Tritium and Fissile Fuel Exchange Between Fusion Hybrids, Fission Power Reactors, and Tritium Production Reactors

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UNIVERSITY OF WISCONSIN

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ABSTRACT

A mathematical model has been developed to describe the fissile fuel and tritium flows in a fusion-fission system consisting of a fusion hybrid reactor (H), a tritium production reactor (TPR), and several fission reactors (FR's). The hybrid reactor plays the role of a fuel factory providing the fission reactors and the tritium production reactor with their fissile fuel needs. The TPR is a fission reactor which is devoted primarily to producing tritium for subsequent use in the hybrid reactor. Different possible combinations of these systems can be obtained by shifting the tritium breeding function among the various parts. At steady state, it has been found that the total thermal power of the fission reactors per unit of fusion power depends only on the total conversion ratio of the fission reactors and of the hybrid. An economic analysis is required to determine which combination of systems will produce electricity at the lowest cost.

I. Introduction

Utilizing neutrons from fusion reactions to produce fissile fuel in fusion-fission hybrid reactor blankets has recently been the subject of several extended studies.(1-11) For the standard case, both fissile fuel and tritium are produced in the hybrid blanket. In addition, the possibility of breeding tritium in fission reactors and transferring it to the hybrid (which may partially breed some tritium) has been studied by several authors.(12-20)

In the study presented here, an extension to the mathematical model used by Harms(15) is developed to describe an overall system which may also include a fission reactor devoted mainly to producing tritium for the fusion reactor. The remaining fission reactors are not necessarily tritium producers. An approach of this sort may be of interest because tritium production reactors are currently operational. Eliminating tritium breeding in the hybrid may simplify early designs and thereby permit somewhat earlier introduction.

In the models discussed here, it is assumed that all the components of the system are in equilibrium. The time needed to reach this equilibrium state is not discussed. In the following sections, the neutron reactions, the mathematical model, and the numerical results for different fusion-fission models are given. A comparison between different model systems and concluding remarks are presented at the end.

II. Neutron Reactions and Model Description

Fissile fuel is produced by capture through the reactions

$$^{232}\mathrm{Th}(n,\gamma)\ ^{233}\mathrm{Th} \xrightarrow[22m]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[27.4d]{\beta^-} {}^{233}\mathrm{U} \qquad (1)$$

$$^{238}\mathrm{U}(n,\gamma)\ ^{239}\mathrm{U} \xrightarrow[23m]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[2.3d]{\beta^-} {}^{239}\mathrm{Pu} \qquad (2)$$

and in the model developed here, consumption of the fissile fuel is assumed to take place only in the fission reactors. As in a symbiotic reactor,[17] the fusion blanket is designed to minimize fissile fuel burning.

The fusion fuel (tritium) is produced by the reactions

$$n + {}^{6}Li \rightarrow T + \alpha \quad Q = 4.38 \text{ MeV} \tag{3-a}$$

$$n + {}^{7}Li \rightarrow T + \alpha + n' \quad Q = -2.7 \text{ MeV} , \tag{3-b}$$

or by neutron capture in deuterium if heavy water is used as a moderator in the fission reactors. The production of tiritum in fission reactors can be enhanced by using lithium in the control rods or by locating lithium in the reactor reflector.[13] The latter case is a choice between using the neutrons for fissile fuel or tritium production.

Tritium is assumed to be consumed only in the fusion core through the reaction

$$D + T \rightarrow n + He^{4} + (17.6 \text{ MeV}) . \tag{4}$$

The general model for the entire system is illustrated in Fig. 1. A tritium producer reactor (TPR) and several fission reactors (FR's) provide tritium to the fusion hybrid (H). The hybrid in turn supplies fissile fuel to both the TPR and the FR's. The fusion hybrid may breed some tritium which is recycled to it and the fissile fuel produced in the TPR and the FR's is also recycled. The coupling coefficients C_{ij} associated with the recycle and transfer of nuclei are shown in the figure. The first subscript identifies the type of fuel (i=1 for tritium, i=2 for fissile fuel) while the second subscript identifies the reactor type (j=H for the fusion hybrid, j=F for the fission reactors, and j=T for the tritium production reactor). The fissile fuel reaction rates, R_{ij}, are also shown on the figure and the subscripts are as described above.

Two limiting systems have been studied, namely:

(a) The sharing system where tritium is produced in the FR's. The TPR may or may not be included in the system.

(b) The dedicated system where tritium is produced only in the TPR. No tritium is produced in the fission reactors.

Some tritium may or may not be produced in the hybrid reactor in either case. Schematic diagrams for both cases are shown in Fig. 2.

In the following section, the mathematical model is given and important parameters are derived in terms of the breeding coefficients, C_{ij}. Two such important parameters are the ratio of the thermal power of the FR's to the fusion power of the hybrid reactor and the corresponding ratio related to the TPR.

