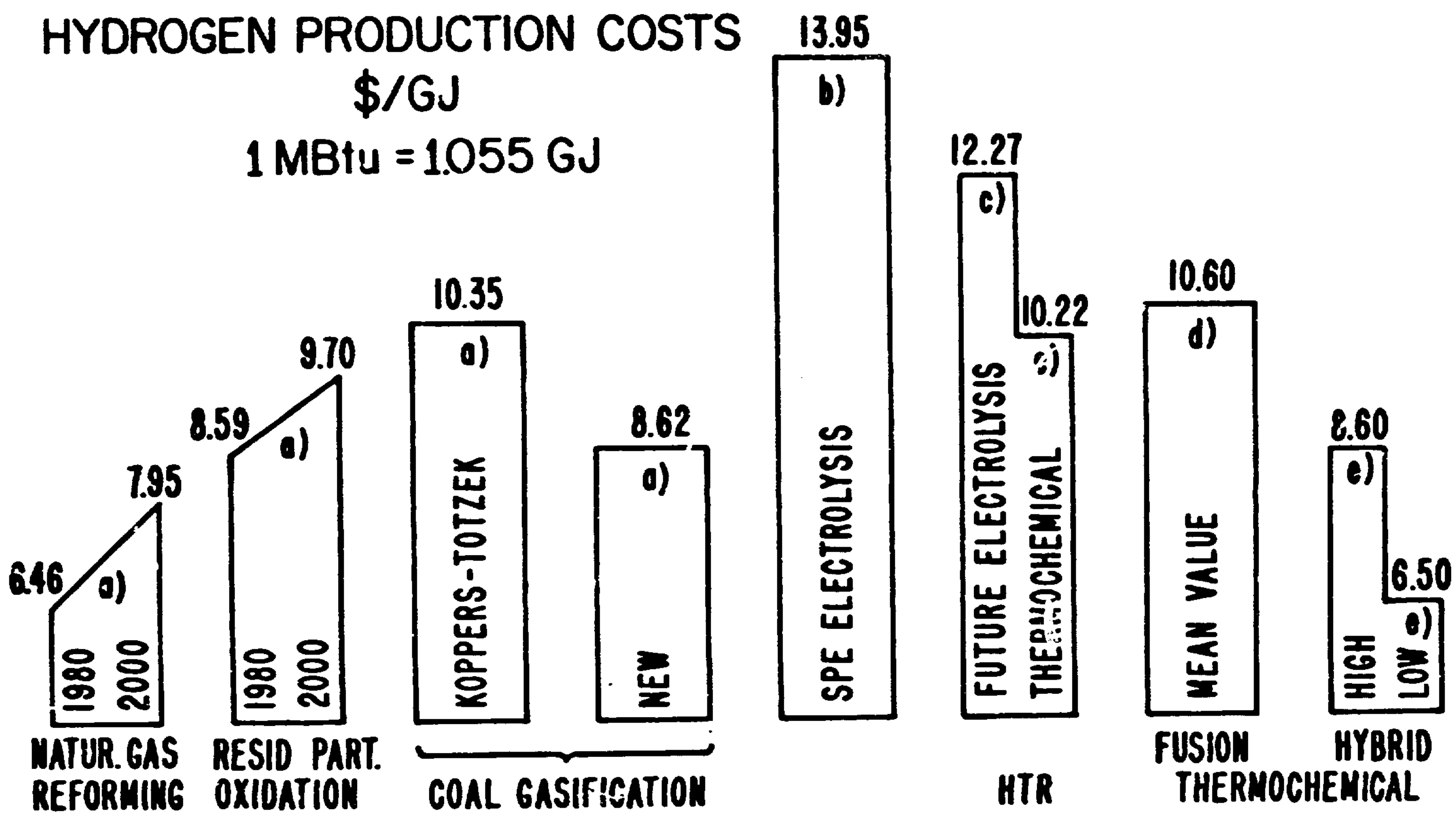

Fig 8 Hydrogen-production-cost comparison.

a) Natural gas reforming and resid partial oxidation for the period of 1980 to 2000. Koppers-Totzek coal gasification using atmospheric pressure and a new process using high pressure, Ref. 8.

b) Solid Polymer Electrolyte Electrolysis, Ref. 8.

c) High-temperature-reactor-driven electrolysis and thermochemical hydrogen, Ref. 9.

d) Pure-fusion-driven-thermochemical hydrogen, Ref. 3.

e) Fusion-fission-synfuel concept. This study.