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POWER GENERATION
VERSUS FUEL PRODUCTION
IN LIGHT WATER HYBRID REACTORS

BY

E. GREENSPAN

**PLASMA PHYSICS
LABORATORY**

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Power Generation Versus Fuel Production in Light-Water Hybrid
Reactors *

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List of Symbols

- A = fuel rod cross section area
- $a = A^f/A^h$
- BU = average fuel burn up per irradiation cycle
- $b = BU^f/BU^h$
- C = fuel cycle cost component of T
- CR = effective conversion ratio
- D_R = ratio of duty factors of fission to hybrid reactors
- F = net fissile atoms gained per fusion neutron
- f_c = ratio of fuel weight in converter to fuel weight in entire blanket.
- I = capital investment
- K = capital cost component of T
- M = blanket energy multiplication
- O = operation and maintenance cost component of T
- P_n = net electrical power output of reactor
- P_{th} = thermal power
- p = defined by Eq. 50
- Q = ratio of fusion energy released to neutral beam energy deposited in plasma
- R = ratio of capital investment per unit of thermal energy for hybrid to that for fission reactors (Eq. 8)
- R_O = indifference value of R
- s = uranium ore cost/(\$20/lb. U_3O_8)
- T = total cost of electric power generation
- W = average loading of first wall in MW/m²
- α = effective capture to fission ratio for P_u
- ϵ = fast fission factor

- ϵ_f = coefficient for extra expense of fabrication of P_u bearing fuel
- ϵ_o = coefficient for extra expense associated with fusion system operation
- ϵ_p = ratio of reprocessing costs without requiring to those with requiring the separation of P_u
- ϵ_w = fraction of first wall covered in the blanket
- η_e = beam injection efficiency
- η_n = net efficiency of a reactor
- η_r = ratio of net efficiencies of fission and hybrid reactors
- η_{th} = thermal efficiency

POWER GENERATION VERSUS FUEL PRODUCTION
IN LIGHT-WATER HYBRID REACTORS

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ABSTRACT

The economic potentials of fissile-fuel-producing light-water hybrid reactors (FFP-LWHR) and of fuel-self-sufficient (FSS) LWHR's are compared. A simple economic model is constructed that gives the capital investment allowed for the hybrid reactor so that the cost of electricity generated in the hybrid based energy system equals the cost of electricity generated in LWR's. The power systems considered are LWR, FSS-LWHR, and FFP-LWHR plus LWR, both with and without plutonium recycling.

The economic potential of FFP-LWHR's is found superior to that of FSS-LWHR's. Moreover, LWHR's may compete, economically, with LWR's. Criteria for determining the more economical approach to hybrid fuel or power production are derived for blankets having a linear dependence between F and M . The examples considered favor the power generation rather than fuel production.

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1. INTRODUCTION

Recently we have proposed¹ a new concept of fusion-fission hybrid power reactors that is fissile fuel-self-sufficient; that is, it has a zero breeding gain ($F=0$). The blanket of this hybrid is composed of natural uranium fuel (in the form of oxide) and light water for the moderator and coolant. This fuel-self-sufficient light water hybrid reactor (FSS-LWHR) is found to possess a unique collection of attractive properties that make it a potentially promising advanced nuclear power reactor. One can visualize a nuclear energy system that consists only of a single type of power reactor - the FSS-LWHR - that can utilize all the resources of fissionable fuel (including depleted uranium) using a simple and safe fuel cycle (relative to the fuel cycle of the light-water reactors).

If we assume that by the time the LWHR can be made commercial the energy system will consist of a large capacity of LWR's, then these reactors will require a large supply of fissile fuel for their operation. As the low cost uranium ore reserves are believed to be quite limited, there will be a real need for fissile-fuel producing capability. This need for assurance of the long-term supply of fissile fuel for the well developed LWR's is one of the primary motivations for fissile fuel producing hybrids. Indeed, the dominant approach to the conception of hybrids emphasizes their fuel production role (see, e.g., the review articles by Leonard² and Lidsky³).

One can visualize an energy system development scenario in which fissile-fuel producing hybrids are first introduced to support the fleet of LWR's already in operation. The capacity of LWR's that phase out of the energy system is then replaced by FSS-LWHR. Thus we can plan on a gradual increase in the relative energy produced by FSS-LWHR which will become, after about 30 years, the dominant source of nuclear energy.

For the foregoing scenario to be the desirable one, it is necessary that either the economics of FSS-LWHR be competitive with that of a combined fissile-fuel producing hybrid plus LWR's power system, or that socio-political considerations favor the FSS-LWHR even if it is not as favorable economically as the alternative power system.

It is possible to use several approaches to design natural uranium light-water based blankets that will have a breeding gain. One way is to design the blanket lattice to have a lower water-to-fuel volume ratio than in the FSS-LWHR blanket. Another way is to add to the FSS-LWHR blanket a fast fission convertor zone similar in principle to that used in the Livermore design.⁴ Such an arrangement is expected to provide the fissile fuel production ability of the fast blankets⁴ and the energy multiplication of the combined fast and thermal blankets. The magnitude of this energy multiplication can be several times the energy multiplication of the fast blanket alone. In this work

we shall consider the latter approach to FFP-LWHR blankets.

The primary goals of this work are: 1) to evaluate the economic potential of LWHR's and, 2: to compare the economics of FFP-LWHR's with that of the FSS-LWHR concept. In addition, we address ourselves to the general question of fuel production versus power generation in hybrid reactors.

In the following section we describe the alternative energy systems considered and develop the economic model for their comparison. In Section 3 we evaluate the economic potential of FSS-LWHR's and in Section 4 that of FFP-LWHR's. To do the latter, we consider an energy system composed of FFP-LWHR's and LWR's in which the number of the two types of reactors are balanced so that all the fissile fuel required to feed the LWR's is provided by the FFP-LWHR's. In Section 5 we discuss the economic outlook for LWHR's and in Section 6 we address ourselves to certain general questions concerning fuel versus power production in hybrid reactors.