III. Mathematical Model

We assume that the transfer and recycling processes are continuous and that losses of either fissile fuel (during reprocessing) and fusion fuel (tritium handling and decay) are negligible. We neglect in this model the burnup of fissile fuel in the fusion hybrid blanket. This is acceptable when the hybrid reactor is devoted primarily to fissile fuel production. Depending on exposure time, burnup in the fusion hybrid could be 10% of the amount of fuel bred. Also, we concern ourselves here only with steady-state operation which represents an equilibrium where no net gain of fuel of either kind takes place.

The variation with time of the number of tritium atoms in the system is

$$\frac{dN_1(t)}{dt} = R_{1H}\, C_{1H} + R_{2F}\, (1 + \alpha_F)\, C_{1F} + R_{2T}\, (1 + \alpha_T)\, C_{1T} - R_{1H} \; . \qquad (5)$$

Likewise, the variation with time of the number of fissile fuel atoms is

$$\frac{dN_2(t)}{dt} = R_{1H}\, C_{2H} + R_{2F}\, (1 + \alpha_F)\, C_{2F} + R_{2T}\, (1 + \alpha_T)\, C_{2T} - R_{2F}\, (1 + \alpha_F) - R_{2T}\, (1 + \alpha_T) \; . \qquad (6)$$

In these equations, C_{1H} and C_{2H} are respectively the number of tritium atoms and the net number of fissile atoms produced in the hybrid blanket per fusion event. C_{1F} and C_{1T} are the number of tritium atoms produced in the FR's and the TPR, respectively, per fissile fuel absorption event. The fissile fuel conversion ratios in the FR's and the TPR are the coefficients C_{2F} and C_{2T}, respectively. R_{2F} and R_{2T} are the fission reaction rates in the FR's and the TPR, respectively, while R_{1H} is the fusion reaction rate in the hybrid. α_F and α_T are the capture to fission ratios in the FR's and the TPR, respectively.

The first term in Eq. (5) is the tritium production rate in the hybrid reactor. The second and third terms are the tritium production rates in the FR's and in the TPR, respectively. The last term is the loss rate in the hybrid core due to the D-T reaction. Similar rates for fissile fuel production are given by the first three terms in Eq. (6). The last two terms represent the loss rate due to absorption in the FR's and in the TPR, respectively.

We define P_F, P_T and P_{fus} as the total thermal power of the fission reactors, the thermal power of the tritium production reactor, and the fusion power, respectively, i.e.,

$$P_F = E_{fiss} R_{2F} ,$$

$$P_T = E_{fiss} R_{2T} , \qquad (7)$$

and

$$P_{fus} = E_{fus} R_{1H} .$$

In these equations, E_{fiss} and E_{fus} are the energies released per fission (~ 200 MeV) and fusion (~ 17.6 MeV) event, respectively. At steady-state, Eqns. (5) and (6) become

$$(1-C_{1H}) = \varepsilon \{\frac{P_F}{P_{fus}} (1 + \alpha_F) C_{1F} + \frac{P_T}{P_{fus}} (1 + \alpha_T) C_{1T}\} \qquad (8)$$

and

$$C_{2H} = \varepsilon \{\frac{P_F}{P_{fus}} (1 + \alpha_F) (1 - C_{2F}) + \frac{P_T}{P_{fus}} (1 + \alpha_T) (1 - C_{2T})\} \qquad (9)$$

where $\varepsilon = E_{fus}/E_{fiss}$. The two power parameters of interest are $P_F/P_{fus} \equiv p_F$, the total thermal power of the fission reactors per unit of fusion power, and $P_T/P_{fus} \equiv p_T$, the thermal power of the tritium production reactor per unit of fusion power. Eqns. (8) and (9) are two linear equations relating the specific power ratios, p_F and p_T, to the coefficients C_{ij}. Taking these ratios as the dependent variables, we find

$$p_F = \frac{(1-C_{2T})(1-C_{1H})-C_{1T}C_{2H}}{\varepsilon(1+\alpha_F)\{C_{1F}(1-C_{2T})-C_{1T}(1-C_{2F})\}} \qquad (10)$$

$$p_T = \frac{(1-C_{2F})(1-C_{1H})-C_{1F}C_{2H}}{\varepsilon(1+\alpha_T)\{C_{1T}(1-C_{2F})-C_{1F}(1-C_{2T})\}} . \qquad (11)$$

The values of C_{ij} can be estimated based upon the large number of hybrid blanket neutronics studies which have been performed. For example, in a hybrid blanket using thorium to breed ^{233}U, the total breeding capacity, C_H, defined as the summation of C_{1H} and C_{2H}, is typically about 1.5. For a blanket that breeds ^{239}Pu from ^{238}U, C_H is about 2.5. Similarly, the total breeding capacity in the FR's, C_F, is $C_{1F} + C_{2F}$ while that in the TPR is $C_T=C_{1T}+C_{2T}$. C_F and C_T are determined by the neutron economy in the FR's and the TPR. The maximum value in either case is $(\eta-1)$ where η is the number of neutrons emitted per absorption event in the fuel. The value of η depends on the fuel cycle utilized (^{232}Th-^{233}U or ^{238}U-^{239}Pu) and the nature of the neutron spectrum (fast or thermal).

