Performance Targets for Fusion-Fission (Hybrid) Reactors

**D. E. Deonigi
R. L. Engel**

January 1977

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PERFORMANCE TARGETS FOR FUSION-FISSION
(HYBRID) REACTORS

by
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January 1977

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SUMMARY

The potential roles for various performance levels of hybrid power plants in the United States have been estimated for various scenarios which describe the systems with which the hybrid plants must compete. Due to the uncertainty in estimating the costs of hybrid power plants, a parametric approach was chosen to identify acceptable characteristics and associated tradeoffs. Because hybrid power plants produce substantial quantities of both plutonium and electricity, a simulation model is necessary which appropriately values each of these products. This would permit design tradeoffs and realistic interactions with other generating plants, such as Liquid Metal Fast Breeder Reactors (LMFBRs) and Light Water Reactors (LWRs), to be estimated. A linear programming model nearly identical to that used for the recent LMFBR cost-benefit analysis was utilized for this purpose. Results for the reference case situation are shown in Table 1 for two different levels of national benefits (1975 dollars) in terms of the allowable capitalized plant cost relative to LWR costs. That is, a hybrid with 0.3 conversion efficiency and a plutonium prediction of 0.5 kg/year has an allowable cost 1.6 times that of an LWR. Benefits are defined as the difference between estimated present worth cost of providing electricity to the nation with and without the hybrid. This formulation is the same as that used in the LMFBR study, with the exception of a 15-year extension of time to year 2040. The allowable cost when benefits are zero represent the performance necessary to first enter the market. To achieve \$10 billion national benefit, the indicated improvements are required.

TABLE 1. Allowable Capital Costs for Reference Case (LWR Cost Equivalence)

Thermal-to-Electrical Conversion	\$Zero Benefits			\$10 Billion Benefits		
	Plutonium Production, kg/year			Plutonium Production, kg/year		
	0.5	1.0	1.5	0.5	1.0	1.5
0.3	1.6	2.0	2.3	1.3	1.6	2.1
0.0	0.4	0.8	1.1	0.1	0.4	0.6
-0.2	NA	0.4	0.7	NA	NA	0.3

During the study, nine separate scenarios were examined. However, the only scenario substantially different from the reference case was when the LMFBR was not utilized. The results of the target performance for this case are shown in Table 2. As can be seen, hybrid power plant costs without the breeder could rise 75 to 100% of that for the reference case and still produce \$10 billion in benefits.

This report does not analyze the potential of any specific hybrid design, but simply outlines targets for performance and performance tradeoffs to assist in optimal designing. With the allowable costs ranging from 1.3 to 2.4 times LWR for the designs which convert most thermal energy to electricity, performance targets may well be achievable. However, in the case of those designs which are net energy consumers, the allowable costs for capital and operation appear to be too small for any practical design. An intermediate area where no net electricity is consumed is of special interest to utility operators. It would not be part of the generating system and would simply be a plutonium factory with much tougher performance targets than those systems which capture a substantial amount of their electrical energy production.

TABLE 2. Allowable Capital Costs for Case Without LMFBR
(LWR Cost Equivalence)

Thermal-to-Electrical Conversion	\$Zero Benefits Plutonium Production, kg/year			\$10 Billion Benefits Plutonium Production, kg/year		
	0.5	1.0	1.5	0.5	1.0	1.5
0.3	1.8	2.3	2.8	1.7	2.2	2.6
0.0	0.5	1.0	1.5	0.4	0.8	1.2
-0.2	NA	0.4	0.9	NA	0.3	0.8

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PERFORMANCE TARGETS FOR FUSION-FISSION (HYBRID) REACTORS

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INTRODUCTION

This report analyzes the potential roles that fusion-fission (hybrid) could have in future electric generating systems of the United States. Unlike other power plants in use or under development, the hybrid produces not only electrical energy but also plutonium as a substantial by-product and, in some cases, the only product. Hybrid power plants could produce excess plutonium at rates about 10 times greater than breeder reactors per megawatt of thermal energy produced. Although breeders and light-water reactors (LWR) also produce plutonium, the plutonium revenues represent only a small fraction of the total electrical generating costs.

A wide range of hybrid designs have been proposed⁽¹⁾ ranging from plants which are called electric breeders because they actually consume electricity and only produce plutonium to plants which primarily produce electricity and have plutonium production rates only about equal to that of breeder reactors. This wide range of potential design characteristics and the uncertainty of the relative price of each product complicates examination of potential roles for hybrid reactors.

There is a wide range of potential scenarios (e.g., ERDA-76)⁽²⁾ which could substantially affect the value utilities would place on the plutonium produced and the electricity. Part of this paper will be devoted to describing the basis for estimating the performance of competing energy systems which, in turn, will set the scene for examining the hybrid role. Due to the wide range of preliminary designs and the uncertainty attached to the refinement of these designs, we chose a parametric approach for examining the hybrid role. To the degree possible, power plant models and cost basis for alternate systems will be consistent with the Liquid Metal Fast Breeder Reactor (LMFBR) cost-benefit analysis contained in the LMFBR final environmental impact statement.⁽³⁾

Many potential energy technologies which may prove feasible by the end of the century have been considered in this analysis.

- Fossil energy is restricted to the direct combustion of coal. (Low Btu gas conversion processes, if they exist, will represent an alternate technology to stack gas cleanup for high sulfur fuels.)
- Solar and geothermal energy systems are assumed to represent a small portion of the generating capacity by the turn of the century and are accounted for by adjusting the total electric demand in the same manner as employed in the breeder studies.
- Fission reactors will be represented in the form of LWRs and LMFBRs. The performance of these technologies will be consistent with that of the breeder studies. High Temperature Gas Reactors (HTGRs) are assumed to be available which, in turn, eliminates the potential investigation of hybrids with thorium blankets.
- Fusion power will be represented by the hypothetical design which is assumed to be marginally cheaper (5%) to operate than an LMFBR and introduced in year 2010.
- Fusion-fission (hybrid) technologies will be represented by a parametric fashion covering ranges of plutonium production and the efficiency of thermal-to-electrical energy conversion.

Details on the specific characteristics of the plants are included in the section titled "Inputs."

The objective of this report is to determine the range of allowable performance characteristics (capital costs, operating costs, plutonium production rate and thermal-to-electrical conversion) which will result in net benefits to the public through reduced electrical costs at levels ranging from zero to \$20 billion. These targets for performance will be established in light of nine different development scenarios for the remaining electric generating alternatives.

METHODOLOGY

The benefits of a research and development program must be estimated on the basis of competing alternative systems which are expected to be available at the time the hybrid technology is demonstrated. To accomplish this, attention must be paid to the cost of competing systems, while understanding the uncertainty that exists even in the cases of existing technologies. It is important to relate dynamically plutonium utilization and the ever-changing costs of electric generation. The linear programming model developed for analysis of the breeder program does this. The model formulation is reviewed in more detail later in this section.

This analysis not only assesses at what time and under what conditions the hybrid technologies would penetrate the market, but also establishes the performance criteria necessary to reduce electrical energy costs to the consuming public. The benefits desirable to support an R&D program would range from approximately 10 billion to 40 billion present worth 1975 dollars.

To establish the point of initial market penetration, a performance characteristic (assigned capital costs) that is too high for market penetration is made available to the simulation model at the selected date of first availability. Then, through a standard feature of linear programming known as reduced cost, the cost reduction necessary to gain entry is automatically calculated. The reduced cost is defined as the amount of cost reduction necessary to bring an alternative system into use in any given year. Subtraction of this reduced cost from the assigned cost then establishes the zero benefit market penetration point. As costs are lowered below this point, the market share given to hybrids will progressively increase, but at the same time will cause a distortion in the original scenario; i.e., plutonium prices will go down because additional supply is available. In most cases, further reduction of the cost parameter will increase use where plutonium consumption by all other systems is completely saturated. At this time the plutonium value would decrease appreciably and there would be no further need to build hybrid power plants. Thus, there is frequently a plateau that is reached which varies depending on the quantity of LWRs in existence and the system growth rate.

