ECONOMICS OF FUSION-FISSION
(HYBRID) REACTORS

by
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D. E. Deonigi

INTRODUCTION

This paper 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 investigated as reported in the Livermore meeting.⁽¹⁾ Designs range from plants 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 energy system scenarios 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 alternative systems will be consistent with the Liquid Metal Fast Breeder Reactor (LMFBR) cost-benefit analysis contained in the LMFBR final environmental impact statement.⁽³⁾

Ref.2?

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.
- Fission reactors will be represented in the form of LWRs and LMFBRs. The performance of these technologies will be consistent with that assumed in breeder studies. High Temperature Gas Reactors (HTGRs) are assumed not to be available which, in turn, eliminates the potential investigation of hybrids with thorium blankets.
- Pure 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 described later.

This paper analyzes 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 by simulating the utility decision process.

This analysis model 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 cost 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 price plateau that is reached which depends 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 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.

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 of 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.

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 mix-

ture 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.

30-Year Plant Cost Coefficients

The single cost coefficient for a plant represents the total cost to build a plant and operate it for its entire 30-year 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.

PROBLEM DEFINITION PARAMETERS AND INPUTS

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 1.

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.

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 1. 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.

WSCC - Western Systems Coordinating Council
 MARCA - Mid-Continent Area Reliability Coordination Agreement
 SWPP - Southwest Power Pool
 ERCOT - Electric Reliability Council of Texas
 MAIN - Mid-America Interpool Network

ECAR - East Central Area Reliability Coordination Agreement
 SERC - Southeastern Electric Reliability Council
 MAAC - Mid-Atlantic Area Coordination Agreement
 NPCC - Northeast Power Coordinating Council

FIGURE 1. Regional Electric Reliability Councils in the United States

TABLE 1. 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⁾ electrical demand forecast through year 2000 (5.8% growth), with a slightly reduced growth rate after year 2000 (3.9%). Most of the cases in this analysis used the moderate high forecast, and one case used the low demand forecast (4.8% growth to year 2000). 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.

The net thermal electrical requirements are then allocated to NERC regions based on normalized individual NERC forecast.⁽⁶⁾ 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.

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 2. 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. There-

TABLE 2. 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

fore, 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 3. Variable costs apply to a full power (100% load factor) year. Both fixed and variable costs are consistent with LMFBR cost-benefit studies.

TABLE 3. 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

Fuel and fuel processing costs are also important costs assumptions. An important feature of this model is that nuclear fuel, both natural uranium and 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 4). 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 pro-

TABLE 4. 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		

cessing costs are presented in Table 5. Most of the fuel cycle costs are based on bids supplied to utilities during 1975. Fossil fuel costs for each NERC are shown in Table 6. 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

TABLE 5. Fuel Processing Cost Estimates (1975 Dollars)

Year	LWR							
	Fabrication				LMFBR		Uranium Conversion, \$/kg	Uranium Enrichment, \$/SWU
	Uranium, \$/kg	Self-Produced Recycle, \$/kg	Full Recycle, \$/kg	Reprocessing, \$/kg	Fabrication, \$/kg	Reprocessing, \$/kg		
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 6. 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.

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 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 7, along with their availability date. The physical fuel requirements of each major alternative energy system are summarized in Table 8. The hybrid is treated parametrically 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 7. 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 8. 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 9. 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.

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:

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

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.

TABLE 9. Parametric Hybrid Analysis Cases

Date of LMFBR Availability ^(a)	Case								
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4(b)</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>
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.

Equation (1) 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 (1).

The allowable capitalized costs can be used to evaluate specific fusion-fission designs. Design tradeoffs between electrical production and fissile production can be established.

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 2 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.

