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D. J. Bender

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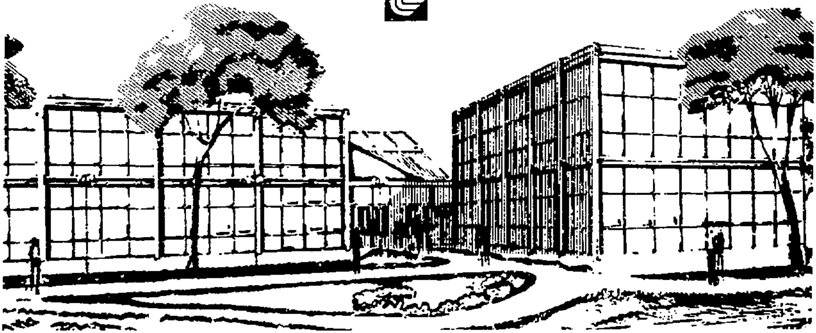

MASTER

# MIRROR HYBRID REACTOR OPTIMIZATION STUDIES*

D. J. Bender
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

## ABSTRACT

A system model of the mirror hybrid reactor has been developed. The major components of the model include (1) the reactor description, (2) a capital cost analysis, (3) various fuel management schemes, and (4) an economic analysis that includes the hybrid plus its associated fission burner reactors. The results presented describe the optimization of the mirror hybrid reactor, the objective being to minimize the cost of electricity from the hybrid fission-burner reactor complex. We have examined hybrid reactors with two types of blankets, one containing natural uranium, the other thorium. The major difference between the two optimized reactors is that the uranium hybrid is a significant net electrical power producer, whereas the thorium hybrid just about breaks even on electrical power. Our projected costs for fissile fuel production are $\sim 50$ \$/g for $^{239}$Pu and $\sim 125$ \$/g for $^{233}$U.

## INTRODUCTION

The primary objectives of the first Lawrence Livermore Laboratory (LLL) fusion-fission hybrid reactor point design[1] were to determine a manner in which all of the necessary system components could be integrated into the reactor, to assess the technological problems, and to obtain a rough cost estimate. The resulting design was not optimized in either an engineering or economic sense, but rather was a reference point design from which further study could proceed.

Based on the point-design cost estimates, it appeared that the requirement of incorporating both fusion and fission components in the hybrid reactor would make the hybrid capital cost (\$/kWe) greater than that for a fission reactor. However, the impressive fissile-breeding performance of the hybrid, as compared to a fast-breeder reactor of comparable thermal rating, indicated that the most promising avenue for commercialization of this reactor concept was as a fissile breeder with electricity production as a by-product. Therefore, the hybrid study at LLL this year has concentrated on optimizing the hybrid for fissile production, employing the technique of parametric system analysis of the plant economics. The optimization was defined as a determination of the reactor parameters which minimize the cost of producing fissile fuel. The optimization thus minimizes the electricity cost component that is attributable to the fissile fuel burned by the fission reactors.

## RESULTS AND DISCUSSION

### SYSTEM MODEL

A large number of independent parameters that define the fusion component of a mirror hybrid are available to the reactor designer. Variation of these parameters can significantly affect the hybrid performance. In addition, plant economics are influenced by the blanket fissile management scheme and by the characteristics of the fission component. To assess the interplay of these various factors, we have developed a computer model of the mirror hybrid that permits rapid evaluation of the many possible reactor configurations. The components of the system model developed for the parametric analysis are as follows:

- Reactor Description
    - Plasma physics
    - Magnet design
    - Blanket geometry
    - Power flow
    - Capital cost

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- Fuel Management

  Time-dependent mass and energy flows
  Capacity factor
  Cash-flow accounting techniques

- "Nuclear Park" Economics

  Hybrid and fission reactors

The mirror reactor model (essentially the analysis developed by Carlson[2]) includes mirror plasma physics, magnet design, blanket geometry and power flows. Capital costs are a key element in the analysis, and here we have attempted to be as thorough and consistent as possible. However, the costing procedure entails a high degree of uncertainty due to the infancy of fusion technology.