It should be emphasized that the energy systems considered in this work are ideal, and their modeling is simplified. It is expected, nevertheless, that such a simplified approach will provide useful indications on the economic potential of LWHR's and on the relative merits of FSS versus FFP hybrids. A detailed assessment of the possible contributions of LWHR's to the national energy program would require a sophisticated benefit versus cost analysis such as developed by Doenigi.⁵ Such an assessment will be necessary when more reliable and complete design and performance data of LWHR's will be available.

2. MODEL FOR ANALYSIS

Three nuclear energy systems are considered:

- I. Light Water Reactors (LWR) only. This is the reference energy system. Two versions of this system will be considered, one without and one with plutonium recycling.
- II. Fuel Self-Sufficient Light Water Hybrid Reactors (FSS-LWHR). An energy system consisting of FSS-LWHR's could utilize all the reserves of fissionable fuel (both uranium and thorium). It appears that such a system is the simplest of all advanced fission systems proposed to date.
- III. A Combination of FFP-LWHR's and LWR's. The hybrid reactors are to breed fissile fuel and to generate power. Their excess fissile fuel is to support the system of LWR's. The ratio of FFP-LWHR's to LWR's is taken to be such that the combined system, at equilibrium (i.e., discounting the addition of new LWR's), can be maintained on natural uranium only, with no need for enrichment services.

2.1 LIGHT WATER REACTORS WITHOUT PLUTONIUM RECYCLING

This is, in fact, the present nuclear energy system and consequently the reference system for our economic analysis. The total cost of electrical power generation in this (and other) systems will be expressed as the sum

$$T = K + C + O$$

(1)

of a capital cost component, K , a fuel cycle cost component, C , and an operation and maintenance (O&M) cost component, O . The fuel cycle will be broken into the following subcomponents

$$C = C_{\text{ore}} + C_{\text{enr}} + C_{\text{fab}} + C_{\text{rep}} + C_{\text{str}}, \quad (2)$$

expressing the contribution of the cost of, respectively, uranium ore, uranium enrichment, fuel fabrication, fuel reprocessing and of the storing and shipping of irradiated fuel and/or waste disposal.

For the relative contribution of the above cost components in the reference energy system we shall assume typical mid-seventies LWR's economy figures:⁶

$$K:C:O = 1:1/4:1/10 \quad (3)$$

and

$$C_{\text{ore}}:C_{\text{enr}}:C_{\text{fab}}:C_{\text{rep}}:C_{\text{str}} = 1:1:1:1/2:1/2 \quad (4)$$

The half-half split between C_{rep} and C_{str} is assumed somewhat arbitrarily. It is interesting to note that even though there was a significant increase in the cost of nuclear power since the beginning of the seventies, the proportional contribution of the different cost components is stable (compare, e.g., Ref. [6] with Ref. [4]). For absolute cost estimates we shall use, as the reference, the 1976 cost values of \$750/kWe and \$20/lb U_3O_8 .

A fuel cycle cost component not included in the breakdown of Eq. (2) is that associated with the interest on the investment

in the fuel inventory. Even though the power density in the hybrid reactor blanket may be lower than the power density in the core of LWR's, the average specific power in the LWHR is expected to be higher¹ than in the LWR. Consequently, the total value of fuel tied up in the reactor is expected to be lower for a LWHR than for a LWR. By disregarding this interest on inventory cost component, we actually underestimate the economic benefit of LWHR's.

2.2 LIGHT WATER REACTORS WITH PLUTONIUM RECYCLING

Plutonium recycling affects only the fuel cycle cost component. Assuming an average LWR conversion ratio of 0.5 the ore and enrichment requirements are reduced by about 20% if the power system is not expanding and only by about 10% in an expanding power system.⁶ The fabrication cost of plutonium bearing fuel is higher, however, than that of uranium-only fuel; we shall assume, somewhat arbitrarily, that plutonium recycling causes a 40% increase in the fuel fabrication costs.

An additional cost component sometimes used in the fuel cycle economics is the cost of the plutonium itself. Since the plutonium is produced as a byproduct in LWR's, its value is not uniquely defined; it depends on the particular use made of the plutonium and on the structure of the energy system. The reference LWR power system has no use, hence no value, (meanwhile) for the plutonium it produces. The alternative power systems we consider consume all the plutonium they produce. Consequently, we shall assign the plutonium no direct cost value in any of the energy systems considered (including the no plutonium recycling case).

To summarize then, the fuel cycle cost component of LWR's with plutonium recycling, C^{rec} , is

$$C^{\text{rec}} = 0.8C_{\text{ore}} + 0.8C_{\text{enr}} + 1.4C_{\text{fab}} + C_{\text{rep}} + C_{\text{str}} \quad (5)$$

where the partial components assume their value without plutonium recycling.

2.3 FUEL SELF-SUFFICIENT LIGHT WATER HYBRID REACTORS

The total cost of electrical power generated by the hybrid reactors will be estimated using a cost breakdown similar to the one we used for fission-only reactors (Sections 2.1 and 2.2). The strategy we shall adopt for assessing the economic potential of the hybrids is to relate their cost components to the corresponding components of fission reactors. The LWHR considered use fuel and fuel cycle technologies which are very similar to those of LWR's. Therefore it is possible to relate the fuel cycle cost components of LWHR's and LWR's with relative ease and confidence. The contribution of O&M to the power cost is relatively small and does not depend strongly on the reactor type. Consequently we shall look for the indifference value of the LWHR capital cost, that is, for the capital cost allowed for the LWHR if the cost of the electrical power generated (for sale) is to equal the cost of LWR generated electricity. Could LWHR's be constructed with a capital investment smaller than the indifference value, they would be expected to be more economical than LWR's and vice versa.

The economic analysis will be performed parametrically, the primary independent variable being the cost of uranium ore. With present uranium costs, no advanced breeder reactor has much chance of competing, economically, with LWR's. It is the concern about the depletion of uranium reserves and the accompanying increase in the price of uranium ore that actually provides the motivation for the development of fission breeders. This uranium price increase can be substantial; certain analyses (see, e.g. Ref. 7) predict that towards the end of this century it will reach approximately \$150/lb U_3O_8 . It is not much before the end of the century that the LWHR could make a substantial contribution to the energy economy.

