Evaluations of Fusion-Fission (Hybrid) Concepts: Market Penetration Analysis for Fusion-Fission Hybrids

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EVALUATIONS OF FUSION-FISSION (HYBRID) CONCEPTS: MARKET PENETRATION ANALYSIS FOR FUSION-FISSION HYBRIDS

EPRI ER-469
(Research Project 268-1)

Topical Report

Part A

January 1976

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ABSTRACT

This report summarizes findings of the fusion-fission studies conducted for the Electric Power Research Institute by Battelle, Pacific Northwest Laboratories, under Contract RP268-1.

This particular study focused on the evaluation of fissile material producing hybrids. Technical results of the evaluation of actinide burning are presented in a companion volume, Part B.

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EXECUTIVE SUMMARY

One of the long-range goals of the Electric Power Research Institute (EPRI) is to bring fusion systems to commercial applicability and utility use. The Fossil Fuel and Advanced Systems Division of EPRI is sponsoring research which addresses some of the more important technological problems that must be resolved if fusion systems are to be achieved. One concept which is receiving increasing interest is to surround a fusion plasma with fissile and/or fertile material in a blanket to beneficially use the 14 MeV neutrons produced by the controlled thermonuclear reaction. Concepts which involve the use of fusion-produced neutrons to ultimately produce fission and/or fissionable material are generally referred to as fusion-fission (hybrid) systems. The interest in hybrids stems from the thought that: 1) hybrid powerplants may be realizable before pure fusion powerplants because the fusion plasma confinement conditions can be relaxed, 2) fissile material can be produced and thereby extend the fuel supply for fission reactors, and 3) radioactive wastes can be changed to less noxious constituents via transmutation and thereby relax the confinement criteria for storage and disposal of radioactive waste. To gain added perspective on hybrid systems, EPRI commissioned Battelle-Northwest (BNW) to conduct a study to evaluate the technical feasibility of using fusion neutrons to burn actinides present in high-level waste from fission reactors and to define ranges of capitalized cost which allow fuel producing hybrids to penetrate the market place. Though the study was not an exhaustive examination of these issues, the results lead us to tentatively conclude that burning actinides in a CTR blanket is marginally attractive and that producing fissile material in a CTR blanket has economic benefits for certain systems if electricity is generated from the waste heat.

The results of the study are summarized in a final project report entitled, "Evaluations of Fusion-Fission (Hybrid) Concepts". The detailed results of the evaluation of fissile material producing hybrids are presented in this report. The detailed results of the evaluation of actinide burning are given in another topical report entitled, "Transmutation of High-Level Actinide Waste in Hybrids".

INTRODUCTION

Hybrid reactors which involve a fusion region surrounded by a fission blanket have the capability of producing both electricity and fissionable material. The market penetration, or the number of hybrids which could be built, will be determined for a combination of capital costs, fuel cycle costs, fissile material production and the degree of electric production, or in the case of the "electric breeder", electric consumption. Because of the wide array of possibilities a parametric approach has been chosen where each of the aforementioned factors are varied. A factor beyond the control of the hybrid designer is the potential competition from other powerplant designs and other sources of fissile material. The primary source of fissile material is natural uranium, with secondary sources in the form of plutonium or ^{233}U produced in either thermal or fast neutron reactors.

The EPRI Fusion Committee was asked to comment on LMFBR characteristics and proposed uranium and separative work assumptions for this study. The basis and resulting cost schedule is contained in Appendix A.

The LMFBR characteristics were a 12-year doubling time with a capital cost of \$150/kW higher than the light water reactor in the initial introduction declining to \$100/kW after 10 years. The initial fissile load is 0.7 kg/MW_t with fissile yield of 0.14 kg/MW_t year.

Three specific situations were chosen for analysis as follows: 1) LMFBR introduced in 1993, 2) No LMFBR introduced at all, 3) LMFBR not introduced, but CTR introduced operating on pure fusion cycle in 2010.

A systems analysis model utilizing linear programming optimization of new electric generation plant selection was utilized in this study. Of particular importance is the fact that rather detailed treatment of fissile flows are an important capability of the model. A second factor is that plutonium values are derived by the model as part of the analysis. Each hybrid design in the parametric analysis is assumed to be available in 1990. Market penetration is estimated based on relative costs of competing plants over their useful lifetime.

A combination of costs, fissile material production and capital operating costs required to just barely penetrate the market is estimated along with the cost characteristics to make a substantial market penetration resulting in benefits to the electric power industry of \$3 to \$15 billion through the Year 2060. Benefits of \$15 billion represent approximately a 4% reduction in electric generating costs in the post-2000 time period.