A unique feature of hybrid reactor economics, as compared to those of strictly power-producing fission and fusion reactors, is that fissile fuel does not generate revenues on a continuous basis. Revenue from fissile fuel is only realized when blanket segments are removed from the reactor and reprocessed. In addition, the blanket multiplication increases and the breeding ratio decreases with increasing fuel exposure, as described by Lee.[3] To model these effects, we developed a fuel management package to evaluate the time-dependent production of power and of fissile fuel as functions of specified fuel-management parameters. In this analysis we also determined the timing and magnitude of fuel and blanket fabrication costs as well as spent-fuel shipping and reprocessing costs. The economics of this time-dependent "fuel-cycle" is evaluated using cash-flow accounting techniques.[4]

A second unusual feature of the economic analysis is that the hybrid produces two products, fissile fuel and electricity. To fix the cost of producing these two products, it is necessary to specify a constraint. In the present analysis, we have chosen to fix the cost of hybrid electricity at the same cost as electricity produced by the fission reactors which burn the hybrid fissile fuel. By considering the hybrid and its associated burner reactors as a single entity producing only electricity, we can calculate the electricity cost. Having established the electricity cost, we can then evaluate the cost of the fissile material from the hybrid.

## RESULTS OF PARAMETRIC ANALYSIS

In optimization studies to date we have employed variations of the following parameters:

- Plasma Physics

  Injection energy
  Mirror ratio
  Injection angle
  Confinement time

- Magnet Design

  Conductor field
  Mirror-to-mirror length

- Fuel Management

  Maximum fertile burnup
  Exposure distribution within the blanket

In our experience these quantities have the most important influence on the economics of the hybrid reactor. Two dependent quantities which have been found to strongly influence plant economics are the blanket coverage and the plant capacity factor.

The geometric relationship between the plasma and blanket are shown in Fig. 1. Holes in the blanket must be provided for plasma leakage and neutral injection. We have found that if the power density in the blanket exceeds 100 to 200 W/cm$^3$, the plenum dimension required to handle the helium flow becomes excessively large, pushing the blanket inward and severely decreasing the blanket coverage. Also, large neutral beam

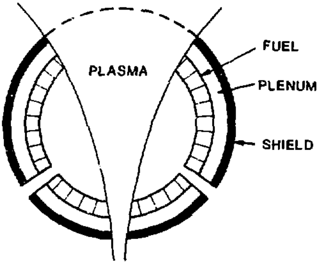

Fig. 1. Blanket coverage.

current requirements demand large injection ports thus reducing the blanket coverage. The equations used to model the plant capacity factor, [illegible], are:

$$\frac{t_{op}}{t_{op} + t_{sm} + t_{um} + t_{bc}} ,$$

$$\approx \frac{1}{1.2 + (t_{bc}/t_{op})} ,$$

$$t_{op} = \frac{\text{exposure (MW-yr/m}^2\text{)}}{\text{flux (MW/m}^2\text{)}} .$$

Here, $t_{op}$ is the operating time for the reactor, $t_{sm}$ is the time for scheduled maintenance, $t_{um}$ is the time for unscheduled maintenance and $t_{bc}$ is the time required for the blanket change operation. The capacity factor evaluates the trade-off between high first-wall [illegible] ed, therefore, high product gene[illegible] ates) and the need for shutting down [illegible] lant to perform blanket change operations after maximum blanket exposure is reached.

The fission reactors chosen as burners of the hybrid fissile fuel are listed listed in Table 1 along with their fuel make-up requirements. For a Pu burner, we have used a light water reactor (LWR) on a Pu recycle fuel cycle which is supplemented with hybrid Pu. As a $^{233}$U burner, we have used a high-gain high temperature gas-cooled reactor (HTGR) on the thorium-$^{233}$U fuel cycle. Another possibility as a $^{233}$U burner, but not yet examined, is the CANDU reactor.

Table 1. Description of thermal converter reactors.

| Parameter | Burner<br>$^{239}$Pu | <br>$^{233}$U |
|---|---|---|
| Reactor type | LWR | High-gain HTGR |
| Fuel cycle | | |
| Fertile feed | Natural U | Th |
| Fissile feed | Pu | $^{233}$U |
| Fissile recycle | Pu | $^{233}$U |
| Conversion ratio | 0.5 | 0.8 |
| Fissile feed requirements (kg/yr/MWe) | 0.333 | 0.185 |

The representative thermal reactor fuel cycles that are used to couple the fusion and fission reactors (Figs. 2 and 3) have been adapted from fuel cycles based on thermal reactor-produced fissile fuel.[5-7] Actually, the fuel cycles used

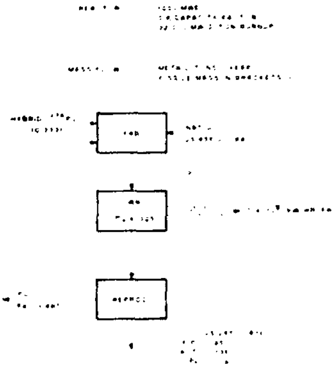

Fig. 2. The LWR fuel cycle.