In the following, a superscript f or h will denote, respectively, fission-only reactors or hybrids. The capital cost component of the hybrid will be related to that of fission-only reactors as

$$K^h = R \eta_R D_R K^f \quad (6)$$

where

$$\eta_R \equiv \eta_n^f / \eta_n^h \quad (7)$$

is the ratio of the net efficiencies of the fission and hybrid reactors, D_R is the ratio of the duty factor of the fission reactor to that of the hybrid and

$$R \equiv \frac{(I^h / P_{th}^h)}{(I^f / P_{th}^f)} \quad (8)$$

is the ratio of the capital investment per unit thermal energy produced in the hybrid reactor to that of the fission-only reactor.

Consider next, the fuel cycle cost. The LWHR does not have enrichment requirements so that

$$C^h = C_{ore}^h + C_{fab}^h + C_{rep}^h + C_{str}^h . \quad (9)$$

The FSS-LWHR is assumed to operate in the fuel recycling mode.¹ After reaching the prescribed burnup level the fuel is removed from the reactor, partially reprocessed to extract the fission products (but not the plutonium), refabricated and refueled. Assuming that the irradiation cycle in the FSS-LWHR reaches a similar burnup level (about 3%) as of LWR's, and that 2% of the fuel gets lost per irradiation cycle, we find that in the LWHR one can extract about 60 times more energy out of a given amount of uranium ore as compared with the LWR. Consequently, we get

$$C_{ore}^h \approx \frac{\eta_R}{60} C_{ore}^f . \quad (10)$$

To relate the fuel fabrication costs, we assume that they are proportional to the total length of fuel rods fabricated, and inversely proportional to the total amount of energy they generate per cycle, getting,

$$C_{fab}^h = \epsilon_f \eta_R \left(\frac{A^f}{A^h} \right) \left(\frac{BU^f}{BU^h} \right) C_{fab}^f \quad (11)$$

where A is the fuel rod cross section area and BU is the average fuel burnup level (per irradiation cycle). The coefficient ϵ_f is to account for the extra expenses associated with the fabri-

cation of plutonium bearing fuel. We shall assume that $\epsilon_f = 1.4$. The fuel reprocessing cost is taken to be proportional to the mass of fuel reprocessed per given amount of electricity generated giving

$$C_{rep}^h = \epsilon_p \eta_R \left(\frac{BU^f}{BU^h} \right) C_{rep}^f \quad (12)$$

where $(1-\epsilon_p)$ is that fraction of the reprocessing cost that is saved when the plutonium does not have to be separated from the uranium, or handled separately. An arbitrary estimate we'll use is $\epsilon_p = 0.8$.

The cost associated with the storage of irradiated fuel and waste products will be assumed to be the same, per given amount of fuel produced, giving

$$C_{str}^h = \eta_R C_{str}^f \quad (13)$$

The operation and maintenance costs are expressed as

$$O^h = \eta_R D_R \epsilon_O O^f \quad (14)$$

where $\epsilon_O \geq 1$ takes into account some extra expenses associated with the fusion system operation and maintenance, including its fuel cycle (mostly tritium management). We shall assume that $\epsilon_O = 1.5$.

2.4 FISSILE-FUEL-PRODUCING LIGHT WATER HYBRID REACTORS

These hybrid reactors are to produce excess fissile fuel in addition to power. This fissile fuel is to support such a

capacity of LWR's that in the combined LWHR-LWR system there will be no need for uranium enrichment. The plutonium produced in the LWR's is recycled in them.

We shall first find the equivalent energy of the fissile fuel produced in the hybrids when this fuel is to be used in LWR's. We shall relate this energy equivalent to the fissile fuel produced, on the average, per square meter of the first wall of the fusion device.

The rate of fissile atoms produced per effective square meter of the fusion device first wall is

$$F \epsilon_w W / (14.1 \times 1.603 \times 10^{-19})$$

where F is the average net number of fissile atoms gained in the hybrid per one fusion neutron reaching the first wall; ϵ_w is the fraction of the first wall that is covered with the breeding blanket; and W is the average neutron first wall loading (in units of MW/m^2).

The total thermal energy that can be generated in the LWR's per fissile atom supplied is, approximately,

$$200 \times 1.603 \times 10^{-19} \epsilon / [(1+\alpha)(1-\text{CR})]$$

where ϵ is the fast fission factor, α is the effective capture to fission ratio of plutonium and CR is the effective conversion ratio (taking into account losses during reprocessing and fabrication). The equivalent electrical power output that can be generated in the LWR's per effective square meter of this hybrid

first wall is therefore

$$P_n^f = \frac{200}{14.1} \eta_{th}^f F \epsilon_w W \frac{\epsilon}{(1+\alpha)(1-CR)} \quad (15)$$

where η_{th}^f is the net thermal efficiency of the LWR's. Notice that P_n^f is the time averaged power, assuming the duty factors of the LWHR and the LWR are the same.

The gross electrical power output of the hybrid reactor per effective square meter of the first wall is, on the other hand,

$$P_g^h = \eta_{th}^h \epsilon_w W \left[M + \frac{17.6}{14.1} \left(1 + \frac{1}{Q} \right) \right]. \quad (16)$$

Here we have assumed the fusion plasma of the hybrid reactor to be driven by the injection of energetic beams of neutral atoms. In Eq. (16) M is the blanket energy multiplication and Q is the ratio of the fusion energy released to the neutral beam energy deposited in the plasma. Here we assume the energy invested in the beam injection system that did not reach the plasma is not recovered. The thermodynamic efficiency takes into account the energy requirement of the auxiliary systems, excluding the neutral beam injection system. The power requirement for the latter system is

$$P_b = \frac{17.6}{14.1} \eta_{th}^h W / (\eta_i Q) \quad (17)$$

where η_i is the beam injection efficiency. The net electrical power output of the hybrid reactor per effective square meter of the first wall is therefore,

$$P_n^h = \eta_{th}^h \epsilon_w W \left\{ M + \frac{17.6}{14.1} \left[1 + \frac{1}{Q} \left(1 - \frac{1}{\epsilon_w \eta_{th}^h \eta_i} \right) \right] \right\} \quad (18)$$

and its net thermodynamic efficiency is,

$$\eta_n^h \equiv P_n^h / P_g^h . \quad (19)$$

Consider now the total cost of electricity generated in the combined power system of FFP-LWHR's plus LWR's relative to the reference LWR cost. The capital cost component in the combined system is the net electrical energy average of K^f and K^h of Eq. (6),

$$K = K^f (R \eta_R^{hf} D_R P_n^h + P_n^f) / (P_n^h + P_n^f) \quad (20)$$

where η_R^{hf} is defined as η_R but is related to the FFP-LWHR.