Hybrids with three different degrees of electric production were considered in this analysis. The first, with electric production at 40% of thermal output, possibly represents a high-temperature gas-cooled system. Second is a powerplant which has a net power production of zero; that is, as much electricity as required to operate the reactor is captured in the generator set. A third plant design, known as the "electric breeder" is assumed to require electricity to operate and none of the thermal energy produced in the hybrid powerplant itself is captured.

The remaining sections of this report will describe the detailed methodology used in the analysis including other important input assumptions and the results of the parametric analysis.

CONCLUSIONS

Allowable capital costs for significant market penetration are in excess of \$400/kW_t which is certainly in the range of preliminary hybrid designs. For electric breeder designs which consume substantial amounts of electrical energy in the production of fissile material, the allowable capital cost for significant market penetration appears to be less than \$100/kW_t. It would seem impossible for any known designs of electric breeders to meet this allowable cost. Designs which capture enough electrical energy to satisfy their own requirement exhibits the virtue of not being a direct part of the utility generating system. These designs have allowable capital cost approximately equal to that for present day light water reactors. Thus if some of the benefits claimed by optimistic designers come true, this could be a viable area for operation.

The ultimate market penetration in all cases is confined by the symbiotic relationship with those reactors which are consuming the excess fissile

material produced by hybrids. As a result 10 to 20% of the total market for new electric generating facilities represents a maximum penetration hybrids could likely achieve. The installed nuclear capacity is expanded through the reduction in the cost of fissile material as much as 60%. Plutonium values range from \$50 to \$75/g fissile for the cases without LMFBR in the Year 2020. For the cases with the LMFBR in operation, the plutonium values are generally under \$40/g fissile. The availability of the CTR in Year 2010 does not reduce the usefulness of hybrid powerplants since fissile material is still required to operate the large number of LWRs operating prior to the entry of a pure fusion machine. Hybrids which produce ^{233}U have an allowable cost about \$80/kW_t above that of plutonium producers at the zero benefit level.

Until better hybrid designs become available, the feasibility of market penetration can be assessed with the use of the enclosed figures. These figures also illustrate the tradeoff between capital cost, operating cost, plutonium production, and electric production.

METHODOLOGY

Prior to developing engineering designs of new technologies, it can be very useful to know the allowable costs that make the technology competitive to alternative methods. This analysis was performed to develop the allowable costs of fission-fusion hybrid plants. The hybrid plants have two important performance characteristics, fissile material production and electrical generation. This study parameterized these two performance characteristics and determined allowable cost for various values of the two performance characteristics.

A computer simulation system⁽¹⁾ developed for the United States Energy Research and Development Administration (ERDA) was used for this study. The simulation estimates the optimum pattern of future electrical supply and is centered around a linear programming (LP) model. The model simulates the industry's process of determining what types of plants to build and when to build them. The decision criterion is the minimization of present worth system cost, subject to many decision limiting constraints. Many of

the constraints have evolved to make the decision process more closely resemble the utility decision process. The system cost includes both construction and operating costs.

In this model, each decision variable represents the number of plants of a certain type to be built in a fixed time interval. Each fueling scheme considered is represented as a unique variable. For instance, several variations of the time (years) that an LWR uses Pu are specified. This allows a simulation of the utility decision process to build an LWR plant without knowing what the lifetime fueling scheme would be. At some future date, if Pu becomes available economically, the utility would start recycling Pu. The LP model optimizes over the whole study horizon and selects the variable that represents switching over to Pu recycle at a later date. This model, of course, is an aggregation of all utilities and does not attempt to model an individual utility.

In this study, a model plant was generated for each combination of the performance characteristics for the hybrid. Then by changing the capital cost of the model plant until the desired effect is obtained, one can estimate the allowable cost for the hybrid. The allowable performance used for the model plants were 0.40, 0.01, and 0.20 MW_e/MW_t and fissile production rates of 0.5, 1.0, and 1.5 kg/ MW_t .

A very desirable feature of this model is that the cost of uranium and fissile material do not have to be specified as a function of time. Rather they are determined by the solution of the model, thus effectively have continuous feedback loops. As the plant mix changes during solution, the cost of uranium and fissile material changes. Uranium cost is specified as an increasing function of the cumulative amount consumed and the solution (plant mix) determines how much uranium is consumed, thus the price. A fissile material stockpile is constrained to never go negative, thus the fissile material must be produced before it can be used. The cost of the plants in the solution thus determines the price of the fissile material.