The same sequence of market penetration cases is performed for nine physical performance characteristic points parametrically selected to represent the range of plutonium production rates and electrical-to-thermal conversion for the hybrid (Table 3). The benefit to allowable capital cost relationship for each parametric set is derived by taking the difference between the total system operating costs in the case with no hybrid and the case with hybrids. The resultant savings represent the benefit of having the hybrid technology available.

As the benefits are not an exactly predictable outcome of the assigned hybrid capital costs, plots must be made in order to interpolate the capital costs to achieve a particular reference benefit. Figure 1 illustrates a particular set of parametric calculations. Based on a few additional calculations it appears that interpolation between the parametric points can be done linearly with little error. Extrapolation of the curves to the point of zero plutonium production represents the allowable capital costs of a pure controlled thermonuclear reactor (CTR) under the same conditions, which was also checked with a test case. For any given plutonium production rate, the demand for plutonium is progressively satisfied with fewer and fewer hybrid plants as the plutonium yield increases. Reductions in thermal-to-electrical efficiency progressively decrease allowable capital cost. For the electric consuming plant (-0.20% efficiency), some cases result in the obviously impossible situation of a plant with no allowable capital cost.

TABLE 3. Physical Characteristics of Parametric Cases

Thermal-to-Electrical Conversion	Plutonium Production Rate, kg/year		
	0.5	1.0	1.5
0.40	x	x	x
0.01	x	x	x
-0.02	x	x	x

FIGURE 1. Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability (with LMFB, 1993; with CTR, 2010)

The allowable performance characteristics for a hybrid plant are also affected markedly by the performance levels of alternative systems available in the same time frame. Table 4 summarizes this sequence of cases. Case 1 allows introduction of the breeder system in 1993. Other scenario assumptions include the energy demand rate, the uranium price and hybrid introduction dates. Details of the electrical energy demand and uranium cost portion of the scenario appear later in this report. The second case considers the absence of breeder technology but with a pure CTR beginning operation in 2010; while the third case considers the further absence of the CTR technology. Case 4, considered the reference case, allows the breeder in 1993 followed by the pure CTR in 2010. Cases 5, 6 and 7 follow the same pattern as Cases 1, 2 and 3 except the introduction date for the hybrid is advanced from the year 2000 reference date to 1990. A reduction in the energy demand growth rate is considered in Case 7 followed by a lower uranium price scenario in Case 8.

TABLE 4. Parametric Hybrid Analysis Cases

Date of LMFBR Availability ^(a)	Case								
	1	2	3	4(b)	5	6	7	8	9
20-Year Doubling	1993	--	--	1993	1993	--	--	1993	1993
12-Year Doubling	1996	--	--	1996	1996	--	--	1996	1996
Date of First CTR Availability	--	2010	--	2010	--	2010	--	--	--
Date of First Hybrid Availability	2000	2000	2000	2000	1990	1990	1990	2000	2000
Electrical System Growth Rate ^(c)	MH	MH	MH	MH	MH	MH	MH	Low	MH
Uranium Schedule ^(d)	EPRI	EPRI	EPRI	EPRI	EPRI	EPRI	EPRI	EPRI	EPRI

(a) LMFBR performance based on designs used for Fast Breeder Final Environmental Statement, WASH-1535.

(b) Referred to as reference case.

(c) Electric growth rate keyed to ERDA 1975 forecasts through year 2000 with a slight decline thereafter.

MH means moderate high.

(d) Cost of uranium based on WASH-1535 forecast as modified by EPRI Fusion Program Committee.

MODEL DESCRIPTION

A computer simulation⁽⁴⁾ that estimates the optimum pattern of future electrical supply was used to determine the target cost for fusion-fission hybrid. The simulation centers around the optimization of a model of the long-range development of the U.S. electrical generating industry on a multi-regional basis. The regionally dependent characteristics include coal and oil price, availability of alternate energy sources, energy demand and system load. Other characteristics, mostly related to the nuclear fuel cycle, are regionally independent, and are therefore represented nationally in the model.

The model simulates the electric utility decision process of determining when and what types of generating plants to build. The decision criterion is the minimization of present worth system cost subject to many decision-limiting constraints. Linear programming is the optimization technique because of its flexibility, its relative simplicity, and its widespread acceptance. Some nonlinear effects are handled outside the optimization model and inserted as linear segments.

The simulation can be used to predict future requirements, given a demand and cost factor scenario. The model can be used for evaluation of new generating alternatives by estimating costs of the new technologies and comparing results to a base case without the new alternative. Effects or regulations can be estimated such as the ban of plutonium recycle or increased safety in coal mining. In this analysis, target cost for fusion-fission hybrids is determined by altering the cost of a model hybrid plant until the desired effect is obtained.

The following are some of the activities that can be estimated over the time span of the simulation:

- Plant building estimates
- Capital requirements for each technology
- Uranium requirements
- Coal and oil required by the electrical sector
- Fuel processing requirements
- Material stockpiles
- Values of fuels.

The model is formulated to simulate a multi-regional schedule of building power plants that will supply projected energy requirements while also satisfying other constraints. The other constraints represent material balances, technological introduction rate constraints, fuel price step functions, committed plant construction, fuel processing capacity, technological phase-out constraints, market share constraints, and resource consumption constraints. Various groups of constraints are optional and will only be generated when requested.

The total electric power economy may be divided into several subsections, each with its own projected energy requirement constraints. These subsections have been used either to represent continuous geographic regions, or to represent limits of fossil power production price levels, ignoring the contiguous geographic region concept. In addition, fossil power production price levels within geographic regions may be represented. Nuclear plants then compete with non-nuclear plants for existence within each subsection, but only as a single category (i.e., total nuclear in a subsection). The competition between specific nuclear types is based on national competitions; they are not sited in a subsection.

In reality, the time variable is continuous over a range of a simulation. However, to make the problem fit a linear programming format, the time span is broken into a finite number of discrete time intervals. The time interval sizes, as well as the beginning and ending times, are variable and specified by the user. The interval size may even be changed in the range of time under study; for instance, time intervals of one year could be specified for the first 10 years, then relaxed to 2-year intervals for, say, 20 years, and then further relaxed to 5-year intervals. This allows for increased detail in the early part of the simulation. Up to three different time schedules may be specified, with different groups of constraints using different time schedules. If no time schedule is specified, one consisting of 2-year intervals, from 1970 to 2040 is generated.

VARIABLES

In this model, each variable represents an activity during a specific time interval, such as the amount of a fuel type used in year 1980 or the number of plants of a certain type built in 1978. The variables in the model may be subdivided into two general classes for discussion: independent variables and dependent variables. The independent variables represent the plants to be built, and the dependent variables represent the resulting effects from those plants, such as material balances, fuel usage, etc.

Each variable is represented in the linear programming (LP) matrix by a vector or column of coefficients. Each coefficient of an independent variable represents its effect on the constraint, while the dependent variables usually measure the status of a constraint and are commonly represented by a coefficient of ± 1 .

Independent Variables

Each independent variable represents the construction of a particular type of power plant in a particular discrete time interval. A type of plant is identified by the plant design, fueling scheme, and a predetermined lifetime load history. Currently, two load histories are allowed in the model. The model assumes that all plants constructed will start power production at the midpoint of the associated time period and will shut down only at the end of its lifetime. To date, all plants have had an assumed 30-year power producing lifetime.