Consider next the fuel cycle cost of the LWR's in the combined system,

$$C^{fh} = C_{ore}^{fh} + C_{fab}^{fh} + C_{rep}^{fh} + C_{str}^{fh} . \quad (21)$$

Following the rationale used to derive Eq. (10) we find

$$C_{ore}^{fh} \approx \frac{1}{60} C_{ore}^f \quad , \quad (22)$$

$$C_{fab}^{fh} = C_{fab}^f \epsilon_f \quad , \quad (23)$$

$$C_{rep}^{fh} = C_{rep}^f \quad (24)$$

and

$$C_{str}^{fh} = C_{str}^f \quad . \quad (25)$$

We turn now to the fuel cycle cost of the FFP-LWHR's. It is broken down into the same components as in Eq. (9). For the present economic analysis we shall refer to a FFP-LWHR with a blanket consisting of a converter zone of the Livermore type⁴ that breeds the fissile fuel, followed by a thermal fission blanket that provides additional energy multiplication as well as tritium breeding. Both the power multiplying and converter zones use similar fuel and fuel technology, and we shall assume that both fuels are replaced at the same average burnup level. The converter fuel undergoes a complete reprocessing operation - the plutonium is extracted from it for feeding the LWR's. Assuming that the converter fuel constitutes the fraction f_c of the total blanket fuel weight, and that the fuel utilization

(average burnup) and dimensions are similar to their values for the FSS-LWHR, we get

$$C_{ore}^{hf} = \frac{\eta_R^{hf}}{60} C_{ore}^f \quad (26)$$

$$C_{fab}^{hf} = \eta_R^{hf} \left(\frac{A^f}{A^h} \right) \left(\frac{BU^f}{BU^h} \right) \left[f_c + \epsilon_f (1-f_c) \right] C_{fab}^f \quad (27)$$

$$C_{rep}^{hf} = \eta_R^{hf} \left(\frac{BU^f}{BU^h} \right) \left[f_c + \epsilon_p (1-f_c) \right] C_{rep}^f \quad (28)$$

and

$$C_{str}^{hf} = \eta_R^{hf} C_{str}^f \quad (29)$$

Combining the fuel cycle costs of the hybrid and fission reactors, appropriately weighed by the energy output of each system, we find,

$$C_{ore} = \frac{C_{ore}^f}{60} \left[\eta_R^{hf} P_n^h + P_n^f \right] / \left[P_n^h + P_n^f \right] \quad (30)$$

$$C_{fab} = C_{fab}^f \left\{ \eta_R^{hf} \left(\frac{A^f}{A^h} \right) \left(\frac{BU^f}{BU^h} \right) \left[f_c + \epsilon_f (1-f_c) \right] P_n^h + P_n^f \right\} / \left[P_n^h + P_n^f \right] \quad (31)$$

$$C_{rep} = C_{rep}^f \left\{ \eta_R^{hf} \left(\frac{BU^f}{BU^h} \right) \left[f_c + \epsilon_p (1-f_c) \right] P_n^h + P_n^f \right\} / \left[P_n^h + P_n^f \right] \quad (32)$$

and

$$C_{str} = C_{str}^f \left[\eta_R^{hf} P_n^h + P_n^f \right] / \left[P_n^h + P_n^f \right] . \quad (33)$$

The average operation and maintenance cost, including tritium management is

$$U = U^f \left[\eta_R^{hf} U_R \epsilon_o P_n^h + P_n^f \right] / \left[P_n^h + P_n^f \right] . \quad (34)$$

3. FSS-LWHR versus LWR

To assess the economic potential of the FSS-LWHR we shall calculate the indifference value of R (to be denoted as R_o) as a function of the uranium ore cost as well as of several hybrid reactor parameters (mainly the blanket energy multiplication). If one could build a FSS-LWHR with a capital investment which is smaller, per unit thermal power output, than R_o times the capital investment in a LWR (see the definition of R in Eq. (8)) then the economics of the FSS-LWHR is better than that of the LWR.

The indifference value of R is obtained by equating the total cost of electricity generated in the hybrids, T^h , to that generated in LWR, T^f . Using the expressions developed in Sec. 2.3 we get

$$R_O \eta_R D_R K^f + \eta_R \left[\frac{s}{60} C_{ore}^f + a b \epsilon_f C_{fab}^f + \epsilon_p b C_{rep}^f + C_{str}^f \right] + \eta_R D_R \epsilon_O O^f \quad (35)$$

$$= K^f + s C_{ore}^f + C_{enr}^f + C_{fab}^f + C_{rep}^f + C_{str}^f + O^f$$

where s is the ratio of the uranium ore cost to the reference value (assumed to be \$20/lb U_3O_8),

$$a \equiv A^f/A^h \quad (36)$$

and

$$b = BU^f/BU^h \quad (37)$$

Using the relative cost components defined in Section 2.1, Eq. (35) becomes,

$$R_O = \left[\frac{1.2875}{\eta_R D_R} - \frac{1/32}{D_R} - \frac{\epsilon_O}{10} \right] + \frac{s}{16 D_R} \left[\frac{1}{\eta_R} - \frac{1}{60} \right] - \frac{b}{16 D_R} \left[\epsilon_f^a + \epsilon_p / 2 \right] \quad (38)$$

Notice that in the above we took the increase in the ore cost to affect only the C_{ore} component of the power cost. This is a conservative assumption, as the increase in the power cost resulting from the higher uranium price will cause, in reality, increases in other cost components such as in C_{enr} .