The final thermal power of interest is the total thermal power of the hybrid reactor, P_H, which is given by[21]

$$P_H = P_{fus} \{\frac{1}{\gamma_{in} Q} + 1 + f_n (M-1)\} \tag{12}$$

where Q is the ratio of the fusion power to the power injected to maintain the plasma, f_n is the fraction of fusion energy released in neutrons, M is the hybrid blanket energy multiplication defined as the ratio of energy deposited in the blanket per 14.1 MeV D-T neutron, and γ_{in} is the efficiency of energy injection in the hybrid. One should notice that M is a function of C_{2H}, i.e., a blanket designed to have a high value of C_{2H} may well turn out to have a high value of M, leading to a high value of P_H.

Formally, Eq. (10), Eq. (11) and Eq. (12) and the constraints given by the values of C_H, C_F, and C_T describe the entire system. In the following section, two special cases, the sharing system and the system with dedicated tritium production reactors, are analyzed.

Before proceeding to look at these special cases, some remarks about the general system can be made. Since Eqs. (8) and (9) are sufficient to describe the system, any linear combination of the equations will suffice equally well. One such linear combination arises if Eq. (8) is subtracted from Eq. (9) yielding

$$C_H - 1 = \varepsilon \{p_F(1+\alpha_F)(1-C_F)+p_T(1+\alpha_T)(1-C_T)\} \quad . \qquad (13)$$

The physical meaning of this linear combination is that the rate of production of tritium and fissile nuclei are the same, i.e.

$$\frac{dN_1}{dt} - \frac{dN_2}{dt} = 0 \quad .$$

If the breeding capacity of the hybrid is fixed, Eq. (13) shows that the power ratio in the FR's is bounded. Further, if the breeding capacity in the fission reactors is also fixed, the largest value of p_F is obtained when the second term is zero, i.e. when $p_T = 0$ (implying no TPR) or when the design of the tritium production reactor has been optimized to the point that it has a breeding capacity, C_T, of unity. Only if the TPR were a true breeder ($C_T > 1$), would the addition of a TPR result in an increase in the power available from the FR's because in this case the tritium production reactor is able to produce all the tritium for the hybrid and also produce some fissile fuel for the FR's. Thus, any realistic system ($C_T < 1$) with a TPR leads to lower values of p_F relative to a non-TPR system and other aspects of the overall system, such as early introduction, must be considered to evaluate the merits of adding a TPR.

IV. Special Combinations of Systems

1. The Sharing System

In the sharing system, tritium is assumed to be produced in the fission reactors. The TPR may be included in the system.

1.A. The System Without a Tritium Production Reactor

If there is no dedicated tritium producing fission reactor, p_T is zero and from Eqns. (10) and (11), we find

$$p_F = \frac{1}{\varepsilon(1+\alpha_F)} \cdot \frac{C_{H-1}}{1-C_F} , \qquad (14)$$

with

$$C_{1F}\, C_{2H} = (1-C_{2F})(1-C_{1H}) . \qquad (15)$$

Eqn. (15) relates the coefficients C_{ij} at steady-state. These equations thus describe a system of fission reactors and hybrids in which tritium for the hybrid is produced using the fission power reactors.

From Eq. (14) we see that when the breeding capacities, C_H and C_F, are conserved in the hybrid and the FR's, respectively, the value of the thermal power of the fission reactors per unit fusion power, p_F, is the same regardless of whether tritium is produced in the hybrid reactor or the fission reactors. The same conclusion is true regarding fissile fuel production in either the hybrid or the fission reactors. In table 1, we give the breeding coefficients C_{ij} for four special cases. In all these cases, p_F is the same if C_H and C_F are fixed. In Fig. 3, we show the dependence of p_F on the total breeding capacity C_F in the fission reactors. Two breeding capacity values in the hybrid reactor are considered, namely, $C_H = 1.5$ and $C_H = 2.5$. The former value is typical of a hybrid reactor based on the ^{232}Th-^{233}U fuel cycle and so we have used a value for α_F=0.1. For the ^{238}U-^{239}Pu fuel cycle, C_H is usually about 2.5 and we have used α_F equal to 0.35. Clearly, increasing the breeding capacity in the fission reactors gives higher thermal power in these reactors per unit of fusion power because of the better neutron economy in the fission reactors. The same effect is obtained if the hybrid blanket is designed to have a high value of C_H. Note that the rate of change $\frac{dp_F}{dC_H}$ is about $1/(1-C_F)$ while the rate of change, $\frac{dp_F}{dC_F}$, is approximately $1/(1-C_F)^2$. Thus, better coupling between the hybrid and the fission reactors is obtained if the breeding capacity of the fission reactors, C_F, is near unity.