Dependent Variables

The dependent variables measure some characteristic of the system of plants built. In addition to measuring the characteristic, the nonnegativity requirement of linear programming effectively constrains the model. For instance, variables measuring the plutonium stockpile require the stockpile to not become negative; thus the system of reactors built must produce plutonium before the plutonium may be used. The vector of coefficients representing a dependent variable is generally simpler than the vector for an independent variable and will usually have only one or two coefficients that are ± 1.0 . That is, the stockpile at the end of one time period is used for calculating the stockpile at the end of the next time period.

The following general classes of dependent variables can be generated under user control.

1. The amount of fuel consumed at each price level
2. Material balance and amounts of material purchased or sold outside the system
3. Fuel processing requirements
4. Fuel processing residuals
5. Total nuclear plants with a given load curve required in each subregion
6. A technology's construction capability.

CONSTRAINTS

Mathematically, constraints are used to define the region of feasibility of the model, and the solution algorithm will select the optimum solution from the feasible region. The constraints impose whatever physical conditions the user wishes to impose on the system being modeled. In this model, a constraint usually will impose a physical condition during a single time interval; thus each type of constraint is normally repeated for each time interval.

Power Demand Constraints

In the early development of this model, total installed capacity and total required energy were specified as well as a maximum installed non-nuclear capacity for each subregion, and the LP algorithm decided the most effective mixture of load histories within each geographic subregion. It was soon learned that this cost considerable computer time and resulted in nearly the same load mixture for each case. Thus the formulation was changed to treat the new plant building requirements of each load history in each region as exogenous input. This requirement must allow for both growth in energy requirements and in plants closing down and being removed from the system.

Fuel Usage Constraints

Fuel can be priced as a step function dependent on the amount of fuel used. That is, there is only a fixed amount available at a certain price.

After that amount is used, the next higher price must be paid. The model assumes the lower priced ore will be used first. Ore at the last price step is assumed unlimited, thus it is not constrained.

Material Balance Constraints

One constraint is required for each isotope stockpile in each time interval. The constraint is merely that the stockpile at the end of a time period is equal to the stockpile from the previous time period plus the net effect (discharged less charged) of all plants affecting the stockpile during the time interval concerned, plus any purchased and less any sold outside the system. For nuclear plants, certain fissile materials have been constrained. Up to three isotopes may be combined in a single stockpile, with an assumed mixture used for calculating radioactive decay. For example, ^{239}Pu and ^{241}Pu have commonly been combined as a fissile plutonium stockpile, with the assumption that the combined stockpile is 10% ^{241}Pu . This constraint not only evaluates the stockpile, but the nonnegativity condition of linear programming constrains the model to maintain a nonnegative stockpile at the end of each interval.

Fuel Processing Residual Stockpile Constraint

Stockpile constraints will be generated only when requested by the user. They should be used only when a by-product of a fuel processing plant can be used as fuel in certain plants, such as depleted uranium or perhaps a heavy residue from a refinery. One constraint is required for each time period. This formulation differs slightly from the material balances since a deficit of residual material may be satisfied by the substitution of natural fuel. In other words, these equations merely calculate the amount of residual stockpile or the amount of fuel required to replace the residual requirements, rather than constrain the tails stockpile to a nonnegative value.

Fuel Processing Constraints

Two constraints per time interval are required for the formulation of the fuel processing constraints. To allow preprocessing of fuel, a stockpile of preprocessed fuel is maintained. One constraint stipulates that the change

in the preprocessed fuel stockpile in a time interval is equal to the difference between the processing performed in the time interval and the amount required by all plants operating in the time interval. The other constraint limits the amount of processing that can be performed during a time interval. The limit must be specified by the user and simulates the projected capacity of all processing plants. The limit may be expressed as a function of time to allow for plant expansion and/or addition of new plants. These constraints are optional and are generated only when specified by the user.

Technology Introduction Constraints

The purpose of the technology introduction constraints is to limit the introduction rate of classes of plants and to simulate the limited capability of a new industry. These constraints are formulated such that the number of plants of a class built in a time period must not exceed the number built in the previous period multiplied by some growth factor plus a constant. These introduction constraints are optional and completely flexible. The user must specify which reactors are included in a class, in which time intervals the class is constrained, the multiplier and addition factors.

Present Commitment Constraints

The committed construction constraints are used to fix the number of nuclear plants that are under construction or on order in each region. This constraint also effectively fixes the number of non-nuclear plants to the difference between the total requirement and the committed number.

Technology Phaseout Constraint

One constraint is generated for each time period for each technology constrained. A variable is introduced that represents the new construction capability for a technology. The basic assumption is that construction capability has a 14-year lifetime. This constraint has a smoothing effect on the number of plants of a given technology that are built. This constraint will simulate an existing technology's unwillingness to stop production, and also the caution that a corporation displays when entering a new technology. The new plant construction capability will not enter the solution unless it is economical to stay in for the 14-year lifetime.

Market Share Constraints

Constraints may be generated to limit a technology to a share of the market, such as when a single reactor vendor is promoting a technology. The market share constraints are used to limit a power plant technology class to some fraction of other technologies.

Resource Consumption Constraint

Constraints can be generated to limit the amount of a resource used in either of two ways. The first formulation is a single constraint that limits the number of plants built in a time interval so that the resources used by those plants over their operating lifetimes does not exceed a specified amount. The time interval here probably would be taken as the model lifetime.

The other formulation limits the amount of a resource used by all plants from the start of the model up to the end of each time period. The limit may be input as a function of time, thus simulating the discovery of resource over time.

OBJECTIVE FUNCTION

The objective function is the measure of the optimization and is used to determine the best basic solution to the set of constraints defined previously in this report. In this model, the objective function is the total present worth of the cost of building and operating all the plants from some specified beginning time to a specified ending time, using the conditions specified by the user. Since the objective is to minimize cost, costs are positive and income is negative. The starting time, ending time, and discount factor are specified by the user. Up to 40 objective functions may be generated, but only one at a time may be optimized. The alternate objective functions are then merely evaluative, but may be used for optimization by employing controls built into the LP solution system.

Plant Cost Coefficients

The single cost coefficient for a plant represents the total cost to build a plant and operate it for its entire lifetime or until the end of the problem,

whichever occurs first, minus the costs that are charged in other parts of the model. The costs charged in other parts of the model may be those isotopes stockpiled and fuel purchase and fuel processing already discussed in this report. Stockpiled material required is charged indirectly by forcing the system to be modeled to either produce its own material or purchase it from outside the system.

End effect can cause some unreasonable results near the end of the modeled time span. Two alternate methods are available to determine an equitable cost for plants operating beyond the end of the problem. The first is simply to use the total lifetime cost even if costs occur beyond the model time horizon. The second alternative is to prorate the cost so that the discounted cost per discounted energy is constant, regardless of the number of operating years included in the model time span. That is, if a plant with expected lifetime of L years will operate only N years, $N < L$, then

$$\frac{\sum_{i=1}^N PWC_i}{\sum_{i=1}^N PWE_i} = \frac{\sum_{i=1}^L PWC_i}{\sum_{i=1}^L PWE_i} \quad (1)$$

where

PWC_i = present worth cost in year i.

PWE_i = present worth energy generated in year i.

Present worth is based on the midpoint of the year the item is incurred.

It is assumed that the total revenue for a plant is equal to the total expense. The total expense is calculated so that total expense, less gross revenue tax and state and local income taxes, is equal to the initial capital, plus the sum of the yearly expenses and revenue on equity. The yearly expenses for a plant include:

1. Fuel purchases (U_3O_8 , Th, ^{233}U , and Pu, or fossil fuel)
2. U_3O_8 to UF_6 conversion
3. Fabrication
4. Reprocessing
5. Fuel enrichment
6. Fuel shipping
7. Fixed operating and maintenance expenses (includes nuclear liability insurance and property insurance)
8. Variable operating and maintenance (includes property tax)
9. Interim capital replacements.