Assuming, for the numerical analysis, that

$$\epsilon_o = 1.5$$

$$\epsilon_f = 1.4$$

$$\epsilon_p = 0.8$$

$$D_R = 1.0$$

and $a = (0.5/0.75)^2 = 1/2.25$ (See ref. 1),

Eq. (38) becomes

$$R_o = \frac{1.2875}{\eta_R} - 0.18125 + \frac{s}{16} \left[\frac{1}{\eta_R} - \frac{1}{60} \right] - 0.0639b \quad (39)$$

Figure 1 shows the indifference value for the FSS-LWHR capital cost as a function of the relative uranium ore cost for several values of η_R and $b = 1$. To get some indication on the relation between the values of η_R and the blanket energy multiplication consider, for example, the CIT fusion device recently proposed by Jassby⁸ to drive hybrid reactors. This device is characterized by $Q = 1.5$ and $\eta_i = 0.7$. Assuming that the blanket coverage around this device is $\epsilon_w = 0.75$, we find that $\eta_R = 1.2$ corresponds to a blanket multiplication of $M = 26$, whereas the curve $\eta_R = 1.1$ corresponds to $M = 49$. The actual energy multiplication of the FSS-LWHR blanket is expected¹⁵ to be as high as $M = 26$. It is seen (Fig. 1) that at the present cost of uranium ore ($s = 1$), the capital investment in the FSS-LWHR driven by a $Q \lesssim 1.5$ fusion device will have to be smaller (by several percent) as compared with the capital investment in the LWR.

The $R_O < 1$ situation results because of the relatively large power consumption of the fusion device. There are three ways to reduce the fraction of the hybrid generated power internally circulating: increasing Q , M or ϵ_w . For example, increasing Q , in the $M = 26$ case considered above, from 1.5 to 3 has the effect of reducing η_R from 1.2 to 1.1. The best one can do is getting $\eta_R \rightarrow 1$ (assuming the thermal efficiencies of the hybrid and LWR are the same).

The upper limit of R_O (corresponding to $\eta_R = 1$) is shown in Fig. 1. At the present cost of uranium ore, the FSS-LWHR's are allowed to be 10% more expensive to build than the LWR's (both having the same thermal power output). This allowance increases to 50%, when uranium become 7.5 times more expensive, namely, reaching their end-of-the-century projected value of about \$150/lb U_3O_8 . For comparison, the capital investment in fast fission breeder reactors under development is assumed⁵ to be higher than of LWR's (having the same net electric power output) by about 20%.

Another factor that can affect the economics of the FSS-LWHR is the burnup level their fuel can reach. Shown in Fig. 1 is the effect, on R_O , of increasing this burnup level to 10/3 times the LWR level (for the $\eta_R = 1.1$ case). The high burnup ($b = 0.3$), approximately 100,000 MWD/T, corresponds to the burnup level called for the fast breeder reactors.

4. FFP-LWHR PLUS LWR versus FSS-LWHR and LWR

Following a procedure similar to the one used in the previous section, we shall find the indifference value of the capital investment in FFP-LWHR's that operate in a balanced power system of these hybrids and LWR's. Two sets of values for R_0 will be calculated corresponding to two different reference systems of LWR's; one system is with and the other without plutonium recycling. The plutonium recycling LWR system is the fair reference against which the economics of the FFP-LWHR is to be compared. The no-recycling is used so as to get a common denominator for comparing the economics of the FFP-LWHR with the economics of the FSS-LWHR. Notice that the LWR's in the combined LWHR-LWR system always use plutonium recycling.

Starting with the no-plutonium recycling LWR reference we get, using the expressions developed in Sec. 2.4 for the various cost components,

$$\begin{aligned}
 & \left[(R_0 \eta_R D_R P_n^h + P_n^f) / P_n^t \right] K^f + s \frac{C_{\text{ore}}^f}{60} (\eta_R P_n^h + P_n^f) / P_n^t \\
 & + C_{\text{fab}}^f (\eta_R a b \alpha_f P_n^h + \epsilon_f P_n^f) / P_n^t \\
 & + C_{\text{rep}} (\eta_R b \alpha_r P_n^h + P_n^f) / P_n^t \\
 & + C_{\text{str}}^f (\eta_R P_n^h + P_n^f) / P_n^t + O^f (\eta_R D_R \epsilon_O P_n^h + P_n^f) / P_n^t \\
 & = K^f + s C_{\text{ore}}^f + C_{\text{enr}}^f + C_{\text{fab}}^f + C_{\text{rep}}^f + C_{\text{str}}^f + O^f
 \end{aligned} \tag{40}$$

where

$$P_n^t \equiv P_n^h + P_n^f, \quad (41)$$

$$\alpha_f \equiv f_c + \epsilon_f(1-f_c), \quad (42)$$

$$\alpha_r \equiv f_c + \epsilon_p(1-f_c), \quad (43)$$

and η_R stands for η_R^{hf} ; we shall assume them to be the same.

Using the relative cost components and rearranging, we get

$$\begin{aligned} R_O = & \frac{1}{\eta_R D_R} \left[1 + \frac{3}{16} \frac{P_n^t}{P_n^h} - \frac{1}{16} \left(\epsilon_f + \frac{1}{2} + \frac{1}{2} \right) \frac{P_n^f}{P_n^h} - \frac{1}{32} \eta_R - \frac{1}{10} (\eta_R D_R \epsilon_O - 1) \right] \\ & + \frac{s}{16 \eta_R D_R} \left[\frac{P_n^t}{P_n^h} - \frac{1}{60} \left(\eta_R + P_n^f / P_n^h \right) \right] - \frac{b}{16 D_R} \left(a \alpha_f + \alpha_r / 2 \right). \quad (44) \end{aligned}$$

Assuming, for the numerical analysis, that

$$\epsilon_O = 1.5$$

$$\epsilon_f = 1.4$$

$$\epsilon_p = 0.8$$

$$D_R = 1.0$$

$$a = 1/2.25$$

$$f_c = 1/3$$

$$CR = 0.5$$

we get

$$\alpha_f = 1.267$$

$$\alpha_r = 0.867$$

so that Eq. (44) becomes

$$R_O = \left[\frac{1.2875}{\eta_R} - 0.1813 + \frac{0.0375}{\eta_R} \frac{P_n^f}{P_n^h} \right] + \frac{s}{16\eta_R} \left[\left(1 - \frac{\eta_R}{60} \right) + \frac{59}{60} \frac{P_n^f}{P_n^h} \right] - 0.0623 b \quad (45)$$

In the special case of no fissile fuel production in the hybrid reactor ($F = 0$), Eq. (45) reduces to Eq. (39) except for a small difference in the coefficient of the b term; this is due to the different assumptions we made on the fabrication and reprocessing of the fuel in the two versions of the LWHR blanket.