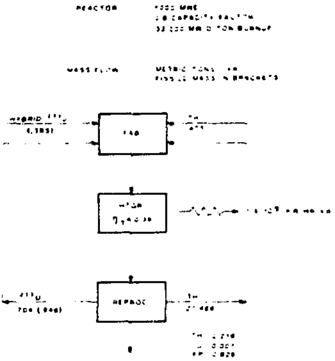

Fig. 3. The HTGR fuel cycle.

should be reevaluated, because the isotopic composition of the hybrid fissile fuel differs from that produced in a thermal fission reactor as a result of differences in flux spectrum and burnup in the two types of reactors.

The LWR fuel cycle[3] (Fig. 2) uses plutonium recycle and has a conversion ratio of [illegible]. Fissile feed consists of the $^{235}U$ component of the natural U fertile feed combined with hybrid-produced $^{239}Pu$. Here we have assumed that hybrid Pu (~90% fissile) is equivalent to Pu from a uranium-fueled LWR (~70% fissile). In future studies we plan to examine a variation of this cycle that will permit higher uranium utilization. The uranium will be recycled and the hybrid Pu feed increased to compensate for the absence of $^{235}U$. Thus, the hybrid fuel cycle may be designed to ultimately fission the majority of the uranium.

The HTGR fuel cycle[6] (Fig. 3) utilizes Th fertile feed, $^{233}U$ recycle and $^{233}U$ fissile feed from the hybrid and has a conversion ratio of .79. This conversion ratio is considerably higher than that of the $^{235}U$ HTGR (CR ~.66) due to the use of $^{233}U$, to the higher fertile to fissile ratio and to the lower burnup (32 000 MWD/T vs 95 000 MWD/T for the $^{235}U$ cycle).

Figures 4 to 7 show some of the details of the optimization process, primarily for the uranium blanket. Figure 4 shows that a rather broad optimum exists for various combinations of mirror ratio and injection energy ($W_{INJ}$).

As shown in Fig. 5, the minimum economical size is about 10 m, mirror-to-mirror. Below this size, the blanket coverage decreases rapidly, strongly degrading the plant economics. A 7.5 m machine appears to be the minimum "demo" size.

The optimization of magnetic field is shown in Fig. 6. For the uranium blanket, a near optimum can be attained at 8 tesla, which yields the optimum blanket power density of ~100 W/cc. For the thorium blanket, 12 to 14T fields are required to minimize the fissile cost.

The variation of fissile cost with fertile burnup is shown in Fig. 7. At low burnup, high fabrication-reprocessing costs and low capacity factor are incurred. As the maximum burnup increases, larger temporal variations occur in the thermal output due to increasing blanket multiplication with burnup. Thus, this situation requires that an increasing fraction of the plant thermal capacity remain idle during periods of non-peak thermal output. Also, the high burnup implies longer delays in the realization of the revenues from fissile breeding. For the uranium blanket, the optimum occurs at a 1% burnup, which is about the maximum tolerable burnup for the U-Mo fuel. For thorium, the 0.5% burnup is well below the maximum obtainable with this fuel.

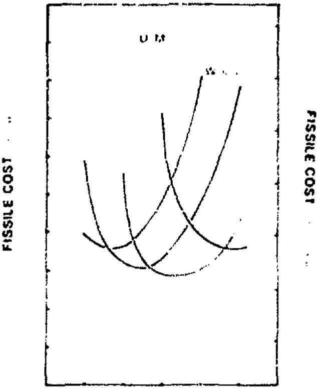

Fig. 4. The plasma physics variation.

There is some degree of uncertainty as to the actual plasma Q that will be attained in mirror reactors. It is possible that microinstabilities will limit Q to a value somewhat below the classical value.[8] A second possibility is that Q enhancement techniques under consideration[9] will elevate Q above our presently predicted values. Figure 8 shows that electricity costs are not strongly perturbed even if classical confinement is not attained. A two-fold enhancement of Q improves the economics of the hybrid reactor but, in general, electricity costs are rather insensitive to higher Q.

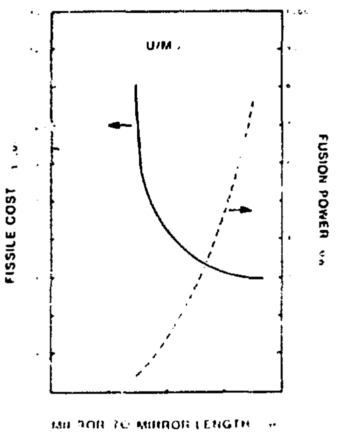

Fig. 5. Variation of fissile cost and fusion power with reactor size.