The coefficient in the objective function is then the total expense less those costs charged in some other part of the model. The reason for adding all costs and then backing out certain costs is to get the correct tax calculation. The cost details are discounted to the startup of the plant, then the total coefficient is discounted to the initial time t_0 .

INPUT ASSUMPTIONS

The model input requirements are presented in four categories as discussed in the model description.⁽⁴⁾ The four categories are:

1. Problem definition parameters
2. Regional energy demand
3. Cost estimates
4. Plant fuel data

PROBLEM DEFINITION PARAMETERS

The model time bounds were from 1968 to 2060, using 2-year intervals until year 2000 and then 5-year intervals. The 1968 to 1975 time interval is included to allow for the backlog of nuclear spent fuel. The plants prior to 1975 have zero cost. The optimization was based on total system cost from 1975 to 2060, discounted at 8.8%. The benefit was computed using total system cost from 1975 to 2040 discounted at 7.5%, excluding income and revenue taxes. Costs are in 1975 constant dollars. The regional structure consisted of three fossil fuel price levels in each of the nine National Electric Reliability Councils (NERCs) shown in Figure 2.

The following optional constraints were specified for all cases:

Material balance constraints were generated for fissile plutonium.

Fossil minimization constraints were generated that forced fossil plant construction to at least 10% of the total construction in each NERC region.

Committed light-water reactor constraints were generated for each NERC region through 1983.

New technology introduction constraints were generated for the first 8 to 10 years of availability for the LMFBR, CTR, and the fusion-fission hybrid.

Technology phaseout constraints were generated for LWRs.

Import/export constraints. Uranium and fissile plutonium were not allowed to be imported or exported.

WSCC - Western Systems Coordinating Council	ECAR - East Central Area Reliability Coordination Agreement
MARCA - Mid-Continent Area Reliability Coordination Agreement	SERC - Southeastern Electric Reliability Council
SWPP - Southwest Power Pool	MAAC - Mid-Atlantic Area Coordination Agreement
ERCOT - Electric Reliability Council of Texas	NPCC - Northeast Power Coordinating Council
MAIN - Mid-America Interpool Network	

FIGURE 2. Regional Electric Reliability Councils in the United States

REGIONAL ENERGY DEMAND

A major input category is the regional energy demand. Energy demand is represented in this model as a plant building schedule for new thermal generating plants within each geographic region, assuming plant operation at either of two predetermined load factor curves. Two load history curves were used in this study as shown in Table 5. The number of plants at each load to be built is input to the model generation such that the model system load factor is achieved.

TABLE 5. Two Load Factor Curves

<u>Time (Years)</u>	<u>Base Load</u>	<u>Load Following</u>
0	0.35	0.20
3.0	0.70	0.50
15.0	0.70	0.50
30.0	0.40	0.20

Determination of the regional plant building schedule started with the 1975 ERDA⁽⁵⁾ forecast through year 2000, with a slightly reduced growth rate after year 2000. Most of the cases in this analysis used the moderate high forecast, and one case used the low demand forecast. This analysis is concerned with future thermal power plants, so the total demand requirements are next reduced by hydroelectric plants and by internal combustion generators and by their forecasted energy production (Tables 6 and 7).

The net thermal electrical requirements are then allocated to NERC regions based on normalized individual NERC forecast⁽⁶⁾ (Table 8). The regional thermal electrical requirements are then reduced by the remaining operational fossil plants built between 1940 and 1970. These net new thermal requirements are then input to a computer program that determines the number of plants of each plant load history to build in each time period. This computer program uses a gradient optimization technique that minimizes the sum of the annual absolute error in regional system load. Finally, the plant building schedule is input to the LP matrix generator and forms the plant building requirements.

COST ESTIMATES

The number of plants to be built is input to the LP model, so the purpose of the LP optimization is to determine the least cost mix of plants that satisfies this requirement. The input cost assumptions are, therefore, critical to the decision process. The following cost assumptions are made. All costs are in 1975 constant dollars.

TABLE 6. Moderate High Electric Demand Forecast

Year	Total Electric Demand				I/C(b)		Hydro		Net Thermal		Load Factor (%)
	TWh (a)	GWe	Load Factor (%)	Average Annual Growth, %	TWh	GWe	TWh	GWe	TWh	GWe	
1980	2,675	630	48.5	5.4	56	53	300	75	2,319	502	52.7
1990	4,820	1,075	51.2	5.5	71	70	380	110	4,369	895	55.7
2000	8,600	1,900	51.7	5.9	92	105	530	150	7,980	1,650	55.2
2010	14,200	3,140	51.7	5.2	115	130	580	165	13,500	2,850	54.1
2020	23,000	5,080	51.7	4.9	150	170	580	165	22,300	4,750	53.5
2030	33,600	7,420	51.7	3.9	190	220	580	165	32,800	7,030	53.3
2040	49,000	10,800	51.7	3.8	245	280	580	165	48,200	10,400	52.9

(a) Trillion watt hours

(b) Internal combustion and gas turbine power plants.

TABLE 7. Low Electric Demand Forecast

Year	Total Electric Demand				I/C ^(b)		Hydro		Net Thermal		Load Factor (%)
	TWh ^(a)	GWe	Load Factor (%)	Average Annual Growth, %	TWh	GWe	TWh	GWe	TWh	GWe	
1980	2,570	605	48.5	4.8	54	51	292	725	2,224	481	52.8
1990	4,400	960	51.3	4.7	64	64	355	99	3,980	800	56.8
2000	7,020	1,550	51.7	4.9	74	74	438	125	6,510	1,351	55.0
2010	9,900	2,200	51.7	3.6	84	84	438	125	9,380	1,990	53.8
2020	14,000	3,100	51.7	3.5	94	94	438	125	13,500	2,880	53.5
2030	20,000	4,400	51.7	3.5	104	104	438	125	19,500	4,170	53.4
2040	28,000	6,200	51.7	3.5	114	114	438	125	27,400	5,960	52.5

(a) Trillion watt hours

(b) Internal combustion and gas turbine power plants.

TABLE 8. Regional Allocation Percentages Derived from NERC Forecasts Reported to Federal Power Commission

	<u>1970</u>	<u>1980</u>	<u>1990</u>	<u>2000</u>
ECAR	15.4	14.8	13.1	12.2
WSCC	17.7	18.8	18.3	18.9
MARCA	3.6	3.5	3.3	3.2
NPCC	11.4	9.5	8.9	8.1
SWPP	7.7	8.3	9.7	11.4
MAAC	10.0	8.6	7.6	6.8
MAIN	7.7	7.7	7.6	7.3
SERC	19.9	21.5	24.2	24.1
ERCOT	6.6	7.3	7.3	8.0

Capital cost is especially sensitive to the decision process, especially the difference in capital cost between different technologies. The capital cost assumptions are shown in Table 9. The increment between LMFBR and LWR is \$150/kWe, reducing to \$100 in year 2000. This increment is initially higher than ERDA's LMFBR Final Environmental Impact Statement⁽³⁾ as recommended by the EPRI Fusion Program Committee. The pure CTR capital was selected to just make the CTR competitive with the LMFBR, since reliable cost estimates for the CTR are not available. Only a single LWR capital cost is used over all regions, while the fossil plants can have different capital costs in each region. Therefore, the regional increment between fossil and LWR capital is maintained by normalizing the fossil capital cost for regions. The determination of the allowable capital cost for the fusion-fission hybrid is the result of this analysis, so it is modified parametrically until the desired effect is obtained.

Assumed nonfuel maintenance and operations costs are presented in Table 10. Variable costs apply to a full power (100% load factor) year. Both fixed and variable costs are consistent with LMFBR cost-benefit studies.

