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**Power Generation Costs for
Alternate Reactor Fuel Cycles**

G. R. Smolen

J. G. Delene

**OPERATED BY
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POWER GENERATION COSTS FOR ALTERNATE REACTOR FUEL CYCLES

G. R. Smolen J. G. Delene

ABSTRACT

The total electric generating costs at the power plant busbar are estimated for various nuclear reactor fuel cycles which may be considered for power generation in the future. The reactor systems include pressurized water reactors (PWR), heavy-water reactors (HWR), high-temperature gas cooled reactors (HTGR), liquid-metal fast breeder reactors (LMFBR), light-water pre-breeder and breeder reactors (LWPR, LWBR), and a fast mixed spectrum reactor (FMSR). Fuel cycles include once-through, uranium-only recycle, and full recycle of the uranium and plutonium in the spent fuel assemblies. The U_3O_8 price for economic transition from once-through LWR fuel cycles to both PWR recycle and LMFBR systems is estimated. Electric power generation costs were determined both for a reference set of unit cost parameters and for a range of uncertainty in these parameters. In addition, cost sensitivity parameters are provided so that independent estimations can be made for alternate cost assumptions.

INTRODUCTION

The Nonproliferation Alternative Systems Assessment Program (NASAP)¹ has served to produce a consistent characterization of a variety of reactor/fuel cycle systems. The consistency and completeness of the data set make it a particularly valuable tool to those making comparative economic assessments of advanced nuclear alternatives. This report contains power generation costs for many of the systems included in NASAP.

The purpose of this report is to present the costs and cost components of the various fuel cycles and not to present a detailed economic evaluation of each fuel cycle concept. The information contained in the report and its appendixes is adequate to estimate fuel and power costs at unit prices (e.g., capital cost, enrichment cost) other than those used in the report. These estimates, however, will be limited by the set of basic ground rules used in the analysis. These include the cost of money, lead and lag times for fuel cycle services, fissile material loss assumptions, and system capacity factors.

Reactor systems for which cost estimates are presented include pressurized water reactors (PWR), heavy-water reactors (HWR), high-temperature gas cooled reactors (HTGR), liquid-metal fast breeder reactors (LMFBR), light-water pre-breeder and breeder reactors (LWPR, LWBR), and a fast mixed spectrum reactor (FMSR). The fuel cycles are once-through, uranium-only recycle, and full recycle of the uranium and plutonium, and include thorium cycle systems.

In addition to the tabulation of fuel cycle and total busbar power generation costs, nominal economic transition points for PWR once-through, PWR recycle, and LMFBRs are estimated. The nominal U_3O_8 price for economic transition from the standard PWR on the once-through cycle to a fuel cycle including the recycle of the uranium and plutonium fuel is estimated in 1978 dollars to be \$20 to \$50/lb U_3O_8 for PWR recycle and \$80 to \$180/lb U_3O_8 for recycle in the LMFBR. The ranges are dependent on uncertainty in fuel process costs and on plutonium valuation assumptions.

The basic information used in the analysis was that generated through the NASAP program. The information, as summarized in this report, includes unit cost estimates for reactor plant capital, operation and maintenance (O&M) and fuel cycle materials and services, and the charge and discharge mass flow data for each reactor fuel cycle.

In addition, a discussion of the methodology used to calculate the power generation cost from the various cost components is given. Since many of the fuel cycles utilize fissile plutonium and/or ^{233}U , the pricing methodology used to value these commodities is critical to the overall cost of a fuel cycle system. The valuation of these commodities by two alternate schemes, the indifference value and the recovery value method, is discussed. The difference in results from the two procedures is examined for plutonium recycle in PWRs or LMFBRs.

POWER GENERATION COST SUMMARY

Total busbar power generation costs in mills/kWh are tabulated in this section for each fuel cycle considered. In addition, the total power generation costs are broken down by cost component. These cost components

include capital investment (including heavy-water investment where applicable), operation and maintenance, and fuel cycle costs. The reference prices for commodities and services used in the cost calculations are given in the Economic Factors section of this report. In order to reflect the effect of uncertainty in the price assumptions on the resulting costs, the power generation costs were recalculated using the unit prices at the high and low ends of the range of uncertainty. These results are given in Appendix A. In all cases the fuel cycle and total power generation costs were determined at three U_3O_8 prices. All cost estimates assumed a 70% reactor capacity factor and are in constant January 1, 1978, dollars.