For a given fusion device and ore cost, Eq. (45) is, essentially, a function of the blanket performance characteristics M , F and b . To express η_R and P_n^f/P_n^h in terms of M and F , we can use Eqs. (7), and (15-19) which can be rearranged as follows:

$$\frac{P_n^f}{P_n^h} = \frac{mF}{M+n} \quad (46)$$

and

$$\eta_R = (M+p)/(M+n) \quad (47)$$

where

$$m \equiv \frac{200}{14.1} \frac{\eta_{th}^f}{\eta_{th}^h} \frac{\epsilon}{[(1+\alpha)(1-CR)]} \quad (48)$$

$$n \equiv \frac{17.6}{14.1} \left[1 + \frac{1}{Q} \left(1 - \frac{1}{\epsilon_w \eta_{th}^h \eta_i} \right) \right] \quad (49)$$

and

$$p \equiv \frac{17.6}{14.1} \left(1 + \frac{1}{Q} \right) . \quad (50)$$

In the present work we consider the specific blanket concept consisting of a Livermore⁴ type converter zone for fissile fuel production, followed by the FSS-LWHR type blanket for extra energy multiplication and for tritium breeding. The F value for this composite blanket was predicted⁴ to be 1.8 . We shall assume a conservative value of $F = 1.6$. The M value of this blanket is expected to be above 26 .

Figure 2 shows the indifference value of R for the FFP-LWHR as a function of the relative cost of uranium ore for two values of blanket energy multiplication (the same values used in Sec. 3) and for two values of F . The difference in the value of R_0 calculated for the two values of F using a given M indicates the contribution of the fissile fuel production to the economics of the hybrid reactor. Following are several observations:

1. For a given value of s and M , the R_0 value for a FFP-LWHR is higher than R_0 for a FSS-LWHR.

2. The value of R_O increases with increasing ore cost. For a given value of M , the increase in R_O with s is stronger for a FFP-LWHR than for a FSS-LWHR.

3. The value of R_O increases with M for a FSS-LWHR. For a FFP-LWHR, on the other hand, R_O decreases with M . In the limit of $M \rightarrow \infty$, R_O for the FSS and FFP-LWHR approach the same value.

We shall now explain these observations one by one:

1. The fuel cycle cost of a LWHR is cheaper than that of a conventional LWR. When the saving in the fuel cycle cost of FSS-LWHR overcompensates for the extra expenses involved in the operation of the hybrid reactor (including higher O&M costs and lower overall energy conversion efficiency, $\eta_R > 1$), we obtain $R_O > 1$.

The FFP-LWHR has an additional source of saving -- the fuel cycle cost of that capacity of LWR's that is supported by the excess plutonium produced in the FFP-LWHR. This saving in the LWR fuel cycle can be invested in the hybrid reactor. For a given value of M , the total power output of the hybrid reactor is independent of F . Therefore, the allowable investment per unit energy produced in the FFP-LWHR is larger than the investment in FSS-LWHR, i.e., $R_O(\text{FFP-LWHR}) > R_O(\text{FSS-LWHR})$.

2. As the cost of ore increases, the saving in the fuel cycle costs also increases for both the hybrids, and the LWR's driven by the hybrid produced plutonium.

3. As M increases for a given value of F ($\neq 0$), the total power output of the LWHR increases (almost linearly), but the total saving in the fuel cycle cost of the supported LWR's stays constant. Consequently, the value of R_0 decreases for a FFP-LWHR with increasing M .

Figure 3 shows the total investment allowed in a 1000 MW_e FFP-LWHR having $F = 1.6$, as a function of its blanket energy multiplication (referring to the fusion device parameters considered earlier, and assuming $\$750/\text{KW}_e$ of the reference LWR's). The horizontal dashed line corresponds to the total investment in the reference 1000 MW_e LWR. It is observed that the lower M , the larger is the allowed capital investment in the LWHR. Why is that so? Remember that the smaller M , the larger is the total quantity of fissile fuel produced per 1000 MW_e hybrid reactor (F fixed). Consequently, the accumulated saving in the fuel cycle of the LWRs that are supported by the FFP-LWHR's **increases** as M decreases, bringing about an increase in I^h .

Does the last observation imply that it pays economically, to design a low M blanket? Absolutely not! As the blanket energy multiplication becomes smaller, the size and/or neutron output of the fusion device must increase to provide the same total electrical power output. This increase in the intensity of the fusion device grows with M stronger than $1/M$, because the net efficiency of the hybrid reactor goes down when M becomes smaller ($\eta_R > 1$). Consider first the $s = 1$ curve of Fig. 3.

Reducing M from 50 to 25, for example, leaves I^h almost unchanged. This implies that one is allowed to spend the same amount of money for constructing a more than twice as powerful a fusion device (corresponding to $M = 25$) as available for constructing the $M = 50$ fusion device.

What happens in the low M and high s regimes? A pertinent indicator for the dependence of the hybrid economics on M is the capital investment allowed for the fusion device per given neutron output. We can get the value of the indicator, to be denoted by I^s , by subtracting from I^h the capital investment required in the thermal-to-electrical energy conversion system and dividing the result by the relative strength of the fusion neutron source. For the first correction factor we shall take $\$375/KW_e$ times the gross electrical power output (proportional to η_R). The second correction factor is $(M + n)/(M_0 + n)$, with M_0 assumed to be 26.

Figure 4 shows the resulting allowed investment in the fusion device normalized to the total neutron output of the reference device (corresponding to $M_0 = 26$). It is seen that I^s increases significantly with M ; the slope of this close to linear increase is larger than 2! We thus conclude that it pays, economically, to extract from a LWHR as much power as possible, for a given rate of fissile fuel production.