Fuel and fuel processing costs are also important costs assumptions. An important feature of this model is that nuclear fuel, both natural uranium and

TABLE 9. Capital Cost, \$/kWe (1975 Dollars)

<u>Year</u>	<u>LWR</u>	<u>LMFBR</u>	<u>CTR</u>	<u>Fossil</u>				
				<u>ECAR</u> <u>NPCC</u>	<u>WSCC</u> <u>SWPP</u>	<u>MARCA</u> <u>SERC</u>	<u>MAIN</u> <u>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	770	540	546	552	561	536

TABLE 10. Operations and Maintenance Costs
Million Dollars per Year per
100 MWe Plant (1975 Dollars)

	<u>Fixed</u>	<u>Variable</u>
Fossil	10.5	21.79
LWR	6.34	3.53
LMFBR	6.73	3.16
CTR	6.6	3.3
Fusion-Fission	6.73	3.16

fissile materials, do not have to be input as a function of time. Uranium cost is specified as a function of the amount consumed. Fissile material stockpile constraints require that fissile is produced by the system before it can be consumed, so these prices are established by the cost of producing plants in the current solution of the model. Two uranium cost functions were used in this analysis, a reference and a low price function (Table 11). As recommended by the EPRI Fusion Program Committee, our reference price is slightly higher for the first 4 million tons and then equal to the reference case in ERDA's fast breeder environmental impact statement⁽³⁾ and our low price case is identical to ERDA's large U_3O_8 supply case. Nuclear fuel processing costs are presented in Table 12. Most of the fuel cycle costs are

TABLE 11. Natural Uranium Cost by Amount Consumed

Reference Case		Low Price	
Cost, \$/lb	Availability Million Tons	Cost, \$/lb	Availability Million Tons
18	0.4	15	1.0
20	0.5	20	1.0
25	0.5	24	1.0
40	0.5	28	1.0
60	1.0	40	1.0
80	1.0	55	1.0
100	1.0	70	1.0
110	1.0	80	1.0
120	1.0	95	1.0
125	Unlimited		

based on bids supplied to utilities during 1975. Fossil fuel costs for each NERC are shown in Table 13. These costs are developed from 1975 FEA data.⁽⁷⁾ The percent of total demand in each region that may be satisfied by each fossil price is based on historical price distributions.

DISCOUNT RATES

Discount rates play two separate roles in the analysis of hybrids. The first role is that of simulating the utility decision process, which applies the time value of money in Equation (1) to estimate the total cost of each alternative energy system. For this purpose, the correct discount rate is derived from the average cost of money to the utility industry. Unfortunately, the cost of money to utilities is not an easily predicted quantity and varies from utility to utility based on their bond rating and tax status. The use of historical cost of money over the last 50 years as a guide to projecting the next 50 years is fraught with problems of dealing with war years, a great depression, etc. and would result in very low discount rates compared with utility experience over the past 10 years. The 10-year average bond interest rate has been about 7.3%, while return on equity is approximately 11%. Using

TABLE 12. Fuel Processing Cost Estimates (1975 Dollars)

Year	LWR							Uranium Conversion, \$/kg	Uranium Enrichment, \$/SWU
	Fabrication		Reprocessing, \$/kg	LMFBR					
	Self-Produced	Full		Fabrication, \$/kg	Reprocessing, \$/kg				
	Recycle, \$/kg	Recycle, \$/kg							
Uranium, \$/kg	Uranium, \$/kg	Recycle, \$/kg	Reprocessing, \$/kg	Fabrication, \$/kg	Reprocessing, \$/kg	Uranium Conversion, \$/kg	Uranium Enrichment, \$/SWU		
1975	102	---	---	168			2.12	32	
1980	95	138	242	156			2.12	76	
1990	79	106	169	133	350	156	2.12	75	
2000	62	84	134	127	226	153	2.12	65	
2010	56	72	110	125	187	152	2.12	65	
2020	50	65	99	123	176	151	2.12	65	

TABLE 13. 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
power plant file.

these rates for the cost of capital, an effective discount rate of 8.8% is derived. It is this discount rate that is used in this study to simulate utility decisions.

The second role of the discount rate is that once the optimum decision is determined using the 8.8% rate for utilities, the benefits (system cost reduction) derived from the new technology availability over a period of time is accumulated. This is done at a different rate, which is the time value of money considering alternative uses outside of the utility industry. This subject is discussed in both the final environmental statement for the LMFB program⁽³⁾ and final generic environmental statement on plutonium recycle.⁽⁸⁾ Each study concluded that a specific value is impossible to measure and thus recommended values of from 4 to 10%. To allow consistency and comparisons with other studies, the base discount rate was chosen at 7.5%. Some comparisons use a 10% discount rate consistent with the Office of Management and Budget for all government cost-benefit studies.

The following additional financial assumptions were made based on national averages for utilities.

Annual Property Insurance Rate	0.0025
Annual Property Tax Rate	0.0320
Federal Income Tax Rate	0.50
State Income Tax Rate	0.03
Gross Revenue Tax Rate	0.04
Bond Interest Rate	0.073
Return on Investment	0.110
Fraction Bonds	0.60

PLANT FUEL DATA

The nuclear fuel cycles that were allowed as alternatives are presented in Table 14, along with their availability date. The physical fuel requirements of each major alternative energy system are summarized in Table 15. The hybrid is treated parametricly and thus shows only a range of characteristics.

Fossil plants were allowed in all time periods with an assumed heat rate of 9000 Btu/kWh. All power plants are assumed to have a 30-year useful life.

Many variations in detailed fuel cycle options are included which involve switching among LWR cycles every 10 years (i.e., 10 years on uranium fuel, then 20 years on self-produced recycle).

TABLE 14. Nuclear Fuel Cycles Allowed

<u>Availability Date</u>	<u>Fuel Cycle</u>
1968	LWR - Uranium Cycle
1977	LWR - Self-Produced Plutonium Recycle
1984	LWR - Full Recycle
1993	LMFBR - (20-Year Doubling)
1996	LMFBR - (12-Year Doubling)
2010	Pure Fusion

TABLE 15. Physical Characteristics of Alternative Energy Systems Potentially Available in 2000

	<u>LWR Uranium</u>	<u>LWR Plutonium</u>	<u>LMFBR</u>	<u>CTR</u>	<u>Hybrid</u>	<u>Coal</u>
Annual Plutonium Yield, kg/MWt	0.069	-0.128	0.142	0	0.5→1.5	0
Initial Plutonium Requirements, kg/MWt	0	0.403	0.684	0		
Annual U ₃ O ₈ Required, tons/kWt	0.075	0.012	0.001		0	
Annual Separative Work Required, kg/MWt	48	2.3	0.080		0	
⁶ Li (Annual), kg	0	0	0	140	~50	0
Annual Nuclear Fuel Processed, kg/MWt	12	12	9.5	0	~20	0
Tons Coal (Lifetime), tons/MWt						18 Thousand
Electrical-to-Thermal Efficiency	0.325	0.325	0.38	0.40	-0.20→0.40	0.40

RESULTS

This analysis has determined the allowable capitalized cost for fusion-fission hybrid systems for a range of economic benefits (total system cost reduction). The nine scenarios are as summarized in Table 16. A scenario represents a combination of assumptions about energy demand, uranium price, and availability dates of new technologies. All scenarios assume fossil and LWR technologies with self-produced plutonium recycle in 1978.

TABLE 16. Summary of Nine Scenarios

<u>Case</u>	<u>Availability Date</u>			<u>Energy Demand</u>	<u>U₃O₈ Price</u>
	<u>Fusion</u> <u>Fission</u>	<u>LMFBR</u>	<u>CTR</u>		
1	2000	1993		Moderate High	Reference
2	2000		2010	"	"
3	2000			"	"
4	2000	1993	2010	"	"
5	1990	1993		"	"
6	1990		2010	"	"
7	1990				
8	2000	1993		Low	"
9	2000	1993		Moderate High	Low

Since this analysis did not deal with any specific fusion-fission design, fuel cycle data were not developed. Fuel cycle processing costs are, therefore, capitalized for this study.