1.B. Systems With a Tritium Production Reactor

If the TPR is included in the system, and if its breeding capacity, $C_T = C_{1T} + C_{2T}$, is unity, then upon examining Eq. (13), we find that p_F is again given by Eq. (18). Thus, the value of p_F is the same for the same C_H and C_F values. However, the thermal power of the tiritum producer reactor per unit of fusion power, p_T, will depend on the values of the tritium breeding coefficients C_{1H} and C_{1F} (or C_{2H} and C_{2F}) even if C_H, C_F and C_T are conserved.

For example, in the special case where tritium is produced in the TPR and the FR's but the TPR does not breed fissile fuel ($C_{1T}=1$, $C_{2T}=0$), we find

$$p_T = \frac{1-C_F-C_{1F}(C_H-1)}{\varepsilon(1+\alpha_T)(1-C_F)} \tag{16}$$

which depends on the tritium breeding coefficient in the FR's, C_{1F}. Results for p_T as functions of C_{1F} are shown in Fig. 4 for two values of the total fission reactor conversion ratio, C_F = 0.6, typical of a light water reactor, and C_F = 0.9, typical of an advanced convertor reactor. Clearly, p_T varies linearly with C_{1F} and the value of C_{1F} in the limiting case where p_T = 0 is

$$C_{1F} = \frac{1-C_F}{C_H-1} , \tag{17}$$

as shown in the first column in Table 1.

If all the tritium is produced in the TPR ($C_{1H}=0$, $C_{1F}=0$), the value of the thermal power of the tritium production reactor per unit of fusion power does not depend on the breeding capacities, C_H and C_F. In this case, p_T assumes the value

$$p_T = \frac{1}{\varepsilon(1+\alpha_T)} , \quad (C_{1H} = C_{1F} = 0) . \tag{18}$$

This value is given by points A and A' in Fig. 4.

2. The Dedicated System

In this system, tritium is not produced in the fission reactors while the TPR is devoted solely to tritium production. We have already discussed the case where all tritium is produced in the TPR. Here we discuss the effect of breeding some tritium in the hybrid blanket. With no tritium bred in the fission reactors ($C_{1F}=0$, $C_{2F}=C_F$), p_T varies linearly with C_{1H} in the simple form

$$p_T = \frac{(1-C_{1H})}{\varepsilon(1+\alpha_T)} \quad . \tag{19}$$

We assume that the TPR has breeding coefficients $C_{1T}=1$ and $C_{2T}=0$. The value of P_F is given again by Eq. (14) and is constant for given values of C_H and C_F regardless of whether tritium is produced in the hybrid or the TPR. As given by Eq. (19), p_T is independent of the breeding capacity in either the fission reactors or the hybrid. The limiting but standard case of all tritium breeding in the hybrid ($p_T=0$, $C_{1F}=0$, $C_{2F}=C_F$) is obtained when $C_{1H}=1$, i.e., when the hybrid reactor is self-sufficient in tritium production. This case is given in the second column in Table 1.

V. Summary

It is found that for given values of breeding capacity in the hybrid and the fission reactors, C_H and C_F, the thermal power of the fission reactors per unit fusion power is the same for the following types of overall system combinations:

a. All tritium is produced in the hybrid reactor and the tritium production reactor (TPR) is excluded from the system. The parameters for this sytem are $P_T=C_{1F}=0$, $C_{2F}=C_F$, and $C_{1H}=1$.

b. All tritium is produced in the fission reactors and the TPR is excluded from the system. This system has the parameters $P_T = C_{1H} = 0$, and $C_{2H} = C_H$.

c. Tritium is produced in the fission reactors and the hybrid reactor. The TPR is excluded from the system. The system has $P_T = 0$, $C_{1H}\neq 0$, and $C_{1F}\neq 0$.

d. Tritium is produced in the fission reactors and the TPR. This system has the parameters $C_{1H}=0$, $C_{1T}=1$, $C_{2T}=0$, and $C_{1F}\neq 0$.

e. All tritium is produced in the TPR. This system has parameters $C_{1T}=1$ and $C_{2T}=C_{1H}=C_{1F}=0$.

f. Tritium is produced in the TPR and the hybrid. This system has the parameters $C_{1T}=1$, $C_{2T}=C_{1F}=0$, and $C_{1H}\neq 0$.

The performance of the overall systems discussed in this paper has been characterized by the power ratios p_F and p_T, the power of the fission reactors and the tritium producing reactor per unit of fusion power. These, however, are not the only nor necessarily the correct figures-of-merit for a system even though they may be adequate for determining the basic merit of a particular combination of reactor types. For example, rather than using the fusion power of the hybrid as a basis, the thermal power of the hybrid could be used. The figure-of-merit would then be P_F/P_H and P_T/P_H. These figures-of-merit would have smaller values, not only because P_H is greater than P_{fus}, but also because P_H depends on the hybrid blanket multiplication, M, which in turn is a function of the two hybrid conversion ratios, C_{1H} and C_{2H}. If the hybrid and the tritium production reactor are viewed as a fuel factory, then a figure-of-merit defined as $P_F/(P_H+P_T)$ might be considered as more appropriate, especially if neither the hybrid nor the TPR produce electricity. If either one or both produce electricity, one might consider adding terms to the numerator of a figure-of-merit to reflect their role as revenue producers as well as fuel producers.