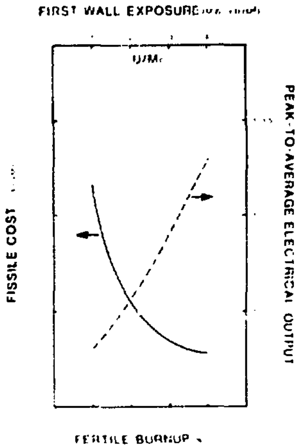

Fig. 7. Variation of fissile cost with fertile burnup.

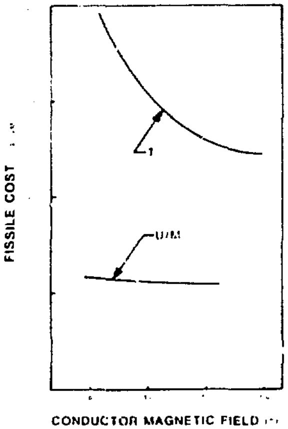

Fig. 6. Variation of fissile cost with magnetic field.

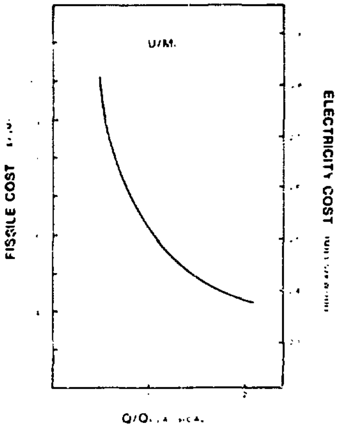

Fig. 8. Variation of fissile value and electricity costs with Q.

Table 2. Parameters for the optimized hybrid reactors.

| Parameter | U/Mo | Th |
|---|---|---|
| Mirror ratio | 2.50 | 2.75 |
| Injection energy (keV) | 100 | 100 |
| Conductor field (T) | 8 | 12 |
| Q | 0.68 | 0.75 |
| Fusion power (MW) | 470 | 1500 |
| First wall flux (MW/m$^2$) | 1.5 | 4.2 |
| Blanket thermal power, average (MW) | 4220 | 3350 |
| Electrical output (MW) | 1040 | -40 |
| Capacity factor | 0.75 | 0.73 |
| Mirror-to-mirror length (m) | 15 | 15 |

## OPTIMIZED REACTOR CONFIGURATIONS

From the reactor parameters for the uranium and thorium blankets (Table 2) several significant differences between the two reactors are evident.

- The uranium blanket, because of its high energy multiplication, results in a plant with a large electrical output. The thorium blanket reactor does not produce net electricity, just fissile fuel.

- Both blankets have about the same thermal rating. This results from the much greater fusion power required for the thorium blanket reactor as compared to the uranium blanket reactor.

- The high fusion power of the thorium blanket reactor is obtained by using a more intense magnetic field than for the uranium blanket reactor. Therefore, the latter may rely on existing NbTi superconductor magnet technology, whereas, the thorium blanket reactor will require the more technologically advanced $Nb_3Sn$ superconductor.

- Optimum economics for the thorium blanket are obtained at high exposure, about 9 MW-yr/m$^2$. The uranium blanket requires only about 4 MW-yr/m$^2$. These results assume that the blanket structure is capable of tolerating these exposures.

The reactor size selected, as given by the mirror-to-mirror length of 15 m, is not an optimum. Rather, this size was chosen as being representative of a plant with good economics and with approximately the same thermal rating as present-day nuclear power plants. A point to be emphasized is that the first-wall fluxes for the two blankets were not arbitrarily chosen. In the present analysis, the first-wall flux is a dependent parameter whose value is determined by an economic optimization of the reactor.

Table 3. Blanket parameters for the optimized reactors.

| Parameter | U/Mo | Th |
|---|---|---|
| Fissile output (kg/yr) | 2360 | 2590 |
| Avg. energy multiplication | 11.1 | 2.8 |
| Blanket coverage | 0.86 | 0.77 |
| Fertile burnup ( ) | 1.0 | 0.5 |
| Blanket exposure (MW-yr/m$^2$) | 4.1 | 9.2 |
| Fuel power density (W/cm$^3$) | 150 | 110 |
| Peak to average electrical output | 1.13 | -- |
| Blanket enrichment, average | 1.02% | 1.06% |

The blanket parameters for the optimized reactors are listed in Table 3. Both blankets produce about 2 1/2 metric tons of fissile fuel per year. However, the thorium blanket requires a rather high exposure, and the possibility of the blanket structure being able to attain ~9 MW-yr/m$^2$ exposure is quite uncertain. For the uranium blanket, the average energy multiplication is higher by about a factor of four than for the thorium blanket; these blanket energy multiplications include the effect of the fractional blanket coverage.