The fusion-fission capitalized costs include plant cost, fuel cycle expense except purchase and sale of nuclear material, and interim capital replacements. It can be written:

$$C = P + \sum_{i=1}^L (1+r)^{-i} (F_i + R_i) \quad (2)$$

where

C = Capitalized

P = Plant cost

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

L = Plant lifetime (30 years in this analysis)

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 replacement, 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 fuel cycle expense, a fuel cycle expense of \$1/kWt year is equivalent to a capital cost of \$9.8/kWt. When evaluating a hybrid design, the estimated plant cost should be increased by the sum of the discounted interim capital replacements in Equation (2) and by either the estimated fuel cycle expense (\$/kWt) multiplied by 9.8 or by the summation of discounted fuel cycle expense as expressed in Equation (2).

The allowable capitalized costs can be used to evaluate specific fusion-fission designs. Design tradeoffs between electrical production and fissile production can be established. To cover the full range of possible hybrid

designs, the thermal-to-electrical efficiency ranged from a high of 0.4 down to a model electric breeder with -0.2. The range of fissile production was zero to 1.5 kg/kWt.

The allowable capitalized costs are presented in Figures 3 through 11 for the nine different scenarios. Each single curve represents the allowable cost for a specified benefit and a single thermal-to-electrical efficiency as a function of fissile production. Each group of curves cover the range of benefits for a single efficiency. Fixing a benefit, interpolation on efficiency is possible, or fixing an efficiency, interpolation on benefit is possible. From these figures, design tradeoffs between initial system cost, operating costs, plutonium production rate, and net electric efficiency can be evaluated. Experiments with additional design points have verified that simple interpolation between data points is quite satisfactory.

In Figure 12 this concept is applied to a mirror plasma confinement concept reported by Moir.⁽⁹⁾ The curves are the breakeven (zero benefit value) for various electric efficiencies. Point A on Figure 12 shows the design location using Moir's cost estimate with A' indicating the allowable cost for fusion-fission concept application in the reference case situation. An alternative design point where more fissile material is produced is indicated by Point B and its associated cost requirement by B'. As can be seen, the design with lower plutonium production is very nearly at an acceptable level, whereas the electric breeder design is substantially off the target value and would require considerable cost reduction to be chosen by the simulation model.

In general, the easier the competition, the higher allowable cost for fusion-fission. This is illustrated by data in Table 17, where allowable costs for nine scenarios and for all of the fusion-fission parameter combinations are presented for a single benefit of \$10 billion. Tables 18A and 18B present the same information in terms of multiples of LWR cost. Cases 3 and 7, with neither CTR nor LMFBR competition, provide the highest allowable cost (ranging from \$525/kWt to \$850/kWt for the 0.40 MWe/MWt, with Case 7 slightly higher because the hybrid is available 10 years sooner; thus a higher cost is allowed that provides the same benefit). Next highest

FIGURE 3. Case 1 - Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability (with LMFB, 1993; No CTR)

FIGURE 4. Case 2 - Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability (with CTR, 2010; No LMFBF)

FIGURE 5. Case 3 - Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability (No LMFB; No CTR)

FIGURE 6. Case 4 - Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability (with LMFBR, 1993; with CTR, 2010)

FIGURE 7. Case 5 - Allowable Capitalized Fusion-Fission Cost with Year 1990 Availability (with LMFBR, 1993; No CTR)

FIGURE 8. Case 6 - Allowable Capitalized Fusion-Fission Cost with Year 1990 Availability (with CTR, 2010; No LMFBF)

FIGURE 9. Case 7 - Allowable Capitalized Fusion-Fission Cost with Year 1990 Availability (No LMFB; No CTR)

FIGURE 10. Case 8 - Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability - Low Energy Demand (with LMFB, 1993; no CTR)

FIGURE 11. Case 9 - Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability - Low Uranium Price (with LMFB, 1993; No CTR)

FIGURE 12. Allowable Capitalized Cost for Fusion-Fission Systems (Year 2000) that Yield Zero Benefit (with LMFBR, 1992; with CTR, 2010)

TABLE 17. Allowable Capitalized Cost for Fusion-Fission that Yields
\$10 Billion Benefit (\$/kwt)

Pu Production, kg/Mwt	Mwe/Mwt	1	2	3	4	5	6	7	8	9
0.5	0.40	LMFBR 1993 No CTR 2000 Availability	No LMFBR CTR 2010 2000 Availability	No LMFBR No CTR 2000 Availability	LMFBR - 1993 CTR 2010 2000 Availability	LMFBR 1993 No CTR 1990 Availability	No LMFBR CTR 2000 1990 Availability	No LMFBR No CTR 1990 Availability	Low Demand LMFBR 1993 No CTR 2000 Availability	Low U Cost LMFBR 1993 No CTR 2000 Availability
1.0		415	480	530	415	425	500	545	375	385
1.5		470	600	680	500	510	625	685	430	435
1.5		550	710	810	640	610	760	810	500	480
0.5	0.01	20	90	125	45	50	110	135	10	25
1.0		85	225	255	100	135	240	270	90	80
1.5		225	340	380	190	230	335	395	125	140
0.5	-0.20	NA	NA	NA	NA	NA	NA	NA	NA	NA
1.0		NA	50	85	NA	NA	55	100	NA	NA
1.5		40	195	240	100	90	185	240	50	20

NA - NOT Acceptable - allowable cost less than zero.

TABLE 18A. Allowable Capital Cost (LWR Equivalence) for Fusion-Fission that Yields \$10 Billion Benefit at 7.5% Discount Rate

Pu Production, kg/MWt	MWe/MWt									
		1	2	3	4	5	6	7	8	9
		LMFBR 1993 No CTR 2000 Availability	No LMFBR CTR 2010 2000 Availability	No LMFBR No CTR 2000 Availability	LMFBR - 1993 CTR 2010 2000 Availability	LMFBR 1993 No CTR 1990 Availability	No LMFBR CTR 2000 1990 Availability	No LMFBR No CTR 1990 Availability	Low Demand LMFBR 1993 No CTR 2000 Availability	Low U Cost LMFBR 1993 No CTR 2000 Availability
0.5	0.40	1.3	1.5	1.7	1.3	1.4	1.6	1.8	1.2	1.2
1.0		1.5	1.9	2.2	1.6	1.6	2.0	2.2	1.4	1.4
1.5		1.8	2.3	2.6	2.1	2.0	2.5	2.6	1.6	1.5
0.5	0.01	0.06	0.3	0.4	0.1	0.2	0.4	0.4	0.03	0.08
1.0		0.3	0.7	0.8	0.4	0.4	0.8	0.9	0.3	0.2
1.5		0.7	1.1	1.2	0.6	0.7	1.1	1.3	0.4	0.4
0.5	-0.20	NA	NA	NA	NA	NA	NA	NA	NA	NA
1.0		NA	0.2	0.3	NA	NA	0.2	0.3	NA	NA
1.5		0.1	0.6	0.8	0.3	0.3	0.6	0.8	0.1	0.06

NA - Not Acceptable - allowable cost less than zero.