So far we have compared the LWHR's against LWR's that use no plutonium recycling. Plutonium recycling was assumed, however, for the LWR's that are part of the combined FFP-LWHR plus LWR

power system. The fair reference to compare the economic potential of such a combined system against is that of LWR's that use plutonium recycling. The indifference value of R for such a scenario is the solution of an equation like Eq. (40) with its right hand side replaced by

$$K^f + 0.8sC_{\text{ore}}^f + 0.8C_{\text{enr}}^f + \epsilon_f C_{\text{fab}}^f + C_{\text{rep}}^f + C_{\text{str}}^f + O^f.$$

Following the procedure used to derive Eq. (45) we find

$$\begin{aligned} R_O = & \left[\frac{1.30}{\eta_R} - 0.1813 + \frac{0.0375}{\eta_R} \frac{P_n^f}{P_n^h} \right] \\ & + \frac{s}{16\eta_R} \left[\left(0.8 - \frac{\eta_R}{60} \right) + 0.783 \frac{P_n^f}{P_n^h} \right] - 0.0623b. \end{aligned} \quad (51)$$

Figure 5 compares the value of R_O for a FFP-LWHR using a plutonium recycling LWR reference system with both R_O for a FFP-LWHR using a reference LWR system without plutonium recycling and R_O for FSS-LWHR's. It is observed that the economic potential of FFP-LWHR is slightly reduced when the plutonium recycling mode of operation is assumed for the reference LWR system. This economic potential is still significantly higher, however, than that of FSS-LWHR's.

5. ECONOMIC OUTLOOK FOR LWHR'S

In order to get a preliminary assessment of the possibility that LWHR's will compete economically with LWR's, we shall evaluate the value of I^h/I^f for two tokamak hybrid designs and compare it with the indifference value R_0 . Consider first, the recent CIT hybrid reactor proposed by Jassby and Lee⁸ (J&L). This hybrid reactor has a gross electrical power output of 740 MW_e and its capital cost is estimated⁸ to be 1430 million dollars.

By replacing the Livermore blanket of the J&L design with the FFP-LWHR blanket considered in Sec. 4, we expect to get a power reactor having a gross power output of 5090 MW_{th} or 1630 MW_e (corresponding to M of 36 and 75% first wall coverage). To remove the extra power generated in the new blanket and convert it to electricity, we shall need additional investment in the heat removal and power conversion capacity. We shall estimate this investment to be \$375/kW_e, half the capital investment in LWR's. This leads us to an estimate of 1763 million dollars for the FFP-LWHR, which gives $I^h = \$346.5/\text{kW}_{th}$. The corresponding value for the LWR is $I^f = \$240/\text{kW}_{th}$ ($=750 \times 0.32$) giving us a I^h/I^f of 1.44. Interpolating the results in Fig. 2 we find that R_0 will reach the value of 1.44 (for M = 36) when the cost of uranium ore will be 4.6 times its present value.

The second hybrid reactor we consider uses the fusion device designed by the Reactor Studies Division (RSD) of the PPPL for a molten-salt based blanket. One of the designs found to be

close to the optimal⁹ has a gross electric power output of 4000 MW_e and a capital investment of 2.85 billion dollars. The fusion device driving this hybrid has a Q value of 2.3 and requires a beam power of 252 MW which is injected with 59% efficiency. The molten-salt blanket has M of 22.3 and F of 0.6 .

Suppose that we replace the molten-salt by a FFP-LWHR blanket that has a 75% wall coverage ($\epsilon_w = 0.75$) and a thermal-to-electrical conversion efficiency of 0.32. We adjust the blanket energy multiplication to obtain the same gross electric power output of 4000 MW_e getting $M \approx 30$. For a first approximation we shall assume that the capital investment in the resulting FFP-LWHR is the same as in the original molten-salt hybrid. This required investment will now be compared with the "allowed" one.

Using the operating characteristics of the R&D fusion device and of the FFP-LWHR blanket proposed for it ($M = 30$, $F = 1.6$) we find that the indifference value of the resulting RSD-FFP-LWHR is $R_o = 0.992 + 0.121s - 0.062b$. For the conventional LWR burnup level ($b = 1$) and present uranium ore costs ($s = 1$) we find that the allowed investment is 2.93 billion dollars. This is already slightly higher than the estimated required investment! The allowed investment will increase to 3.3, 4.3 or 5.1 billion dollars if the uranium ore cost will rise to, respectively, 2, 5 or 7.5 times its present value.

We also find that the allowed capital investment in a FSS-LWHR based on the RSD fusion device considered will break even with the estimated required investment when the uranium ore cost will

be about 2.5 times its present value.

Based on the two examples considered we conclude that the FFP-LWHR has the potential of competing economically with LWR's.

6. DISCUSSION

The analysis of Sec. 4 clearly indicates that it pays economically, to breed* fissile fuel in addition to power generation. In other words, a FFP-LWHR looks more attractive economically, than a FSS-LWHR, both having the same blanket multiplication. This will be the case as long as the energy system will consist of light-water reactors and/or as long as the capital investment in LWR's will be lower than in LWHR.

By providing the fissile fuel (plutonium in our case) to drive the LWR's, one saves on their fuel cycle cost (as compared with the fuel cycle cost of uranium enriched LWR system, with or without plutonium recycling). This saving in the fuel cycle cost of the LWR's can be invested in the construction of the LWHR's. Stating it differently, the total revenue from a LWHR of a given M increases with F .

A similar argument goes the other way around; it will be economical to extract as much power as possible from a blanket of a given fissile-fuel production capability (a constant F). The reason is that the capital investment required to upgrade the power output of a given hybrid reactor is only about half of that required for an equivalent upgrading, of the capacity of a LWR.

* In the following we shall use the term "breed" to imply that the breeding gain > 0 .

One should not preclude the possibility, nevertheless, that under certain circumstances FSS-LWHR will become more economical than the FFP-LWHR system (that includes fission-only reactors). This might happen, for example, if there will be a high economic penalty associated with plutonium recycling (involving plutonium separation and handling at high concentrations) and with criticality accident hazards. The advantages of FSS-LWHR from the public acceptability point of view include¹ better safeguard control system, no possibility of criticality accidents, and reduced probability for plutonium toxicity accidents. The possibility that a FSS-LWHR will be cheaper to build than a LWR should also not be precluded.