The economic parameters for the hybrid are listed in Table 4. The higher capital cost of the thorium blanket hybrid is associated with the fusion components required to generate the higher fusion power. The $^{233}U$ cost is more than two times greater than the Pu cost. The lower cost for Pu results from the lower capital cost and from electrical power production revenues. However, because of the lower fissile requirements of the HTGR, as compared to the LWR, the cost of the electricity from the two fission power plants is approximately the same.

Table 4. Economics for the optimized hybrid reactors.

| Cost | U/Mo | Th |
|---|---|---|
| Capital cost ($10^9$\$) | 2.3 | 3.3 |
| (\$/kWe) | 2200 | – |
| Fissile material cost (\$/g) | 55 | 127 |
| Capital | 80 | 103 |
| Fuel cycle | 13 | 21 |
| Operation and maintenance | 1 | 1 |
| Electricity revenues | -39 | 2 |
| Electricity cost (mills/kW-hr) | 24.8 | 25.3 |

The breakdown of the fissile material costs indicate that they are dominated by capital costs. The fuel-cycle costs account for blanket fabrication, fuel fabrication, reprocessing and spent-fuel shipping. Current (high) estimates for the fuel services have been used,[10] but they are not a dominant cost. For the uranium blanket reactor, approximately 60% of the plant revenues are generated by fissile production. This is in contrast to the thorium hybrid reactor where 100% of plant revenues are generated by fissile material.

The fission reactor economics are listed in Table 5. Here, the category "fuel cycle without fissile material" refers to all normal fuel cycle charges excluding the cost of fissile fuel, i.e., fabrication, reprocessing, spent-fuel shipping and purchase of fertile fuel. The fissile fuel cost is the cost of producing this material in the hybrid reactor. Here, the important result is that the hybrid fissile fuel costs of 4.1 and 5.3 mills/kW-hr are a small fraction of the total cost of the electricity. Based on our current capital cost model, we conclude that the mirror hybrid reactor is capable of converting the world's large fertile resources into fissile fuel at a cost that does not strongly influence the net cost of electricity.

Table 5. Economics for the fission reactors.

| Cost | LWR | High-gain HTGR |
|---|---|---|
| Capital cost (\$/kWe) | 750 | 750 |
| Electricity cost (mills/kW-hr) | 24.8 | 25.3 |
| Capital cost | 16.1 | 16.1 |
| Fuel cycle without fissile material | 3.9 | 3.2 |
| Fissile fuel | 4.1 | 5.3 |
| Operation and maintenance | 0.7 | 0.7 |

Table 6. Economics for the hybrid/thermal reactor complex.

| Cost | U/Mo | Th |
|---|---|---|
| Installed capacity (MWe) | 8130 | 14 000 |
| Hybrid | 1040 | – |
| Fission reactors | 7090 | 14 000 |
| Capital cost (\$/kWe) | 935 | 985 |
| Electricity cost (mills/kW-hr) | 24.8 | 25.3 |
| Capital | 19.7 | 20.5 |
| Fuel cycle | 4.3 | 4.0 |
| Operation and maintenance | 0.8 | 0.8 |

The overall nuclear park economics are shown in Table 6. Examining the U hybrid/LWR combination, we see the 1040-MWe hybrid supports fissile requirements for about seven 1000-MWe thermal reactors. The combined capital cost of the hybrid and the fission reactors is 935 \$/kWe vs 750 \$/kWe for the LWR's. The Th hybrid produces enough fissile material to support fourteen 1000-MWe HTGR's, resulting in a capital cost for the nuclear complex of 985 \$/kWe vs 750 \$/kWe for the HTGR. The fuel cycle costs do not include any cost for fissile fuel since this material is produced entirely within the hybrid-fission reactor complex.

The fact that the hybrid fissile production costs are capital cost dominated (see Table 4) dictates that we regard these fissile costs with a degree of uncertainty, reflecting both the infancy of fusion engineering and our inability to accurately assign costs to reactor components which are merely conceptual designs. However, the presently predicted costs are within the realm of being economically attractive. In our opinion, this conclusion justifies vigorous support of the hybrid concept, with future design efforts continuing to refine the engineering and to incorporate experimental results as they become available. The result could well be an energy option that will ease the transition to a full fusion power economy in the next century and will provide comparatively early benefits from the large R&D investment that will be required to commercialize this energy source.

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