Allowable Capital Cost (LWR Equivalence) for Fusion-Fission that Yields \$10 Billion Benefit at 10% Discount Rate

Pu Production, kg/MWt		MWe/MWt													
0.6	0.40	1		1		1		1		1		1		1	
1.0		1.1		1.2		1.1		1.2		1.1		1.2		1.1	
1.5		1.2		1.5		1.7		1.5		1.4		1.6		1.3	
0.5	0.91	NA		0.96		0.2		0.3		0.36		0.2		NA	
1.0		0.1		0.3		0.6		0.6		0.3		0.7		0.06	
1.5		0.6		0.7		0.9		0.2		0.7		0.9		0.2	
0.5	-0.20	NA		NA		NA		NA		NA		NA		NA	
1.0		NA		NA		NA		NA		NA		NA		NA	
1.5		NA		0.2		2.4		NA		0.03		0.5		NA	

NA - NOT Acceptable - allowable cost less than zero.

allowable cost ranging from \$475/kWt to \$640/kWt for 0.40 MWe/MWt are the cases with CTR and without LMFBR, Cases 2 and 6. Although the CTR cost was set to be competitive with LMFBR in 2010, the later CTR availability provides a higher allowable hybrid cost. Case 6 with the earlier hybrid availability is again slightly higher. The cases with LMFBR provide the lowest allowable cost ranging from \$375/kWt to \$640/kWt for 0.40 MWe/MWt. Of the LMFBR cases, Cases 8 and 9 with lower energy demand and lower uranium cost respectively provide the least opportunity for the hybrid. An interesting point is illustrated by Case 4 compared to Case 1. In Case 4, even though there is additional competition because pure fusion is available, the hybrid target cost is higher. This is because the CTR has forced out the LMFBR, yielding a better plutonium market.

In the reference case, a window in time exists for the hybrid power plant between its approximate time of introduction in year 2000, when plutonium supplies are still short, and the time of introduction of the pure fusion technology. After the pure fusion alternative is available, there is still a strong continuing need for fissile material supplied to the large number of light-water reactors in operation by year 2000. Figure 13 shows the impact on the reference case of introducing hybrids in year 2000 with a relatively high electrical efficiency (0.4 MWe/MWt) and an annual yield of 1.0 kg of fissile plutonium/MWt. The number of hybrids built was quite small due to the availability of the pure CTR only 10 years after the availability of the hybrid. However, the effect is significant; 30% more LWRs operating in year 2020 using hybrid-produced plutonium, yielding a \$10 billion electrical system benefit.

The number of fusion-fission plants that would be operational in year 2030 to yield the \$10 billion benefit is presented in Table 19. Generally, more hybrids are required to yield the \$10 billion benefit in the cases where LMFBR is available with a lower allowable cost for hybrid. In the cases with less competition, \$10 billion benefit can be obtained with fewer plants. In other words, when competition is less, more benefit is obtained per plant, even when the plant cost is higher.

FORECASTED OPERATING ELECTRIC GENERATION CAPACITY FOR THE REFERENCE CASE

FORECASTED OPERATING ELECTRIC GENERATION CAPACITY WITH HYBRID

FIGURE 13. Impact of Hybrid on Plants Operating in Reference Case (Hybrid Production Parameters - 0.4 MWe/MWt and 1.0 kg/MWt, Yielding a \$10 Billion Benefit)

Number of Fusion-Fission (2500 Mwt) Plants Operating in Year 2030 when Benefit is \$10 Billion.

Pu Production, kg/MWt		MWe/MWt																				
0.5	0.40	1500	460	600	400	1000	400	500	1000	500	1000	1500										
1.0														970	220	450	190	190	180	350	640	1050
1.5														600	130	280	140	150	130	250	450	700
0.5	0.01	2500	800	1000	700	700	500	900	1700	2750												
1.0														1050	310	550	250	310	260	300	860	1270
1.5														500	160	340	200	180	180	250	520	920
0.5	-0.20	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA										
1.0														NA	260	450	NA	NA	300	550	NA	NA
1.5														600	160	400	130	110	180	500	580	1050

NA - Not acceptable - allowable cost less than zero.

Table 20 presents the ratio of LWRs to fusion-fission plants for all nine scenarios. When the market is saturated with fusion-fission plants, the ratio is about 2, 4, and 6, respectively, for fissile production rates of 0.5, 1.0, and 1.5 kg/MWt. Higher ratios indicate that the market is not saturated. This high ratio occurs frequently in the cases where LMFBR is not available and in cases with earlier fusion-fission availability, again because the \$10 billion benefit is easier to attain.

Figure 14 shows the unit cost over time for uranium and fissile material for the reference case. The leveling off of these costs is the result of the introduction of the breeder reactors and eventually the CTRs after the turn of the century. The marginal value of plutonium is a result of the calculation optimizing this model. The marginal value is dependent on both the cost of plants that produce it and the value to plants that use plutonium. The marginal value in year 2030 is presented in Table 21 for all nine scenarios, for both the base case (without fusion-fission) and the \$10 billion fusion-fission benefit. The plutonium value in cases with \$10 billion benefit is about \$70 to \$85/g without the LMFBR and about \$30 to \$45/g in cases with the LMFBR. The plutonium value in the base cases (without fusion-fission) is \$88 to \$89/g in cases without the LMFBR and ranges from \$45 to \$57/g in cases with the LMFBR. In the case with both LMFBR and CTR (Case 4), the plutonium marginal value is \$75/g, because the LMFBR, the plutonium producer, is replaced by the CTR by year 2030.

The amount of uranium consumed by year 2030 is presented in Table 22 for all nine scenarios. With LMFBR, 4.6 million tons is consumed in cases without fusion-fission, and with the fusion-fission from 2.8 to 4.2 million tons are consumed. Fusion-fission thus results in a saving of between 2.2 and 0.4 million tons, depending on the scenario. With CTR and without LMFBR, 6.4 million tons is consumed without fusion-fission, and with fusion-fission, 4.8 to 5.2 million tons is consumed. Fusion-fission saves between 1.2 and 1.6 million tons. In the cases with neither CTR nor LMFBR, fusion-fission saves between 0.9 and 1.5 million tons from the 7.3 million tons consumed without fusion-fission.

TABLE 20. Ratio of LMR/Fusion-Fission when Fusion-Fission Benefit is \$10 Billion

Pu Production, kg/MWt	MWe/MWt							
		1	2	3	4	5	6	7
0.5	0.01	LMFBR 1993 No CTR 2000 Availability	No LMFBR CTR 2010 2000 Availability	No LMFBR No CTR 2000 Availability	LMFBR - 1993 CTR 2010 2000 Availability	LMFBR 1993 No CTR 1990 Availability	No LMFBR CTR 2000 1990 Availability	No LMFBR No CTR 1990 Availability
1.0		1.8	5.0	4.3	5.0	2.3	5.2	6.0
1.5		2.7	8.7	7.3	12.0	9.1	10.9	9.0
0.5		6.1	16.9	9.7	15.5	22.0	12.5	11.6
1.0	-0.20	1.9	3.0	3.3	3.6	3.2	4.5	3.2
1.5		4.7	7.1	5.7	9.7	8.2	8.7	9.5
0.5		5.7	15.0	10.0	12.2	10.9	11.9	11.6
1.0		NA	NA	NA	NA	NA	NA	NA
0.5	7.0	NA	8.5	7.3	NA	NA	7.8	6.9
1.0		7.0	14.5	8.9	18.3	17.5	13.3	7.1
1.5								
0.5								
1.0	5.9	Low Demand LMFBR 1993 No CTR 2000 Availability						
1.5		2.1	4.1	2.0	4.1	2.0	4.1	2.0
0.5		2.2	4.5	6.2	2.0	4.1	5.9	6.0
1.0		2.0	6.2	2.0	4.1	5.9	6.0	6.0

NA - Not acceptable - allowable cost less than zero.