The estimated capital investment cost contribution to the total power generation cost is given in Table 1 for each of the reactor types. These costs were levelized over a nominal 30-year reactor lifetime using a constant dollar fixed charge rate of 10.1%.

Table 1. Reactor capital cost
(mills/kWh)

PWR	13.18
HWR ^a	16.81
HTGR	13.84
LMFBR	18.28
LWBR — high gain converter	13.51
LWBR — seed blanket	13.84
FMSR	18.28

^aInitial heavy-water inventory included (2.64 mills/kWh).

The estimated operation and maintenance (O&M) cost contributions to the total power generation costs are given in Table 2. The O&M cost for the heavy water reactor includes heavy-water makeup requirements.

The fuel cycle and power generation costs of each of the reactor systems at the various U_3O_8 prices are summarized in Tables 3 and 4. The systems are identified by a pair of abbreviations that follow a methodology which is outlined in Appendix C. Briefly, the system is identified

Table 2. Operation and
maintenance costs
(mills/kWh)

PWR	2.23
HWR	2.72
HTGR	2.07
LMFBR	2.89
LWBR	2.23
FMSR	2.89

by the type of reactor, the type of fuel used, and the enrichment level if applicable. All the systems are assumed to be stand-alone (systems where no two or more fuel cycles are related symbiotically). All net fissile material produced or consumed is sold to or bought from an open market. The fuel cycle and total power costs at U_3O_8 prices, other than the reference values, may be found by linear interpolation or extrapolation to the higher or lower U_3O_8 price. The methodology section describes in detail how each cost was computed.

There are three categories by which each of the systems can be characterized. Once-through systems dispose of the spent fuel after a certain cool-down period, taking no credit for the remaining or bred fissile materials. Uranium-only recycle systems take credit only for fissile uranium, ^{235}U and/or ^{233}U , in the spent fuel. No credit is assumed for the discharged fissile plutonium in this case. Full recycle systems take credit for all fissile material in the spent fuel, except in cases where the fissile enrichment of the ^{235}U is less than tails. Some systems, such as the PWR-LEU(5), can operate in more than one of these modes, whereas other systems, such as the LMFBRs, are limited to only one type of characterization.

The data in these tables should only be used for comparative studies where the competitiveness of one system over others is required. In this study, as in all such studies, knowledge of the assumptions used to determine the costs is vital. The capacity factor, lead and lag times, and the data used in determining the money costs affect the results. The power

Table 3. Fuel cycle costs^a
(mills/kWh)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
A. Once-through systems			
PWR — LEU5(U)	6.3	10.6	15.0
PWR — LEU5(U) — X	5.7	9.8	13.8
PWR — LEU5(U) — 15%	5.5	9.4	13.3
PWR — LEU5(U) — 30%	4.7	8.0	11.3
HWR — LEU5(U)	3.3	5.8	8.2
HTGR — MEU5(U,Th)	5.9	9.2	12.5
HTGR — MEU5(U,Th) — 6	5.5	8.5	11.5
FMSR — LEU5(U)	5.6	9.0	12.5
B. Uranium-only recycle			
PWR — LEU5(U)	6.4	10.1	13.8
PWR — LEU5(U) — X	5.8	9.5	13.1
PWR — LEU5(U) — 15%	5.6	9.1	12.6
PWR — LEU5(U) — 30%	4.9	8.0	11.2
PWR — MEU5, U3(U,Th)	8.5	12.2	16.0
PWR — MEU3(U,Th)	6.1	9.4	12.8
HWR — LEU5(U)	4.6	7.1	9.5
HWR — MEU5, U3(U,Th)	11.2	13.6	16.1
HWR — MEU5, U3(U,Th) — X	5.6	7.6	9.6
HWR — MEU3(U,Th)	9.5	11.8	14.3
HTGR — MEU5, U3(U,Th)	5.0	7.5	10.0
HTGR — HEU5, U3(Th)	5.3	7.5	9.7
HTGR — HEU5, U3(Th) — S	5.9	8.1	10.3
HTGR — HEU3(Th)	5.0	6.9	8.8
HTGR — MEU3(U,Th)	5.2	7.9	10.6
LWPR — HEU5(Th) — B	8.1	11.2	14.4
LWPR — HEU5(Th) — B,S	10.2	13.4	16.5
LWPR — MEU5(U,Th) — HGC,B	11.6	16.0	20.4
LWPR — HEU5(Th) — HGC,B	10.6	13.8	17.0
LWPR — HEU5(Th) — HGC,S	14.7	17.9	21.1
LWPR — MEU5(U,Th) — T1M	17.0	21.6	26.2
LWBR — HEU3(Th) — SB	14.2	18.4	22.7
LWBR — HEU3(Th) — HGC	14.7	17.1	19.7
LWBR — HEU3(Th) — HGC, X	8.7	11.0	13.4
LWBR — MEU3(U,Th) — HGC	7.6	10.7	13.8
LWBR — HEU3(Th) — T1M	21.7	25.6	29.7