None of these figures-of-merit are truly satisfactory because they do not necessarily reflect which system supplies electricity at the lowest cost. An economic analysis is thus required which would account for changes in costs as the various parts of the system taken on different roles (for example breeding only fissile fuel as opposed to breeding fissile fuel and tritium) as well as changes in revenue patterns (for example, whether or not a component produces electricity). Krakowski and Tai[(22)] have made such an analysis for one particular combination wherein all fuel is produced in the hybrid, i.e. $P_T=0$, $C_{1F}=0$. An extension of such a technique to cover all combinations is necessary to obtain proper comparisons.

Table 1 The Value of Breeding Coefficients C_{ij} for Four Special Cases of the Sharing System. The TPR is Not Included.

	All Tritium is Bred in:		All Fissile Fuel is Bred in:	
	The FR's	The Hybrid	The FR's	The Hybrid
The Hybrid (H) Tritium Breeding Coefficient, C_{1H}	0	1	C_H	$\frac{C_F C_H - 1}{C_F - 1}$
Fissile Breeding Coefficient, C_{2H}	C_H	C_{H-1}	0	$\frac{1 - C_H}{C_{F-1}}$
The Fission Reactors (FR's) Tritium Breeding Coefficient, C_{1F}	$\frac{1 - C_F}{C_H - 1}$	0	C_{F-1}	C_F
Fissile Fuel Breeding Coefficient, C_{2F}	$\frac{C_H C_F - 1}{C_H - 1}$	C_F	1	0

Figure Captions

Figure 1 General material flows, conversion ratios, and reaction rates for an overall energy system consisting of fission reactors, fission-fusion hybrid reactors, and tritium production reactors.

Figure 2 The two limiting systems studied (a) The Sharing System
(b) The Dedicated System.

Figure 3 The variation of the thermal power of fission reactors per unit of fusion power which can be supported by a hybrid as a function of the conversion ratio of the fission reactors. ε is the ratio of the energy per fusion event to the energy per fission event. The two curves characterize U-Pu cycle systems or Th-^{233}U systems.

Figure 4 p_T as a function of the tritium breeding coefficient in the fission reactors. At $C_{1F} = 0$, all tritium is produced in the TPR.

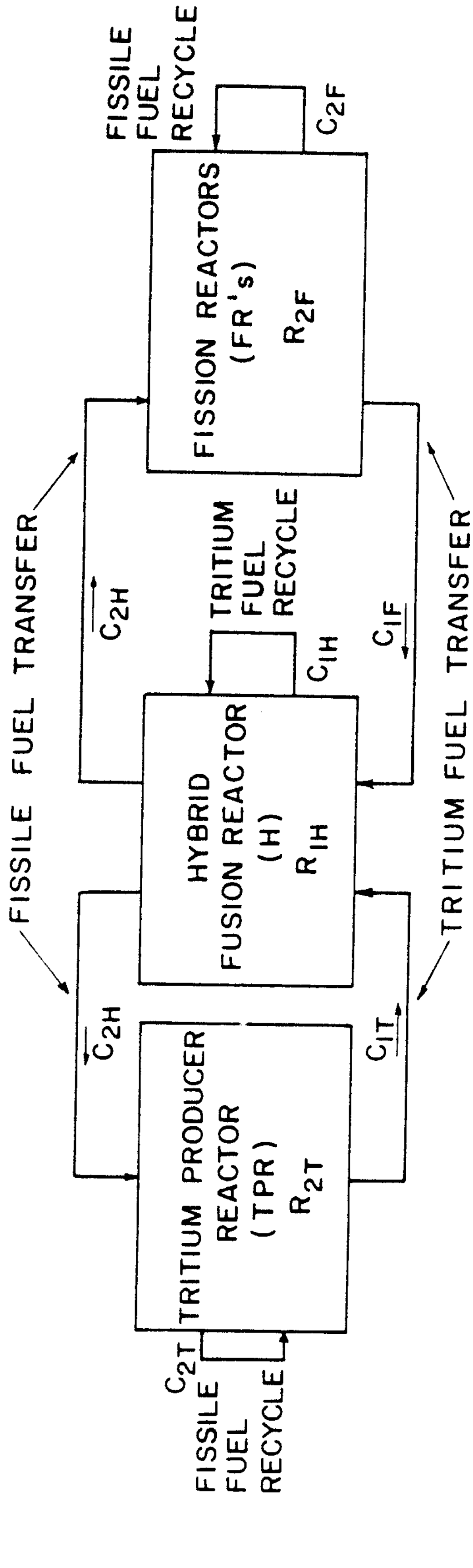

FISSILE FUEL RECYCLE
C_{2F}
FISSION REACTORS (FR's) R_{2F}
FISSILE FUEL TRANSFER
C_{2H}
TRITIUM FUEL RECYCLE
C_{1H}
C_{1F}
TRITIUM FUEL TRANSFER
HYBRID FUSION REACTOR (H) R_{1H}
C_{2H}
C_{1T}
TRITIUM PRODUCER REACTOR (TPR) R_{2T}
C_{2T}
FISSILE FUEL RECYCLE