For each of the parametric conditions listed in Table 10, a complete simulation is carried out for a case first without the existence of the hybrid alternative and then for a case with a hybrid, at progressively lower cost to establish the targets to achieve a given national benefit. Figure 3

TABLE 10. 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 2. Allowable Capitalized Fusion-Fission Cost with Year 2000 Availability (with LMFBR, 1993; with CTR, 2010)

FIGURE 3. Forecasted Operating Electric Generation Capacity for the Reference Case

shows a typical forecast of operating electrical generating capacity for the case without hybrid present. By introducing hybrids with a one kilogram of plutonium per megawatt thermal year production capability and a 30% thermal-to-electrical conversion efficiency, 190 hybrids are forecast to be built by year 2030. This will yield a benefit of \$10 billion if the cost are 1.45 times that of LWRs. Comparing Figure 3 with Figure 4 (which illustrates the forecasted generating capacity with hybrids) it can be seen that the LMFBRs

FIGURE 4. Forecasted Operating Electric Generation Capacity with Hybrid

still operate in the system, and that the primary beneficiary of hybrid development is the LWR which increases its market share by about 15%. The small number of hybrids is directly related to the number required to fuel all of the existing LWRs in year 2030.

The analysis of each parametric point also yields a forecast of uranium prices and plutonium prices as a function of time. For the same generating forecast situation shown in Figure 3 and 4, the plutonium and U_3O_8 prices are estimated as shown in Figure 5. As expected, U_3O_8 prices will increase with time as the low cost reserves are depleted and only minor variations in this situation are shown with the addition of hybrid systems. With plutonium,

FIGURE 5. Fissile Plutonium and U_3O_8 Prices as Affected by the Introduction of Fusion-Fission Systems in Year 2000

however, the case is different because in order to produce national benefits, it is necessary for the hybrid plants to provide fissile material at a cost less than that found in the reference case. For this particular parametric point, the plutonium cost from hybrids must drop from about \$80/g to \$60/g. The goal of supplying fissile material at this lower price should be achieved in a mature hybrid economy. It may not be necessary for the early hybrids to achieve this target performance; in fact, any value less than \$80/g should make the market interesting. This would provide a secure future source of fuel for the large numbers of LWRs expected to be in operation by the utilities in year 2000.

Figure 6 illustrates the possible evolution of allowable cost that might take place in a developing economy. First commercial plants for most technologies have generally been slightly above the point of initial market penetration which might be expected to take place at the zero benefit curve. Historically, the utilities, industry and government have supported the investment in early plants based on the anticipated benefits from the mature industry. Learning through the construction of early plants and larger plants, an eventual standardization should be target at reducing the cost of plants by about 25% from that estimated for the first commercial plants.

To document the complete series of parametric points calculated, the results are reported in Table 11 in terms of the necessary capitalized cost to achieve a \$10 billion benefit for each of the nine scenarios. As expected, the target cost goes up as plutonium production or efficiency improve or as the competition for the fusion plant is withdrawn. The cases with low energy demand and low uranium costs show remarkably small changes in the allowable cost compared with the reference scenarios (case Number 1). For a number of the cases where the -0.2 efficiency is used, the allowable cost would be less than zero. It would appear that "electric breeders" will have to have very high plutonium production rates per megawatt-thermal in order to be attractive.

The value of plutonium which for hybrids translates into the allowable production cost is illustrated for the same scenarios and parametric conditions in Table 12. In this case, the plutonium value is generally independent of plutonium production rates and efficiency as this is a pure commodity and the condition of production is of no consequence. However, the role of competing

FIGURE 6. Allowable Capitalized Cost for Fusion-Fission System (2000) With LMFBR (1993)—With CTR (2010)

TABLE 11. Allowable Capital Cost (LWR Equivalence) for Fusion-Fission
that Yields \$10 Billion Benefit at 7.5% Discount Rate

Pu Production, kg/MWt	MMe/MWt	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	2	3	4	5	6	7	8	9
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.