The allowable costs of the hybrid were determined for three different competitive situations. The first uses the latest ERDA estimate for

availability in 1992, of the early oxide LMFBR with a 28-year doubling time, followed by the advanced oxide LMFBR with a 12-year doubling time in 1998. The first case also assumes no CTR. The second case assumes neither the LMFBR nor CTR become available. The third case assumes no LMFBR but the CTR becomes available in 2010. For the plutonium producing hybrid cases, it was assumed that there were no HTGR reactors.

The electrical demand is an exogenous input to this model. The demand growth rate for all three cases was keyed to the ERDA (1975 version of WASH-1139) moderate high estimate through Year 2000, with a slowly declining growth rate after 2000.

The model solution is sensitive to input cost estimates, especially capital cost and uranium cost. The EPRI fusion committee was solicited to refine input estimates for uranium and separative work costs shown in Table 1 and Table 2 respectively.

TABLE 1. U_3O_8 Price/Availability (1975 dollars)

<u>Thousand Tons Available</u>	<u>U_3O_8 Price (\$/lb)</u>
400	18
500	20
500	25
500	40
1,000	60
1,000	80
1,000	100
1,000	110
1,000	120
3,000	125

TABLE 2. Separative Work Cost (1975 Dollars)

<u>Year</u>	<u>\$/SW Unit</u>
1980	76
1990	75
2000	70
2010	65

The discount rate used in this study was 8.8%. All costs are in 1975 constant dollars.

Capital cost is an important input, especially the cost of one technology relative to the other technologies. Table 3 shows the capital cost

TABLE 3. Fossil and Nuclear Capital Costs (\$/kW_e) (1975 Dollars)

	<u>LWR and HTGR</u>	<u>LMFBR</u>	<u>CTR</u>	<u>Fossil</u>				
				<u>ECAR NPCC</u>	<u>WSCP SWPP</u>	<u>MARCA SERC</u>	<u>MAIN ERCOT</u>	<u>MAAC</u>
1975	365			285	285	285	285	285
1980	598			496	503	509	518	494
1990	632	782		530	537	543	552	527
2000	640	740		540	546	552	561	536
2010	640	740	710	540	546	552	561	536
2040	640	740	710	540	546	552	561	536

estimates used in this analysis. The capital costs of fossil and nuclear plants increase in the near term due to an assumed increased cost for improved environmental and safety control. These input assumptions include the utility response which indicated the early LMFBR costs \$150/kW over the LWR, declining to \$100/kW over LWR in Year 2000. The regional variations in capital cost are maintained by the fossil capital costs. The regional structures used in this study are the National Electric Reliability Councils (NERC).

Fossil fuel costs for each NERC are shown in Table 4. These costs are derived from 1975 Federal Power Commission (FPC) data. The percent of demand in each region that may be satisfied by each fossil price is based on historical price distribution. Nuclear plants compete with fossil plants in each region.

RESULTS

The allowable capitalized cost for hybrid plants for the three cases are presented in Figures 1-3. The curves representing allowable hybrid cost are grouped by level of electrical production. The $0.40 \text{ MW}_e/\text{MW}_t$ value depicts a hybrid system with a highly efficient conversion of thermal to electrical energy. The near zero $0.01 \text{ MW}_e/\text{MW}_t$ value depicts a hybrid system which consumes nearly all of the electric energy produced. The $-0.20 \text{ MW}_e/\text{MW}_t$ depicts a so called "electric breeder",⁽²⁾ a hybrid plant that requires substantial electric energy from an external source. Each curve represents the allowable cost for a hybrid that yields a fixed benefit for various levels of fissile production. The benefit is the reduction in total discounted system cost as compared to a base case without any hybrids. Zero benefit is a price where the hybrid just begins to penetrate the market; i.e., is a source of fissile material equivalent to all other sources in the base case.

The analysis used model plants for annual production rates of 0.5, 1.0, and $1.5 \text{ kg}/\text{MW}_t$, but after the computing was finished, it became apparent that lower production was important. By considering the pure CTR as a hybrid with zero production, computer runs were already available that provided more accuracy for extending the figures below the $0.5 \text{ kg}/\text{MW}_t$ fissile production rate than would be obtained by merely extrapolating the values above 0.5. The zero benefit allowable cost was $\$365/\text{kW}_t$ for Case 1 with LMFBR, $\$380/\text{kW}_t$ for Case 2 without either the LMFBR or CTR, and $\$308/\text{kW}_t$ for Case 3 with the CTR.