Fig. 1

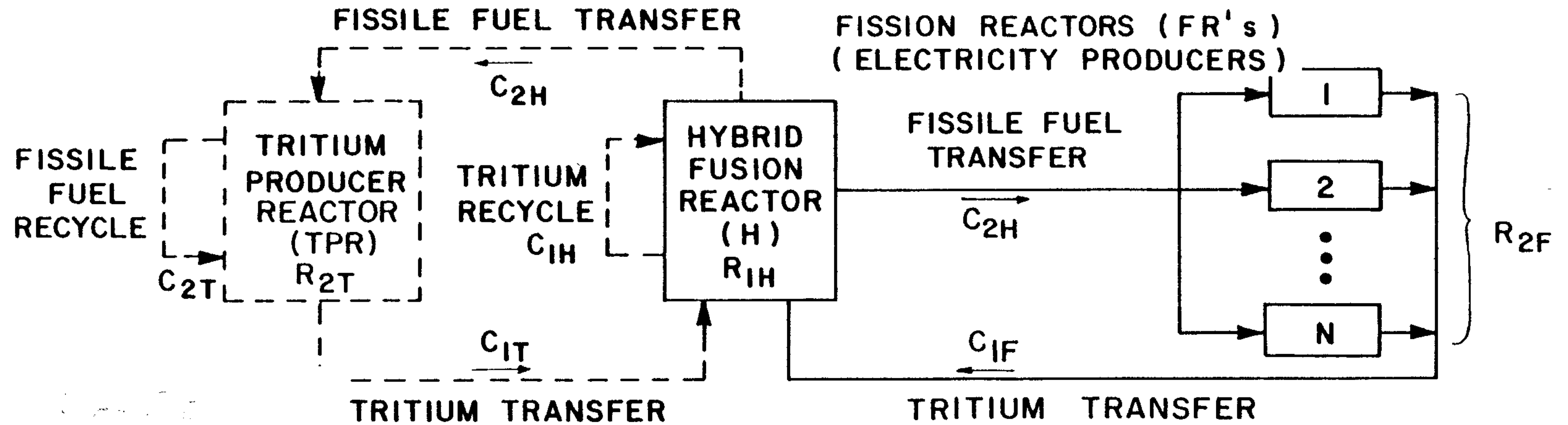


Fig. 2A <u>THE SHARING SYSTEM</u>. THE FR's PROVIDE THE HYBRID WITH TRITIUM WHICH IN TURN PROVIDES THE FR's WITH FISSILE FUEL. THE HYBRID MAY OR MAY NOT PRODUCE TRITIUM. THE TPR MAY BE INCLUDED.