Table 3 (continued)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
C. Full recycle credit			
PWR — LEU5(U)	5.9	9.0	12.2
PWR — LEU5(U) — X	5.5	8.8	12.1
PWR — LEU5(U) — 15%	5.3	8.4	11.5
PWR — LEU5(U) — 30%	4.6	7.5	10.3
PWR — MEU5, U3(U,Th)	8.3	11.9	15.4
PWR — MEU3(U,Th)	5.9	9.0	12.2
PWR — LEU5, Pu(U)	5.8	8.9	12.0
PWR — LEU5, Pu(U) — S	6.2	9.3	12.3
PWR — LEU5, Pu(U) — X	5.5	8.8	12.1
PWR — LEU5, Pu(U) — X, S	5.6	8.9	12.2
PWR — Pu(U)	5.9	9.1	12.2
PWR — Pu(U) — S	7.1	10.3	13.4
PWR — Pu(U) — X	5.2	8.8	12.3
PWR — Pu(U) — X, S	6.0	9.6	13.0
PWR — Pu(Th)	6.1	9.0	11.6
PWR — Pu(Th) — S	7.1	9.9	12.6
HWR — LEU5(U)	4.2	6.1	8.1
HWR — MEU5, U3(U,Th)	11.1	13.5	15.9
HWR — MEU5, U3(U,Th) — X	5.6	7.5	9.5
HWR — MEU3(U,Th)	9.4	11.7	14.0
HTGR — MEU5, U3(U,Th)	5.0	7.4	9.8
HTGR — MEU3(U,Th)	5.1	7.6	10.1
HTGR — Pu(Th)	4.5	6.4	8.1
LMFBR — Pu(U)/U/U — HT	6.7	8.3	9.9
LMFBR — Pu(U)/U/U — HT, S	8.1	9.8	11.4
LMFBR — Pu(U)/Th/Th — HT	7.2	8.4	9.5
LMFBR — Pu(U)/Th/Th — HT, S	8.4	9.7	10.8
LMFBR — Pu(U)/U/U — HM	5.2	6.3	7.3
LMFBR — Pu(U)/U/U — HM, S	6.6	7.7	8.7
LMFBR — Pu(U)/Th/Th — HM	5.3	5.9	6.4
LMFBR — Pu(U)/Th/Th — HM, S	6.5	7.0	7.5
LMFBR — Pu(Th)/Th/Th — HM	6.4	6.9	7.2
LMFBR — Pu(Th)/Th/Th — HM, S	7.9	8.4	8.7
LMFBR — MEU3(U)/Th/Th — HM	7.9	10.8	13.8
LWTR — MEU5(U,Th) — HGC, B	11.1	15.0	18.9
LWPR — Pu(Th) — HGC	7.6	10.4	12.9
LWPR — Pu(Th) — HGC, S	8.7	11.5	14.1
LWPR — MEU5(U,Th) — TIM	16.8	21.2	25.5
LWBR — MEU3(U,Th) — HGC	7.3	10.1	13.1

^aDefinition of abbreviations is found in Appendix C.