Figure 1 presents the allowable cost for hybrids for Case 1 where the LMFBR is available in 1992 at a cost of $\$780/\text{kW}_e$ decreasing to $\$740/\text{kW}_e$ in 2000. The efficient conversion hybrid, $0.40 \text{ MW}_e/\text{MW}_t$, has a break-even

TABLE 4. Fossil Fuel Cost by Region
(1975 Dollars)

<u>NERC Region</u>	<u>Cost^(a) ¢/MBTU</u>	<u>Percent^(b) of Demand</u>
ECAR	80	33.4
	87	33.4
	163	33.2
WSCC	57	33.4
	100	33.3
	220	33.3
MARCA	59	28.4
	86	39.0
	172	32.6
NPCC	125	44.4
	160	36.4
	204	19.2
SWPP	60	33.2
	90	33.1
	175	33.7
MAAC	99	31.7
	160	38.8
	206	29.5
MAIN	80	34.5
	95	33.9
	180	31.6
SERC	80	33.3
	100	33.3
	187	33.4
ERCOT	25	33.7
	70	32.5
	180	33.8

a. Derived from recent FPC data

b. Demand function steps based on historical cost distribution from Battelle-Northwest powerplant file.

FIGURE 1. Allowable Capitalized Cost
EPRI Case 1, with LMFBR --
Without CTR

FIGURE 2. Allowable Capitalized Cost
EPRI Case 2, Without LMFB --
Without CTR

FIGURE 3. Allowable Capitalized Cost
EPRI Case 3, With CTR --
Without LMFBR

cost (zero benefit) ranging from $\$430/\text{kW}_t$ when producing plutonium at the rate of $0.25 \text{ kg}/\text{kW}_t$ annually, to $\$725/\text{MW}_t$ when producing plutonium at the rate of $1.5 \text{ kg}/\text{MW}_t$ annually. The hybrid cost required to yield a benefit of \$15 billion ranges from $\$340/\text{kW}_t$ to $\$510/\text{kW}_t$. \$15 billion represents less than 2% total discounted system cost, but is about 4% of the post-2000 cost. The same plant mix yields a much higher benefit if a lower discount rate is used. The allowable capital costs for the near zero electrical production hybrid ($0.01 \text{ MW}_e/\text{MW}_t$) are about $\$350/\text{kW}_t$ less than the allowable costs for the efficient electric producer. The break even allowable hybrid costs range from $\$55/\text{kW}_t$ to $\$370/\text{kW}_t$ while the allowable costs that yield a benefit of \$15 billion range from $\$15/\text{kW}_t$ to $\$170/\text{kW}_t$. The so-called electric breeder ($-0.20 \text{ MW}_e/\text{MW}_t$) must produce plutonium at least at the rate of $0.7 \text{ kg}/\text{MW}_t$ to just pay for the electrical energy consumed; i.e., zero allowable cost and the allowable cost ranges up to $\$240/\text{kW}_t$ for $1.5 \text{ kg}/\text{MW}_t$ plutonium production rate. The \$15 billion benefit cannot be realized for the electric breeder, even with the $1.5 \text{ kg}/\text{MW}_t$ plutonium production rate at zero cost.

Figure 2 presents the allowable cost for hybrids for case 2, without either the LMFBR or the CTR. The electrical producing hybrid has a break-even allowable cost ranging from $\$470/\text{kW}_t$ to $\$850/\text{kW}_t$, while the allowable cost that yields a discounted benefit of \$15 billion ranges from $\$400/\text{kW}_t$ to $\$620/\text{kW}_t$. For the higher ($\geq 0.75 \text{ kg}/\text{MW}_t$) fissile production plants, this is approximately $\$100/\text{kW}_t$ higher than case 1 where the LMFBR is available. The break-even allowable cost for the near zero electrical producing hybrid ranges from $\$75/\text{kW}_t$ to $\$450/\text{kW}_t$, while the allowable cost that yields a \$15 billion benefit ranges from $\$35/\text{kW}_t$ to $\$260/\text{kW}_t$. This averages about $\$65/\text{kW}_t$ higher than case 1 when the LMFBR is available for higher ($\geq 0.75 \text{ kg}/\text{MW}_t$) plutonium production plants. The electric breeder that produces plutonium at the annual rate of $1.5 \text{ kg}/\text{MW}_t$ has an allowable cost of $\$290/\text{kW}_t$ for zero benefit and $\$100/\text{kW}_t$ for \$15 billion benefit.