FIGURE 14. Fissile Plutonium and U₃O₈ Prices as Affected by the Introduction of Fusion-Fission Systems in Year 2000

TABLE 21. Plutonium Value in Year 2030 when Fusion-Fission Benefit is \$10 Billion (\$/g)

Pu Production, kg/Mwt	Mwe/Mwt	1	2	3	4	5	6	7	8	9
0.5	0.40	LMFBR 1993 No CTR 2000 Availability	No LMFBR CTR 2010 2000 Availability	No LMFBR No CTR 2000 Availability	LMFBR - 1993 CTR 2010 2000 Availability	LMFBR 1993 No CTR 1990 Availability	No LMFBR CTR 2000 1990 Availability	No LMFBR No CTR 1990 Availability	Low Demand LMFBR 1993 No CTR 2000 Availability	Low U Cost LMFBR 1993 No CTR 2000 Availability
1.0		45	80	80	50	40	75	80	30	45
1.5		40	85	80	42	45	85	75	35	35
0.5	0.01	40	80	80	40	45	80	80	34	30
1.0		30	80	75	45	34	80	75	30	22
1.5		35	88	75	42	35	80	75	30	40
0.5	-0.20	40	80	75	45	45	75	75	27	30
1.0		NA	NA	NA	NA	NA	NA	NA	NA	NA
1.5		NA	71	80	NA	NA	71	80	NA	NA
Base Case		40	80	75	30	45	80	77	30	35
		57	89	88	75	57	89	88	45	53

NA - Not acceptable - allowable cost less than zero.

TABLE 22. U_{308} Used (Million Tons) by Year 2030 when Fusion-Fission Yields \$10 Billion Benefit

Pu Production, kg/Mwt	MWe/Mwt									
		1	2	3	4	5	6	7	8	9
0.5	0.40	4.0	5.2	6.0	4.2	2.8	4.0	6.1	3.1	5.9
1.0		3.9	4.8	6.8	4.0	3.7	5.5	6.1	3.1	5.9
1.5		3.9	5.4	6.2	4.0	3.5	5.2	6.2	3.0	5.8
0.5	0.01	3.9	5.8	6.1	4.2	3.4	5.1	6.0	3.2	6.0
1.0		3.9	5.0	6.4	4.2	3.2	4.8	6.4	3.2	6.0
1.5		4.0	5.5	6.1	4.0	2.9	4.9	6.2	3.1	6.0
0.5	-0.20	NA	NA	NA	NA	NA	NA	NA	NA	NA
1.0		NA	5.2	6.3	NA	NA	5.1	6.1	NA	NA
1.5		3.9	5.6	6.0	4.2	3.7	5.1	5.8	3.2	5.9
Base Case		4.6	6.4	7.3	4.7	4.6	6.4	7.3	3.9	6.9

NA - Not acceptable - allowable cost less than zero

To examine the effect of the different scenario assumptions, we compare a hybrid design point for various cases. The design point selected was the one previously discussed, 0.40 thermal-to-electrical efficiency and annual plutonium yield of 1.0 kg/Mwt. Case 4 is the assumed reference case. It assumes both the LMFBR in 1993 and the pure CTR in 2010.

The first nonreference situation examined involves the elimination of the pure CTR as a future energy source. Table 23 summarizes this analysis, comparing it with the case when the CTR is available. Note that the allowable 30-year cost is higher with the CTR. This is caused by the CTR forcing the LMFBR out of the system so there is a better market for plutonium. The uranium consumption is basically unchanged as is the value of plutonium. The result is that many more fusion-fission plants are required without CTR; these operate in a symbiotic fashion with the expansion of light-water capacity as the preferred substitute for the CTR market share. At the allowable 30-year cost shown, the hybrid-LWR combination is preferred over the LMFBR.

The next competitive situation considered, Table 24, involves the elimination of the LMFBR from the available alternatives to a utility. In this case the optimal solution in the absence of hybrid availability involves a considerable expansion of the energy supplied by fossil-fired power plants. As a result, the addition of hybrid technology into this situation with very high plutonium values requires only half as many plants to yield the same \$10 billion in system cost reduction. In this case, the allowable cost of the hybrid is up to 2.2 in LWR equivalence units. Uranium consumption stops about 2020, but use prior to hybrid introduction still exceeds that used with LMFBR available.

The importance of the date when fusion-fission systems become available is shown in Table 25 for the 1990 and 2000 dates. The earlier introduction results in accumulative savings at an earlier date with higher present worth importance. Also, fewer light-water plants which consume plutonium from hybrids are in operation. The higher allowed capital cost (\$510/kW) eventually limits the total market available to hybrids and LWRs in competition with the LMFBR technology. Due to the earlier introduction, less total uranium is consumed through year 2030.

TABLE 23. Effects of CTR Availability (LMFBR - 1993, CTR - 2010)

	<u>CTR</u>	<u>No CTR</u>	<u>Change Magnitude</u>
Fusion-Fission 30-Year Cost (\$/kWt)	500	470	30
LWR Equivalence	1.6	1.5	0.1
U ₃ O ₈ , Required (Million Tons) By 2030	4.0	3.9	0.1
Plutonium Value, 2030 (\$/g)	38	38	0
Fusion-Fission Capacity, 2030 (GWe)	190	970	780
LWR Capacity, 2030 (GWe)	2280	2620	340

TABLE 24. Effects of LMFBR Availability (LMFBR - 1993, No CTR)

	<u>No LMFBR</u>	<u>LMFBR</u>	<u>Change Magnitude</u>
Fusion-Fission 30-Year Cost (\$/kWt)	680	470	210
LWR Equivalence	2.2	1.5	0.7
U ₃ O ₈ , Required (Million Tons) by 2030	6.8	3.9	2.9
Plutonium Value, 2030 (\$/g)	80	40	40
Fusion-Fission Capacity, 2030 (GWe)	450	970	520
LWR Capacity	3280	2620	660

TABLE 25. Effects of Fusion-Fission Availability Date (LMFBR - 1993, No CTR)

	<u>1990</u>	<u>2000</u>	<u>Change Magnitude</u>
Fusion-Fission 30-Year Cost (\$/kWt)	510	470	40
LWR Equivalence	1.6	1.5	0.1
U ₃ O ₈ , Required (Million Tons) by 2030	3.7	3.9	0.2
Plutonium Value, 2030 (\$/g)	45	40	5
Fusion-Fission Capacity, 2030 (GWe)	190	970	680
LWR Capacity, 2030 (GWe)	1730	2620	890

The cost of uranium, which is a ready substitute for plutonium produced by fusion-fission systems, has a minor effect on allowable cost. When the schedules of cost and availability changes from the reference case to the low schedule, a \$35/kWt reduction in the allowable cost results. This is shown in Table 26 for the situation with LMFBRs available. The uranium usage is considerably higher at the lower prices and LWR capacity also expands, along with a slight increase in the need for fusion-fission systems.

The demand for electricity is another important factor which is uncertain today and considerably more uncertain in the time period examined in this analysis. A lower energy demand reduces demand for uranium as shown in Table 27 by nearly a million tons through 2030. This reduced demand reduces plutonium values and necessarily lowers target cost for hybrids to produce a competitive product.

TABLE 26. Effects of Uranium Cost Schedule (LMFBR - 1993, No CTR)

	<u>Reference Schedule</u>	<u>Low-Cost Schedule</u>	<u>Change Magnitude</u>
Fusion-Fission 30-Year Cost (\$/kWt)	470	435	35
LWR Equivalence	1.5	1.4	0.1
U ₃ O ₈ , Required (Million Tons) by 2030	3.9	5.9	2
Plutonium Value, 2030 (\$/g)	40	35	5
Fusion-Fission Capacity, 2030 (GWe)	970	1050	80
LWR Capacity, 2030 (GWe)	2620	4720	2100

TABLE 27. Effects of Energy Demand (LMFBR - 1993, No CTR)

	<u>Moderate High</u>	<u>Low</u>	<u>Change Magnitude</u>
Fusion-Fission 30-Year Cost (\$/kWt)	470	430	40
LWR Equivalence	1.5	1.4	0.1
U ₃ O ₈ , Required (Million Tons) by 2030	3.9	3.1	0.8
Plutonium Value, 2030 (\$/g)	40	35	2
Fusion-Fission Capacity, 2030 (GWe)	970	640	330
LWR Capacity, 2030 (GWe)	2620	2620	0

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