Table 4. Power generation costs^a
(mills/kWh)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
A. Once-through systems			
PWR — LEU5(U)	21.7	26.0	30.4
PWR — LEU5(U) — X	21.2	25.2	29.2
PWR — LEU5(U) — 15%	20.9	24.8	28.7
PWR — LEU5(U) — 30%	20.1	23.4	26.7
HWR — LEU5(U)	22.8	25.3	27.8
HTGR — MEU5(U,Th)	21.8	25.1	28.4
HTGR — MEU5(U,Th) — 6	21.4	24.4	27.4
FMSR — LEU5(U)	26.8	30.2	33.7
B. Uranium-only recycle			
PWR — LEU5(U)	21.8	25.5	29.2
PWR — LEU5(U) — X	21.2	24.9	28.5
PWR — LEU5(U) — 15%	21.0	24.5	28.0
PWR — LEU5(U) — 30%	20.3	23.4	26.6
PWR — MEU5, U3(U,Th)	23.9	27.6	31.4
PWR — MEU3(U,Th)	21.5	24.8	28.2
HWR — LEU5(U)	24.2	26.6	29.0
HWR — MEU5, U3(U,Th)	30.7	33.2	35.6
HWR — MEU5, U3(U,Th) — X	25.1	27.1	29.1
HWR — MEU3(U,Th)	29.0	31.4	33.8
HTGR — MEU5, U3(U,Th)	20.9	23.4	25.9
HTGR — HEU5, U3(Th)	21.2	23.4	25.6
HTGR — HEU5, U3(Th) — S	21.8	24.0	26.2
HTGR — HEU3(Th)	20.9	22.8	24.7
HTGR — MEU3(U,Th)	21.2	23.8	26.5
LWPR — HEU5(Th) — B	24.2	27.3	30.4
LWPR — HEU5(Th) — B,S	26.3	29.4	32.6
LWPR — MEU5(U,Th) — HGC,B	27.3	31.7	36.1
LWPR — HEU5(Th) — HGC,B	26.3	29.6	32.7
LWPR — HEU5(Th) — HGC,S	30.4	33.7	36.8
LWPR — MEU5(U,Th) — T1M	33.1	37.7	42.2
LWBR — HEU3(Th) — SB	30.3	34.5	38.8
LWBR — HEU3(Th) — HGC	30.4	32.9	35.4
LWBR — HEU3(Th) — HGC, X	24.4	26.8	29.2
LWBR — MEU3(U,Th) — HGC	23.3	26.4	29.5
LWBR — HEU3(Th) — T1M	37.4	41.4	45.4

Table 4 (continued)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
C. Full recycle credit			
PWR — LEU5(U)	21.3	24.5	27.6
PWR — LEU5(U) — X	20.9	24.2	27.6
PWR — LEU5(U) — 15%	20.7	23.8	26.9
PWR — LEU5(U) — 30%	20.1	22.9	25.7
PWR — MEU5, U3(U,Th)	23.7	27.3	30.8
PWR — MEU3(U,Th)	21.3	24.4	27.6
PWR — LEU5, Pu(U)	21.2	24.3	27.4
PWR — LEU5, Pu(U) — S	21.6	24.7	27.8
PWR — LEU5, Pu(U) — X	20.9	24.2	27.5
PWR — LEU5, Pu(U) — X,S	21.0	24.3	27.6
PWR — Pu(U)	21.3	24.5	27.6
PWR — Pu(U) — S	22.5	25.7	28.8
PWR — Pu(U) — X	20.6	24.2	27.7
PWR — Pu(U) — X,S	21.4	25.0	28.5
PWR — Pu(Th)	21.5	24.4	27.0
PWR — Pu(Th) — S	22.5	25.3	28.0
HWR — LEU5(U)	23.7	25.7	27.7
HWR — MEU5, U3(U,Th)	30.7	33.0	35.4
HWR — MEU5, U3(U,Th) — X	25.1	27.1	29.0
HWR — MEU3(U,Th)	28.9	31.2	33.6
HTGR — MEU5, U3(U,Th)	20.9	23.3	25.7
HTGR — MEU3(U,Th)	21.0	23.5	26.0
HTGR — Pu(Th)	20.4	22.3	24.0
LMFBR — Pu(U)/U/U — HT	27.8	29.5	31.1
LMFBR — Pu(U)/U/U — HT,S	29.3	31.0	32.6
LMFBR — Pu(U)/Th/Th — HT	28.3	29.6	30.7
LMFBR — Pu(U)/Th/Th — HT,S	29.6	30.8	31.9
LMFBR — Pu(U)/U/U — HM	26.4	27.5	28.5
LMFBR — Pu(U)/U/U — HM,S	27.8	28.8	29.9
LMFBR — Pu(U)/Th/Th — HM	26.5	27.1	27.5
LMFBR — Pu(U)/Th/Th — HM,S	27.6	28.2	28.7
LMFBR — Pu(Th)/Th/Th — HM	27.6	28.1	28.3
LMFBR — Pu(Th)/Th/Th — HM,S	29.1	29.6	29.8
LMFBR — MEU3(U)/Th/Th — HM	29.0	31.9	35.0
LWPR — MEU5(U,Th) — HGC,B	26.8	30.7	34.6
LWPR — Pu(Th) — HGC	23.3	26.1	28.7
LWPR — Pu(Th) — HGC,S	24.5	27.3	29.8
LWPR — MEU5(U,Th) — T1M	32.9	37.2	41.6
LWBR — MEU3(U,Th) — HGC	23.0	25.9	28.8