Figure 3 presents the allowable cost for hybrids in case 3, where the LMFBR is not available but the CTR becomes available in Year 2010. The electrical producing hybrid has a break-even allowable cost ranging from

\$470/kW_t to \$850/kW_t when producing plutonium at the rate of from 0.25 kg/MW_t to 1.5 kg/MW_t respectively. The allowable cost that would yield a benefit of \$15 billion ranges from \$360/kW_t to \$590/kW_t. The break-even values are almost identical to case 2, without either CTR or LMFBR, but the penetration is lower and thus the allowable cost to yield benefits must be lower, about \$50/kW_t lower for the \$15 billion benefit. The near zero electrical producing hybrid also has an almost identical break-even allowable cost as case 2 and the allowable cost that yields a benefit of \$15 billion is also lower than case 2, about \$50 kW_t lower. The allowable cost for the zero electrical producer ranges from \$70/kW_t to \$450/kW_t and for \$15 billion benefit from \$25/kW_t to \$210/kW_t. The electric breeder has a break-even allowable cost of \$350/kW_e if the plutonium production rate is 1.5 kg/MW_t, which is \$50 higher than case 2 without the CTR. This is caused by a lower electrical power cost provided by the CTR, thus the power consumed by the electric breeder costs less. The \$15 billion benefit allowable cost for the electric breeder is about \$50/kW_t, again less than case 2 because of reduced penetration.

Figures 4 and 5 present the hybrid allowable capitalized cost (same values as Figures 1-3) grouped to show cross case comparisons. Figure 4 is for zero benefit and Figure 5 is for \$15 billion benefit.

The capitalized costs in Figures 1-5 include plant cost, fuel cycle expense except purchase and sale of nuclear material, and interim capital replacements. It can be written

$$C = P + \sum_{i=1}^L (1 + r)^{-i} (F_i + R_i) \quad (1)$$

where

C = Capitalized cost

P = Plant cost

r = Discount rate (8.8% used in this analysis)

L = Plant lifetime (30 years in this analysis)

FIGURE 4. Allowable Capitalized Cost for Hybrids that Yield Zero Benefit

FIGURE 5. Allowable Capitalized Cost for Hybrids That Yield \$15 Billion Benefit

F_i = Fuel cycle expense for year i excluding nuclear material purchase or credits. Included in this category are costs for tritium, D_2O , fabrication costs, spent fuel reprocessing costs, and shipping costs.

R_i = Interim capital replacements, included here because some designs require large interim capital replacement due to deterioration of the first wall.

Not included as capitalized cost are plant operating and maintenance cost, cost or credit for electrical energy, nuclear fuel purchase and credits, taxes and insurance. These items are included elsewhere in the model.

As an alternate way of capitalizing the non-nuclear material fuel cycle expense, a fuel cycle expense of $\$/kW_t$ year is equivalent to a capital cost of $\$9.8/kW_t$. When evaluating a hybrid design, the estimated plant cost should be increased by the sum of the discounted interim capital replacements in Equation 1 and by either the estimated fuel cycle expense ($\$/kW_t$) multiplied by 9.8 or by the summation of discounted fuel cycle expense as expressed in Equation 1.

By using Figures 1-3, or Figure 6, the allowable cost for case 2 zero benefit interpolated on electrical to thermal ratio, the designer can analyze trade-offs between capital costs, national economic benefit, fissile material production, and electrical generation. The worthiness of a potential hybrid design may be evaluated. For instance, several versions of a hybrid design using a mirror plasma confinement concept are discussed by Moir.⁽³⁾ The unoptimized version of the mirror design is 2000 MW_t with electrical production of 600 MW_e for a 0.3 MW_e/MW_t efficiency and 700 kg of plutonium for a production rate of 0.35 kg/ MW_t . The estimated capital cost for this design is $\$600/kW_t$ plus an estimated fuel cycle expense of 7.9 $\$/kW_t$ which is equivalent to total capitalized cost of $\$677/MW_t$, point A in Figure 6. Using linear interpolation between the 0.01 MW_e/MW_t and 0.40 MW_e/MW_t curves in Figure 2, the zero benefit allowable capital cost for this design is $\$400/kW_t$, point A in Figure 6. Therefore, this design is about 70% too expensive, even in the most opportune case without the LMFBR. A high-power fast-fission-blanket reactor was also presented in the