In most of the blanket concepts it is not possible to control F and M independently, as we did in the analysis above. Usually, as one wants to increase F , M goes down, and vice versa. In certain blankets a variation in the control variables leads to a linear relationship between F and M of the form

$$F = a - bM \quad (52)$$

where a and b are positive coefficients. For the RSD molten-salt blanket, for example, $a = 1.242$ and $b = 0.038$.¹⁰

The hybrid reactor community is disputing the question of what approach to hybrids is more economical - power generation or fuel production. The low M high F (i.e., fuel production) proponents include Lidsky,³ the Livermore groups of the mirror driven hybrids^{4,11} and of the laser driven hybrids,¹² and Bussard.¹³ An analysis performed recently by Chapin and Mills¹⁴ concludes that a high M low F blanket is the more promising direction.

The simple economical model developed in previous sections can be used to check the question of the more economical approach to the design of LWHR's. Thus, suppose we have a given fusion device of a certain size and operating characteristics. The total investment allowed in this fusion device depends on the M and F values of the values of the blanket it drives. The indifference value of the capital investment, I^h , in the FFP-LWHR for a given F and M value is (See Sec. 4),

$$I^h = 750 \eta_{th}^h R_o P_{th}^h (\$) \quad (53)$$

where P_{th}^h is expressed in kilowatts. Subtracting from the I^h the investment required for the heat removal and power generation systems, we get the allowed investment in the fusion device, I^s , (including the natural uranium light-water blanket, the cost of which will be assumed independent of M and F). Taking, as before, \$375 per kW_e of gross power we get,

$$I^s = I^h - 375 \eta_{th}^h P_{th}^h = 375 \eta_{th}^h P_{th}^h (2R_o - 1) \quad (54)$$

We shall now express I^s in terms of F and M . From Eqs. (16) and (50) we have

$$P_{th} = \epsilon_w P_n (M + p) \quad (55)$$

where P_n is the total fusion neutron power (in kW).

Equation (45) can be rearranged as follows

$$R_o = \frac{1}{\eta_R} \left(\alpha - \beta \eta_R + \gamma \frac{p_n^f}{p_n^h} \right) \quad (56)$$

where

$$\alpha \equiv 1.2875 + s/16 \quad (57)$$

$$\beta \equiv 0.1813 + s/960 + 0.0623b \quad (58)$$

$$\gamma \equiv 0.0375 + 95s/60 \quad (59)$$

Both η_R and p_n^f/p_n^h are functions of M via Eqs. (46) and (47). The latter depends also on F . Expressing F in terms of M via the relation of Eq. (52), we get a functional relationship between I^S and M . Equating the derivative dI^S/dM to zero, we find the following expression for b :

$$b_o = \frac{[2(\alpha - \beta) - 1]}{2\gamma m} \quad (60)$$

This value of b_o represents the rate of change of F with M that leaves the total investment allowed for the fusion device under consideration unchanged (as compared with I^S for the reference M-F pair). Blankets for which $dF/dM < b_o$ will give a more economical LWHR if designed to have the highest possible value of F . Conversely, blankets for which $dF/dM > b_o$ are economical to design with the highest possible M . The observation that certain hybrids are more promising as power reactors whereas, other hybrids are more promising as fuel producers was recently arrived at by Tenney¹⁰ based on Deonigi's results for economic regimes of fission-fusion energy systems.⁵ As numerical examples consider the FFP-LWHR dealt with in Sec. 4 along with the two

blankets dealt with in Sec. 5. The indifference value of b (i.e., b_0) we calculate for the FFP-LWHR is 0.2824 and 0.0927 for relative ore costs of, respectively, 1.0 and 7.5. It is observed that as the cost of uranium increases, the blanket should have a larger increase in energy multiplication in order to make up for a given reduction in the fuel production rate. The RSD molten salt blanket has a b value¹⁰ of 0.038. Had the LWHR the same value of b , it would have been more economical to design it as a power generating blanket (the highest M possible). The F vs. M dependence of the Livermore blanket has¹⁰ b of 0.02 (the control variable is the plutonium content in the fuel). Here again we conclude that had the LWHR the same F vs. M dependence, it would have been more economical to design it as a high M low F blanket.

7. CONCLUSIONS

1. Fissile fuel-producing light-water hybrid reactors (using the specific FFP blanket type considered in this work) are more economical than fuel-self-sufficient (breeding gain = 0) light-water hybrid reactors.
2. FFP-LWHR's may compete economically with LWR's even with the present cost of uranium ore. The economic advantage of FFP-LWHR's increases as the ore cost increases.
3. FSS-LWHR's may become more economical than present LWR's when the ore costs will approach their end-of-the-century forecasted value.

4. For a given fuel production capability it pays, economically, to design the blanket to have as high a value of energy multiplication as possible. A vice-versa, for a given M it pays to have as high a value of F as possible.
5. It is possible to design a FFP-LWHR blanket that has the fuel production capability of the Livermore fast blanket⁴ and more than twice its energy multiplication. Such a blanket is estimated to be significantly more economical than either the original Livermore low M blanket⁴ or the low F FSS-LWHR blanket.¹
6. Whether it is preferable, economically, to construct a power generating hybrid reactor or a fuel producing one, depends on the characteristics of the specific fusion device and blanket under consideration. The two tokamak designs and two blanket concepts we have examined (Sec. 6) favor power generation over fuel production.

Even though derived for LWHR's and based on a simple economic model, we expect that many of the above conclusions will be valid for other types of hybrid reactors as well.

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¹⁶Note added in proof: This M value might be too high.

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Fig. 1. Indifference Value (R_0) of the Relative Capital Investment for the FSS-LWHR as a function of the Relative Uranium Ore Costs.

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Fig. 2. Indifference Value (R_0) of the Relative Capital Investment in FFP-LWHR ($F = 1.6$) and in FFS-LWHR ($F = 0$) as a Function of the Relative Uranium Ore Costs.

Fig. 3. The Effect of the Blanket Energy Multiplication (M) and Relative Uranium Ore Costs (s) on the Indifferent Investment (I^h) in a 1000 MW_e FFP-LWHR ($F = 1.6$).

Fig. 4. The Allowed Investment, I^S , in Fusion Devices that Drive a $F = 1.6$ FFP-LWHR (normalized to the same fusion neutron output) as a Function of the Blanket Energy Multiplication (M) and Relative Uranium Ore Costs (s).

Fig. 5. The Effect of Plutonium Recycling in LWR on the Indifference Value of LWHR.

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