^aDefinition of abbreviations is found in Appendix C.

cost of each system in this study was estimated using a consistent set of economic factors and should lead to valid comparisons provided the underlying assumptions are valid. The use of different money costs and/or methods for pricing fissile materials (Pu, ^{233}U) can lead to different comparisons.

All analyses shown in this report were completed at a 70% capacity factor. The comparative results would have been similar had the analyses been made at other capacity factors (60 to 80%) which do not vary appreciably from this reference. However, higher capacity factors produce lower electric costs, and systems with higher capacity factors would be more competitive than those shown in this analysis.

POWER COST COMPARISONS

The power generation costs that were calculated under the assumed ground rules are most valuable when viewed in relation to each other. The economic ground rules that were used should not be assumed to correspond to a particular utility, so that in absolute terms the power costs derived for any of the systems when taken by themselves have little value. Yet, when comparisons of cost are made among the different systems, judgments can be made as to relative economic viability under a specific economic environment. Thus, the most important and valuable worth in the power generation costs, presented in this report, is that they are all computed under consistent ground rules. In order to demonstrate how the estimated costs might be used in making comparisons, evaluations of some competitive reactor systems are presented in this section.

PWR Once-Through vs Recycle

The controversy over whether spent fuel should be reprocessed so that the fissile materials will not be wasted involves several arguments. One argument that is relatively free of subjective feelings is based on the economic viability of this alternative.

Using the reference prices given in the economics section of this report, the power generation costs of a PWR in both the once-through and the

recycle mode can be plotted as a function of U_3O_8 price (Fig. 1). The intersection of the cost vs U_3O_8 price plots for these two modes indicates the U_3O_8 price at which both options are equally competitive. As the U_3O_8 price increases, the system whose power cost vs U_3O_8 price plot has the smaller slope (the recycle mode) becomes more economical than the other system. Since U_3O_8 prices are currently in the range of 35 to 45 \$/lb U_3O_8 , it can be concluded that based on the economic parameters used in this analysis, the power generation cost of a PWR which recycles its uranium and plutonium is now competitive with current once-through PWRs. As the price of U_3O_8 increases, the power generation cost differential favoring the recycle mode becomes greater and greater relative to the once-through mode. Of course, improvements can be made to increase the fuel utilization of the once-through system which would have the effect of reducing the sensitivity of the once-through system to the U_3O_8 price and therefore would increase the price at which break even occurs.

Fig. 1. Power generation costs for two modes of PWR generation.

Transition to the LMFBR

Another area of controversy concerns the potential economic viability of the LMFBR. In order to determine the fuel cost of the fast breeder reactor, assumptions must be made to determine the value of plutonium. Two methods are discussed in the section on Fissile Material Values. These methods are the indifference value method and the recovery method. The fuel cycle costs given in Table 3, where applicable, use a plutonium price based on the indifference value for recycle in light-water reactors. Where there is a large stock pile of unprocessed spent fuel, the recovery value for plutonium might be more appropriate. The power generation costs for the LMFBR based on both plutonium valuation procedures are shown in Fig. 2.

Significantly different conclusions can be reached about the economic viability of the breeder based on the two sets of plutonium assumptions.

Fig. 2. PWR and LMFBR power generation costs.

The truth probably lies somewhere in between. Using the recovery method, the power generation cost for the LMFBR decreases with rising U_3O_8 prices because the breeder is receiving credit for the recovered uranium in the spent PWR fuel. Where the plutonium is valued at its indifference value for PWR recycle, the high capital cost of an LMFBR prevents it from gaining an economic edge over its competitors. Eventually, the LMFBR will have the lowest power generation cost because the fuel cost increases less rapidly relative to the fuel cost of the PWR. Although the breeder is a net seller of plutonium, the breeder's fuel cost does not have a negative slope since the carrying charges on the fuel are greater than the net gain from the sale of fissile material.