same report. This design doubled the power and the plutonium production at a cost of $\$400/\text{kW}_t$ yielding $\$477/\text{MW}_t$ including capitalized fuel cycle expense, point B in Figure 6. This is still higher than the zero benefit allowable cost of $\$400/\text{kW}_t$ but only about 19% too high. Another design with a higher energy multiplication factor and a lower breeding ratio, producing electricity at $0.35 \text{ MW}_e/\text{MW}_t$ and plutonium at $0.14 \text{ kg}/\text{MW}_t$, has an estimated plant cost of $\$330/\text{kW}_t$ or a capitalized cost, including fuel cycle expense of $\$407/\text{kW}_t$, point C in Figure 6. The allowable zero benefit allowable cost from interpolating data in Figure 2 is $\$395/\text{kW}_t$ point C in Figure 6. This design cost is within 3% if the LMFBR is not available. A mirror design for an electric breeder was presented in the same report with an electrical to thermal ratio of -0.1 and plutonium production rate of $0.84 \text{ kg}/\text{MW}_t$ for an estimated cost of $\$334/\text{kW}_t$, point D in Figure 6. From data in Figure 2, a hybrid with this performance has an allowable cost of only about $\$145/\text{kW}_t$, point D' in Figure 6. Thus this design, with fuel cycle expense, is too expensive by a factor of over two, even in the absence of the LMFBR.

Tables 5 and 6 summarize the LP solutions that were used to develop the hybrid allowable costs. Table 5 presents the number of plants installed at the beginning of Year 2020, the first year any hybrids are retired, and Table 6 presents the five year average building rate for Years 2020-2024. The assumed plant size is 1000 MW_e nominally for LWR, LMFBR, and CTR, and 2500 MW_t for hybrids. Items 1 through 9 represent the base case and the hybrid saturation level for case 2, the case without either the LMFBR or CTR. The ratio of LWR to hybrid is dependent on the fissile production and is approximately 2:1, 4:1, and 6:1, respectively for annual plutonium production rate of 0.5, 1.0, and 1.5 kg/MW_t when the hybrid is saturated. All of the case 2 saturation solutions have a total installed nuclear capacity ranging from 3140-3800 MW_e , while without hybrid (item 1) the total nuclear installed is only 2200.

Items 10 through 13 in Tables 5 and 6 show the effects as the price of the hybrid are reduced and the hybrid becomes saturated for case 1, the case with the LMFBR. Since the LMFBR also produces plutonium for use in LWRs, the ratio of LWR to hybrid is higher in this case until the hybrid price gets so low that the LMFBR is forced completely out of the solution. The

FIGURE 6. Allowable Capitalized Cost for Case 2 Hybrids That Yield Zero Benefit, Interpolated Between Model Values for MW_e/MW_t

TABLE 5. Solution Summary

Case No.	Optional Nuclear Technology in Addition to LWR	Hybrid Production Rates		Disc Benefit \$ Billion	Installed at Beginning of Year 2020 ^(a)				Total Nuclear (GW _e)	Ratio LWR/Hybrid
		Elec. (MW _e /MW _t)	Fissile (kg/MW _t)		Hybrid Plants	LWR Plants	LMFBR Plants	CTR Plants		
1.	2	None		0		2200			2200	
2.	2	Hybrid	0.01	15	1540	3360			3400	2.2
3.	2	Hybrid	0.40	15	1040	2400			3140	2.0
4.	2	Hybrid	-0.20	14	600	3500			3200	5.7
5.	2	Hybrid	0.01	15	800	3400			3400	4.2
6.	2	Hybrid	0.40	15	720	3080			3800	4.3
7.	2	Hybrid	-0.20	15	570	3530			3250	6.2
8.	2	Hybrid	0.01	15	550	3460			3470	6.2
9.	2	Hybrid	0.40	15	470	3000			3470	6.3
10.	1	LMFBR		20 ^(b)		1400	1400		2800	
11.	1	LMFBR-Hybrid	0.40	6	220	1800	1350		3370	8.0
12.	1	LMFBR-Hybrid	0.40	10	270	2000	1200		3470	7.3
13.	1	LMFBR-Hybrid ^(c)	0.40	15	550	3250			3800	5.9
14.	3	CTR		19 ^(b)		2140		60	2200	
15.	3	CTR-Hybrid	0.01	10	1100	2970		60	3060	2.7
16.	3	CTR-Hybrid	0.40	15	560	2730		60	3350	4.8

(a) Assumed plant size, Hybrid = 2500 MW_t, all other = 1000 MW_e

(b) Benefit compared to Case 2 Base Case (Item 1)