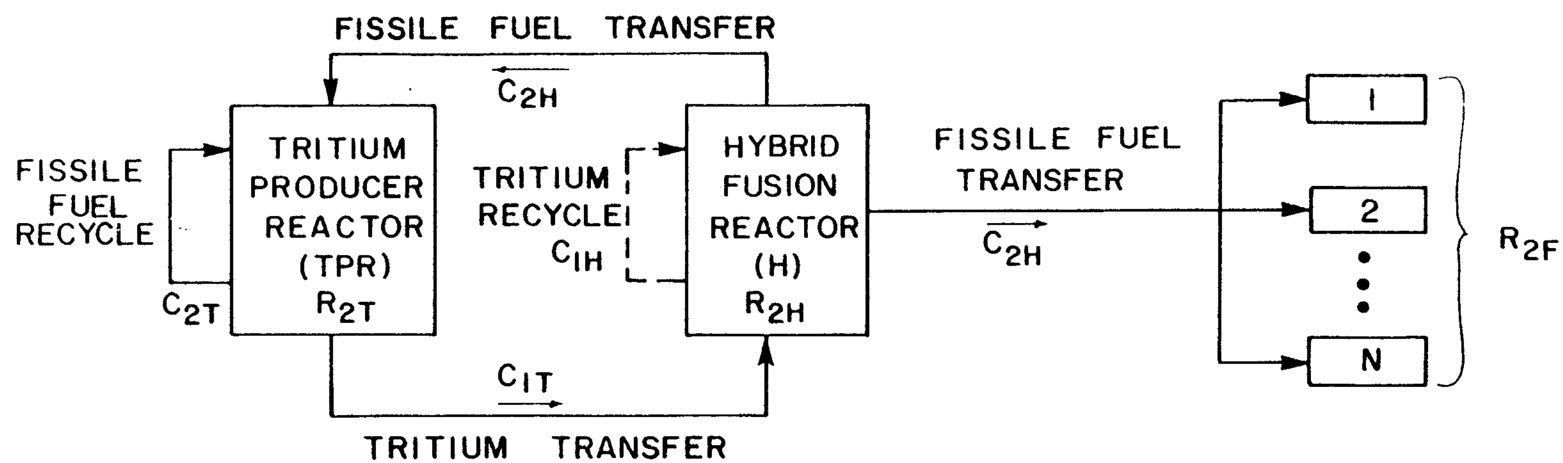


Fig. 2B <u>THE DEDICATED SYSTEM</u>. THE TPR PROVIDES THE HYBRID WITH TRITIUM; THE HYBRID PROVIDES THE TPR AND THE FR's WITH FISSILE FUEL; THE HYBRID MAY OR MAY NOT BREED TRITIUM.

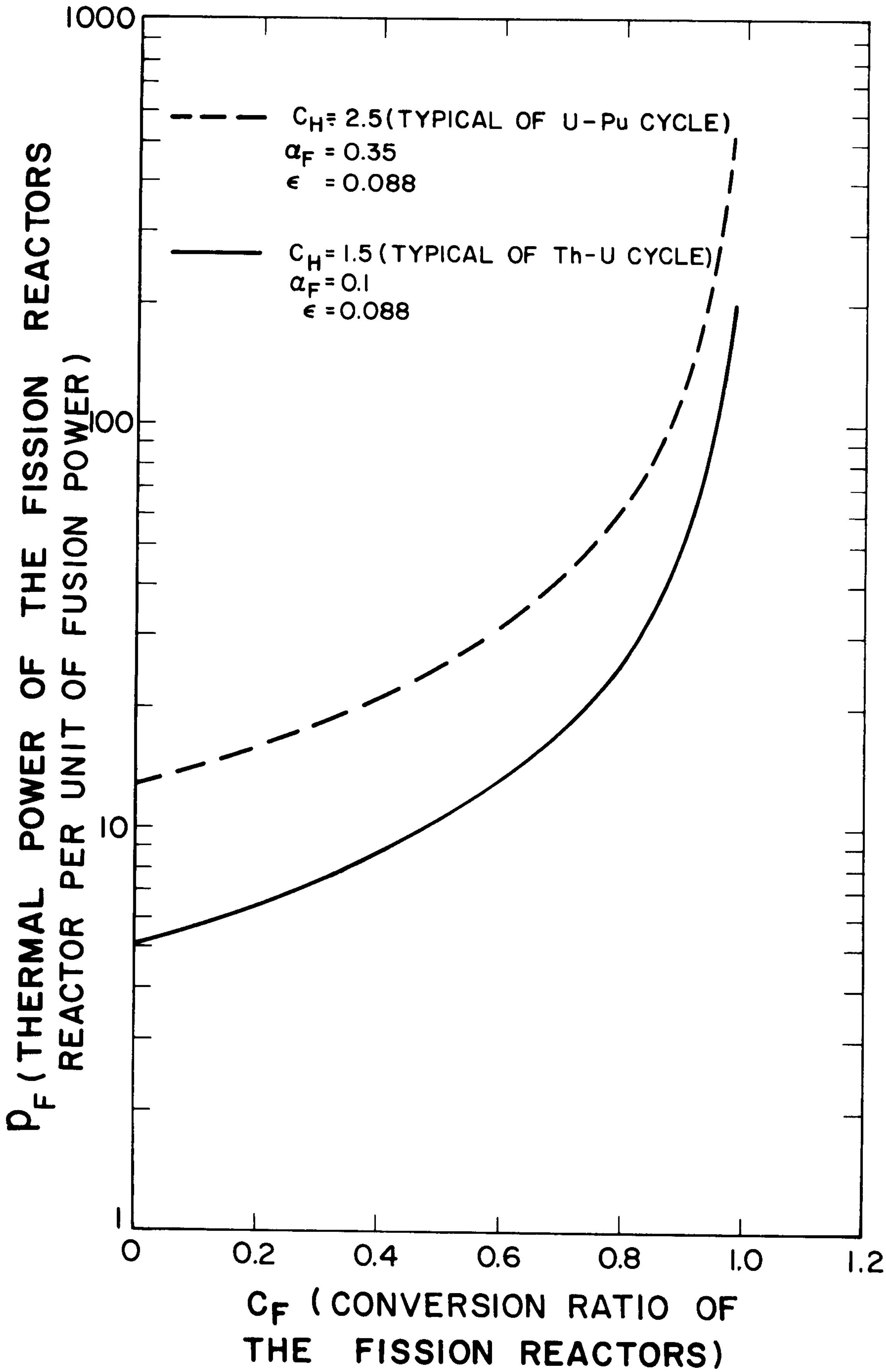
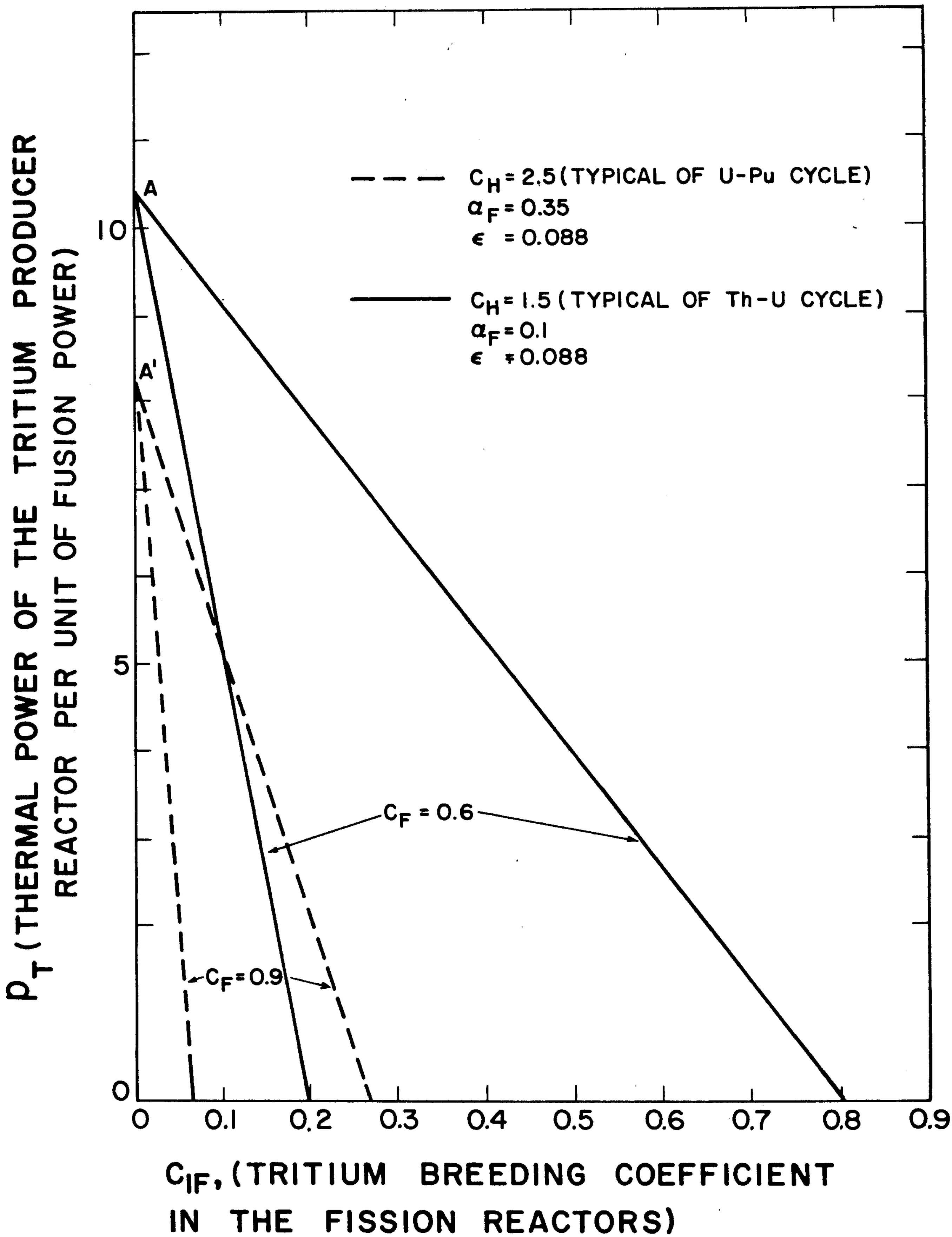

1000
100
10
1
0
0.2
0.4
0.6
0.8
1.0
1.2
CH = 2.5 (TYPICAL OF U-Pu CYCLE)
αF = 0.35
ε = 0.088
CH = 1.5 (TYPICAL OF Th-U CYCLE)
αF = 0.1
ε = 0.088
PF (THERMAL POWER OF THE FISSION REACTORS
REACTOR PER UNIT OF FUSION POWER)
CF (CONVERSION RATIO OF
THE FISSION REACTORS)

Fig. 3



C_H = 2.5 (TYPICAL OF U-Pu CYCLE)
α_F = 0.35
ε = 0.088
C_H = 1.5 (TYPICAL OF Th-U CYCLE)
α_F = 0.1
ε = 0.088
A
A'
C_F = 0.6
C_F = 0.9
0
5
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
p_T (THERMAL POWER OF THE TRITIUM PRODUCER REACTOR PER UNIT OF FUSION POWER)
C_IF, (TRITIUM BREEDING COEFFICIENT IN THE FISSION REACTORS)

Fig. 4

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