TABLE 12. Plutonium Value in Year 2030 when Fusion-Fission Benefit is \$10 Billion (\$/g)

Pu Production, kg/Mwt	MWe/Mwt	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	2	3	4	5	6	7	8	9
0.5	0.40	45	80	80	50	40	75	80	30	45
1.0	0.01	40	85	80	42	45	85	75	35	35
1.5		40	80	80	40	45	80	80	34	30
0.5		30	80	75	45	34	80	75	30	22
1.0	-0.20	35	88	75	42	35	80	75	30	40
1.5		40	80	75	45	45	75	75	27	30
0.5		NA	NA	NA	NA	NA	NA	NA	NA	NA
1.0	Base Case	NA	71	80	NA	NA	71	80	NA	NA
1.5		40	80	75	30	45	80	77	30	35
Base Case		57	89	88	75	57	89	88	45	53

NA - Not acceptable - allowable cost less than zero.

systems is very important; they influence the allowable plutonium price either through their purchases of plutonium, or by limiting the price through operation of lower cost alternative energy systems. This table is for the \$10 billion benefit level, which should be expected of mature plants; first commercial plants may well be targeted at 20 to 30% above these values.

The use of hybrids generally appears at distinct levels: first when hybrids become a source of fissile material for then existing light-water reactors and second when a combination of light-water reactors plus hybrids are a less expensive system than some other alternative for new generating capacity. At the \$10 million benefit level, generally not much more than supplying plutonium to existing light-water reactors or possible perpetuating them at their expected market share is required. Table 13 shows the ratio of LWRs to hybrids for all nine scenarios in parametric situations. It might be expected that as plutonium production rates change there will be change in the LWR ratio in direct proportion; this generally true. However, due to the dynamics of the system, changes in the introduction rate and competition do affect the ratio. This can be seen for the reference case with a 0.4 thermal-to-electrical efficiency as the plutonium production is triple something just slightly greater than tripling occurs in the LWR to hybrid ratio. Rather high numbers occurs in Scenarios 5, 6, and 7 with the early introduction of hybrids.

To illustrate the case where a hybrid can displace other competing systems, a recent calculation without the pure fusion (CTR) plant available in a low growth rate of electrical energy demand resulted in the forecast of generating capacity shown in Figure 7 for the case without the hybrid. But when the hybrid added has the same performance characteristics used in the reference case, the forecast of operating electrical generating capacity shown in Figure 8 results. In this case, the LWR which was introduced seven years before the hybrid is displaced by the hybrid technology and the LWR takes over a major market share in concert with the hybrid development. The resulting uranium and plutonium prices are shown in Figure 9 for the zero benefit situation which is equivalent to the case with no hybrids and the \$10 billion benefit

TABLE 13. Ratio of LWR/Fusion-Fission when Fusion-Fission Benefit is \$10 Billion

Pu Production, kg/Mwt	MWe/Mwt	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	2	3	4	5	6	7	8	9
0.5	0.01	1.8	5.0	4.3	5.0	2.3	5.2	6.0	2.1	2.2
1.0		2.7	8.7	7.3	12.0	9.1	10.9	9.0	4.1	4.5
1.5		6.1	16.9	9.7	15.5	22.0	12.5	11.6	6.2	6.2
0.5		1.9	3.0	3.3	3.6	3.2	4.5	3.2	2.0	2.0
1.0		4.7	7.1	5.7	9.7	8.2	8.7	9.5	4.0	4.1
1.5	-0.20	5.7	15.0	10.0	12.2	10.9	11.9	11.6	5.9	5.9
0.5		NA	NA	NA	NA	NA	NA	NA	NA	NA
1.0		NA	8.5	7.3	NA	NA	7.8	6.9	NA	NA
1.5		7.0	14.5	8.9	18.3	17.5	13.3	7.1	5.9	6.0

NA - Not acceptable - allowable cost less than zero.

FIGURE 7. Forecasted Operating Electrical Generating Capacity For Low Demand Growth with Hybrid

FIGURE 8. Forecasted Operating Electrical Generating Capacity for Low Demand Growth With Hybrid

FIGURE 9. Forecasted Pu Values with Low Demand Growth
And With LMFBR

situation which is the case of a mature hybrid which must be capable of supplying plutonium at about \$40/g.

This paper has reported on the research in the United States to establish targets of performance in terms of parameters that can be easily related to the systems design efforts and also to the wide range of possible future energy development scenarios. It is hoped that these results can act as a guide for the designers of hybrids in the United States and possibly in the Soviet Union.

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