(c) At \$15 benefit, LMFBR is driven out of the solution

TABLE 6. Solution Summary

		<u>Average Plant Building Rates Year 2020-25^(a)</u>				
	<u>Case No.</u>	<u>Hybrid</u>	<u>LWR</u>	<u>LMFBR</u>	<u>CTR</u>	<u>Ratio LWR/Hybrid</u>
1.	2		105			
2.	2	110	200			1.8
3.	2	62	145			2.3
4.	2	65	220			3.4
5.	2	55	200			3.6
6.	2	42	180			4.3
7.	2	36	220			6.1
8.	2	36	210			5.8
9.	2	30	180			6.0
10.	1		43	145		
11.	1	1	75	140		75.0
12.	1	3	75	135		25.0
13.	1	32	200			6.2
14.	3		48			
15.	3	10	77		150	7.7
16.	3	0	85		150	

(a) Assumed plant size, Hybrid = 2500 MW_t, all other = 1000 MW_e

total installed nuclear in Year 2020 grows from 2800 MW_e without the hybrid to 3800 MW_e when the hybrid is saturated.

Items 14 through 16 in Tables 5 and 6 show the effects of hybrids for case 3 when the CTR is available in Year 2010. The installed nuclear capacity in Year 2020 grows from 2200 MW_e without the hybrid to 3350 MW_e when the hybrid is saturated. With the CTR, the hybrid acts only as an intermediate source, as shown by the zero hybrid building rate in Years 2020-2024.

A useful feature of this model is the fissile material accountability constraint set. Fissile material must be produced by a plant in the model before it can be consumed in another plant. The advantage in this feature is that the cost of fissile material is determined by the cost of the plants in the model, thus the price is not an exogenous input. Thus, the effect of a major contributor, such as the hybrid, is inherent in the model structure and acts as a continuous feedback loop. The plutonium shadow price in Year 2020 from this analysis is presented in Table 7. As the price of hybrid cost is lowered to determine the economic benefit, the effective cost of plutonium is automatically reduced. The 2020 cost varies from \$85/g without either LMFBR or CTR or Hybrid down to \$32/g with LMFBR and saturated hybrids.

A case was also solved to evaluate a ²³³U producing hybrid. This case introduced HTGR, but constrained the number of HTGRs to 20% of nuclear. The case used was without LMFBR and without CTR. The results are summarized in Table 8. The hybrid used was the electric power producing (0.40 MW_e/MW_t) medium fissile producing (1.0 kg/MW_t) model plant. The allowable capitalized cost was \$500/MW_t for a benefit of \$8 billion. This corresponds to approximately \$590/MW_t for an \$8 billion benefit in the case of the plutonium producing hybrid. The \$590 value was obtained by interpolating in Figure 2. Due to the large reduction in ²³³U shadow price, the allowable cost of the ²³³U producing hybrid would be expected to be higher than the Pu producing hybrid. This expectation is supported by comparing the zero benefit allowable costs, Table 9, with the allowable cost curves, Figure 2. The lower allowable cost for obtaining a benefit in the ²³³U case solution is caused by the 20% constraint on HTGRs (fewer plants can be affected, thus the savings per plant must be higher). This has an effect of spreading the groups of allowable cost curves for ²³³U producing hybrids.

TABLE 7. Plutonium Shadow Price in Year 2020

<u>\$ Billion Benefit</u>	<u>Case 1 LMFBR</u>	<u>Case 2 No LMFBR No CTR</u>	<u>Case 3 CTR</u>
0	58	85	82
5	40	71	65
10	35	60	50
15	32	56	50

TABLE 8. Summary of Thorium Case
Solution for Year 2020

	<u>Base Case</u>	<u>With Hybrid</u>
^{233}U Shadow Price	110	35
Installed LWR	1874	2133
Installed HTGR	467	523
Installed Hybrid		84
Objective Function	\$1101 Billion	\$1093 Billion

TABLE 9. Zero Benefit Allowable Cost for
 ^{233}U Producing Hybrid

<u>^{233}U Production (kg/MW_t)</u>	<u>Electrical Generation (MW_e/MW_t)</u>		
	<u>-0.20</u>	<u>0.01</u>	<u>0.40</u>
0.5	---	182	580
1.0	220	380	780
1.5	450	570	960