Since most of the unit costs for services for advanced reactors and even some unit reprocessing costs for conventional reactors are uncertain, comparisons based on the range of uncertainties could yield useful results. In this manner one could determine the range of U_3O_8 prices at which the transition from the once-through PWR system to any number of alternatives might occur.

METHODOLOGY

The busbar power generation cost consists of capital cost (costs associated with the initial investment in the reactor plant), operation and maintenance costs, and fuel costs. For the HWR, a fourth cost item, heavy water cost, is also included. A more detailed discussion of power generation cost methodology may found in Ref. 2.

The power cost results, given in this report, are in terms of dollars of constant January 1978 purchasing power. The prices for commodities and services used in the analysis assume that the dollar can, on the average, buy the same as it could in January 1978. Therefore, inflation has been removed from the analysis. Since price inflation was not considered, the inflation expectation was also removed from the cost of money. The unit costs and the cost of money used in the analysis are given in the Economic Factors section of this report.

Although inflation is removed from the analysis in a constant dollar calculation, there can still be price escalation caused by resource

depletion or by other factors. The resource depletion effect on U_3O_8 price is included in this analysis by assuming several U_3O_8 prices.

Capital Cost

The capital investment cost component of the power generation cost is obtained by applying an annual fixed charge rate to the initial capitalized investment in the reactor plant. The annual fixed charge rate is the fraction of the initial investment which must be set aside each year of operation to meet charges resulting directly from the investment. The fixed charge rate used in this analysis was 0.101.^{2,3} The contribution of the capital investment cost to the cost of generating power was calculated according to

$$\text{mills/kWh} = \frac{(\$/\text{kWe}) \times \left(\frac{\text{annual fixed}}{\text{charge rate}} \right) \times (1000 \text{ mills}/\$)}{(8760 \text{ h/year}) \times (\text{capacity factor})}.$$

For the 70% capacity factor and the 0.101 fixed charge rate, capital investment cost (mills/kWh) = (0.01647) • (specific capital cost, \$/kWe).

Heavy-Water Cost

The contribution of the cost of the initial heavy-water inventory to the power generation cost is calculated for the HWR. The heavy-water makeup cost is assumed to be included with the O&M cost component.

The heavy-water contribution to the power cost is calculated in a manner similar to the capital cost using the following relationship

$$\text{mills/kWh} = \frac{(\$/\text{kWe}) \times \left(\frac{\text{heavy-water}}{\text{charge rate}} \right) \times (1000 \text{ mills}/\$)}{(8760 \text{ h/year}) \times (\text{capacity factor})}.$$

Heavy water is a nondepreciating asset. The heavy-water charge rate used in the analysis was 0.102.

For the 70% capacity factor and the 0.102 charge rate:

$$\text{Heavy water cost (mills/kWh)} = (0.01663) \times (\text{specific heavy-water cost, \$/kWe}) .$$

Operation and Maintenance Costs

The operation and maintenance costs include all costs (other than fuel costs) which are expended to operate and to maintain the plant. These are usually presented in the form of a fixed and a variable portion. The fixed costs are those which are independent of plant operating factors over the normal range of plant operation. The variable part of the O&M costs are expenditures directly related to the reactor operation.

The fixed and variable portions of the O&M costs used in the analysis are given in the following section on economic factors. The O&M contribution to the cost of generating power was calculated according to

$$\text{mills/kWh} = \frac{\left[\left(\frac{\text{Fixed}}{\text{\$/kWe-year}} \right) + \left(\frac{\text{Variable}}{\text{\$/kWe-year}} \right) \times \left(\frac{\text{Capacity}}{\text{factor}} \right) \right] \times (1000 \text{ mills/\$})}{(8760 \text{ h/year}) \times (\text{Capacity factor})} .$$

Fuel Cycle Cost

The fuel cost is composed of several subcosts or cost items which make up the various fuel cycle materials and service requirements and credits received for the residual fuel materials. The subcost items include: U_3O_8 purchase, UF_6 conversion, fuel enrichment, thorium purchase, fuel fabrication, fuel recovery (includes reprocessing, shipping, and waste disposal), discharged uranium credit, fissile plutonium purchase and credits, ^{233}U purchases and credits, and permanent spent fuel storage.

Each fuel cycle cost was estimated using a modified version of the REFCO^{4,5} computer program and is the levelized cost over the reactor lifetime (nominally 30 years). Basically, a discounted cash flow (DCF) analysis is used. The DCF analysis establishes an energy "cost" associated with the fuel by requiring that the revenue from the sale of energy be adequate to pay the required return on outstanding capital, to pay income

taxes, and to retire the outstanding investment to zero by the end of the economic life of the set of fuel investments.

In the REFCO program, the DCF procedure is applied on a "batchwise" basis for each subcost item or component; that is, levelized fuel subcosts are calculated for each discrete batch* of fuel elements loaded into the reactor. The REFCO program accounts for all fuel associated payments as investments. Fuel cycle back end credits (such as recovered uranium, plutonium) are treated as the salvage value of a capitalized investment. The batch levelized fuel cycle cost is the cost of energy such that the sales revenue from the energy produced by the batch during its in-core residence recovers all investments in the batch and pays all carrying charges.

The equation solved in REFCO for each batch, B, and each fuel cost item, C, is

$$P_{B,C} = \frac{\int K_{B,C,t} e^{-X't} dt + r \int D_{B,C,t}^T e^{-X't} dt}{(1 - r) \int Q_{B,t} e^{-X't} dt},$$

where the exponential discount rate

$$X' = \ln(1 + X),$$

and the tax adjusted discount rate

$$X = (1 - r) \lambda_b f_b + \lambda_e f_e$$

(see Table of Nomenclature, Appendix C for definitions).

The total levelized cost for a fuel batch can be obtained by summing the above equation over all cost components associated with a particular fuel batch. The total fuel cycle cost calculated for the analysis in this report is the cumulative levelized cost over all cost components and over all fuel batches used in the reactor lifetime.

REFCO uses a continuous discounting procedure. The cash payments for cost items are made at discrete times corresponding to the refueling

*A fuel batch is defined as a set of fuel elements with a specific charge and discharge time and with the same fuel composition at the time of charge.,

period plus or minus the lead or lag times; thus the numerator of the fuel cost equation is a series of delta functions with nonzero values only at discrete times. Power is produced, however, on an assumed continuous basis, and REFCO assumes that the income from power sales is received continuously at time of production.

In order to calculate the cash payments for a cost item at time t after plant startup, the unit costs and the required quantities of materials and services are needed. The unit costs are given in the Economic Factors section of this report. The quantities required are obtained from reactor charge and discharge mass flow data.

The reactor charge and discharge mass flow data used in this analysis are those furnished to the NASAP program by various organizations and are summarized along with other information in Ref. 6.

The quantity of materials and services needed, based on the mass flow data, were adjusted for losses and then multiplied by the unit costs to obtain the cash payments. The cash payment lead and lag times, relative to when the material is charged or discharged from the reactor, are used to determine actual time of cash payment for the DCF analysis.

The charge and discharge mass flow information were often for capacity factors other than the 70% used in this analysis. In order to have the same fuel burnup in the REFCO calculation as for the original mass balances, the cycle times between refuelings were adjusted by the ratio of the capacity factor for the mass balances over the 70% capacity factor (e.g., for a 75% capacity factor, 30-year mass balance set with 1-year refueling interval, the refueling interval used in REFCO would be $75/70 = 1.0714$ years, and the reactor life would be 32.143 years).

ECONOMIC FACTORS

The economic factors used in the power generation cost calculations are given in Tables 5 through 9. These factors are the same as those recommended for the NASAP analysis. Both a reference value and the range of uncertainty are given for the unit cost numbers. The capital investment costs for the various power plants including interest during construction and owner's costs are given in Table 5. The reference fuel fabrication

Table 5. Capital investment costs
(1/1/78 \$/kWe)

Power plant type	Capital cost ^a	
	Reference	Range
PWR	800	800
HWR ^b	860	800-960
HTGR	840	800-960
LMFBR	1110	1000-1200
LWBR (high-gain converter)	820	825-880
LWBR (seed blanket)	840	840-920
FMSR	1110	1000-1200

^aCosts are for 1000-MWe-sized plants, including interest and 7% owner's cost during construction.