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APPENDIX A

ASSUMPTIONS REGARDING URANIUM AND SEPARATIVE
WORK COSTS AND LMFBR CHARACTERISTICS

URANIUM

Uranium costs have gone through a rapid price adjustment in the last two years far exceeding overall inflation. The present cost level is one more realistic estimate of future prices because the supply and demand, after many years of excess supply, are nearly in balance. Reports by EPRI⁽⁴⁾ and Battelle⁽⁵⁾ indicate that the sufficient quantity of uranium is available but at these higher prices. These reports and ERDA⁽⁶⁾ projections agree that as the rich ores are depleted, prices will rise still further. The Battelle simulation of the electric power economy⁽⁷⁾ utilizes a uranium price function which increases with total consumption in a step wise manner appropriating a smooth curve. The following cost steps are proposed for the analysis (Table 10). Because it is not known when the total consumption will reach a particular step, the current dollar costs are approximate.

TABLE 10. Proposed Uranium Function

Quantity, at price thousands tons U_3O_8	400	500	500	500	1000
Constant 1975 dollar, average price, \$/lb U_3O_8	16	20	25	40	60
Approximate year of use	1988	1996	2004	2016	2024
Approximate current dollar price, \$/lb U_3O_8 (8% escalation)	43	80	149	347	694

SEPARATIVE WORK

Historically the AEC and now ERDA have built and operated all the separative work facilities. However, during the period when hybrids may be available (1990-2000), this capacity will have been augmented by privately owned or new government facilities at substantially higher prices. Various reports^(8,9,10) have been in general agreement ($\pm 20\%$) on estimated costs for additional diffusion plants and centrifuge capacity. The centrifuge would seem to offer some advantage but has yet to be proven in any large

scale operation. Laser and other advanced separation processes are often reported but are even less proven and may take some time to bring into production.

Normally, the marginal producer of a commodity sets the market price. Thus, even if these new technologies are adopted for new plants, the price for SW will continue being set by the diffusion technology for some time (Table 11). Because the agreement in the estimates made by the various investigators is good, the EEI Committee estimates of costs escalated to 1975 are proposed to be used for the analysis. A tails composition of 0.3% ^{235}U is also proposed as the operating conditions.

TABLE 11. Proposed Separative Work Cost, \$/SWU

	Year			
	<u>1980</u>	<u>1990</u>	<u>2000</u>	<u>2010</u>
Constant 1975 dollars	85	85	85	85
Current dollars (escalated at 7%)	120	234	461	907

LMFBR PERFORMANCE

The recently published "Proposed Final Environmental Statement - LMFBR Program" represented the most recent projection of possible performance. However, a wide range of doubling times ranging from 7 to 28 years were considered with the reactor offer to the market from 1986 to 1992. Battelle proposes to use performance characteristics which are more conservative than the ERDA base case because we think the ERDA estimate is optimistic in time and breeding ratio.

In fact, more recent ERDA⁽¹¹⁾ estimates of LMFBR introduction as a commercial plant are now 1993 which we propose to adopt for this study. It should be noted that included in this study are cases where no breeder is available. The lowest doubling time will be held to 12 years represented by the "Advanced Oxide" design. As in the environmental impact statement, an "early commercial" plant will represent the LMFBR for the first six years. Table 12 contains a list of characteristics for these plants. It is proposed the LMFBR cost be held \$75/kW above LWR cost for the early plant and \$50/kW above LWR for the advanced oxide model.

TABLE 12. Plant Characteristics

<u>Design</u>	<u>Fuel</u>	<u>Availability Date</u>	<u>Core Burnup, MWD/MT</u>	<u>Maximum Linear Power kW/ft</u>	<u>Breeding Ratio</u>	<u>Simple Doubling Time, yr.</u>
Early oxide	PuO ₂	1993	110,000	16	1.15	28
Advanced oxide	PuO ₂	1999	110,000	18	1.25	12.5
Advanced Carbide	PuO ₂	—	110,000	31	1.46	7.4

Separative Work Costs

	<u>Year</u>			
	<u>1980</u>	<u>1990</u>	<u>2000</u>	<u>2010</u>
Constant 1975 Dollars				
Initial	85	85	85	85
Revised	76	75	70	65
Current Dollars				
Initial	120	234	461	907
Revised	106	205	405	800

U₃O₈ Cost Function

Quantity					
Thousand Tons U ₃ O ₈	400	500	500	500	1000
Final Year of Use	1988	1996	2004	2016	2024
Constant 1975 Dollars/lb					
Initial	16	20	25	40	60
Revised	18	20	25	40	60
Current Dollars/lb					
Revised*	34	80	171	591	
Revised**	50	100	232	938	

* For average year of use.

** For final year of use.