^bHeavy water excluded.

unit costs in Table 6 are the high-capacity industry unit costs recommended in the NASAP Economic Data Base.³ The total fuel cycle back end costs (Table 7) include shipping costs and either fuel element disposal costs in the case of the once-through systems or reprocessing and waste disposal costs in the case of recycle systems. The money costs used in the comparative analysis are given in Table 8. The analysis was done in constant January 1, 1978, dollars with no inflationary escalation of the unit prices of materials and services with time; inflation was also removed from the cost of money. Both the uninflated (i.e., those used in the analysis) and the corresponding actual costs of money (at a 5.5% inflation rate) are tabulated here.

The fissile plutonium and ²³³U prices (Table 9) are based on the analysis given in the Fissile Material Values section of this report. The plutonium and ²³³U values used for the power generation cost calculations are the indifference values of these fissile materials for recycle in standard light-water reactors (LWR). In the analysis where the recovery method was used to estimate the cost of plutonium makeup for the breeder, a nominal plutonium value of zero was assumed.

Table 6. Fabrication costs
(1/1/78 \$/kg·HM)

Reactor-fuel type	Unit cost	
	Reference	Range
<u>PWR</u>		
LEU5(U)		
Current	110	110
High burnup, 15% improved	120	110-150
30% improved	130	110-170
MEU5(U,Th)	120	110-150
MEU3(U,Th)	570	430-830
Pu(U)	370	280-540
Pu(U) - spiked	580	430-840
Pu(Th)	380	290-550
Pu(Th) - spiked	580	430-840
<u>HWR</u>		
LEU5(U)	75	70-80
MEU5(U,Th)	80	70-110
MEU3(U,Th)	490	370-710
<u>HTGR</u>	<u>C/HM</u>	
MEU5(U,Th) - OT	385	620
MEU5(U,Th)	295	550
MEU3(U,Th)	240	1230
HEU5(Th)	169	370
HEU5(Th) - spiked	169	840
HEU3(Th)	169	840
HEU3(Th)	143	660
MEU3(U,Th)	195	970
Pu(Th)	375	1460
<u>LMFBR</u>		
Pu(U)	580	430-810
Pu(U) - spiked	930	700-1320
Pu(Th)	590	440-820
Pu(Th) - spiked	1010	760-1440
U3(Th)	990	740-1400
UO ₂ radial blanket	130	100-170
ThO ₂ radial blanket	140	110-190
<u>LWBR/LWPR</u>		
Duplex fuel		
U5(Th)	180	140-260
U5(Th) - spiked	850	540-1450
<u>Single fuel</u>		
U5(Th)	120	110-150
U5(Th) - spiked	570	430-830
U3(Th)	570	430-830
Pu(Th)	380	290-550
Pu(Th) - spiked	580	430-840
Th blanket	120	110-150
<u>FMSR</u>		
LEU5(U)	240	210-270

Table 7. Total fuel cycle back end costs
(1/1/78 \$/kg•HM)

Reactor-fuel type	Unit cost	
	Reference	Range
<u>Once-through systems</u>		
PWR	135	70-200
HWR	70	40-110
HTGR	440	240-640
FMSR	210	110-310
<u>Recycle systems</u>		
PWR		
(U,Pu)O ₂	330	290-480
(U,Pu)O ₂ - spiked	350	310-520
(²³³ U,Th),O ₂	350	310-520
HWR		
(U,Pu)O ₂	290	260-450
(²³³ U,Th)O ₂	310	280-490
HTGR	C/HM	
MEU5, U3(Th)	295	580
MEU3(Th)	195	490
HEU5, U3(Th)	169	470
HEU3(Th)	143	450
Pu(Th)	375	690
LMFBR		
(Pu,U)O ₂	560	470-760
(Pu,U)O ₂ - spiked	610	510-820
(Pu,U,Th)O ₂	610	510-820
LWBR/LWPR		
(²³³ U,Th)O ₂	350	300-500
(Pu,Th)O ₂	350	300-500
Duplex pellet fuels	480	370-820

Table 8. Money costs for power plants

	Uninflated	Actual ^a
Debt interest, λ_b , %	2.5	8.1
Equity return, λ_e , %	7.0	12.9
Debt fraction, f_b	0.55	
Equity fraction, f_e	0.45	
Effective rate of return, %	4.53	10.3
Tax adjusted discount rate, %	3.84	9.55
Exponential discount rate, %	3.77	9.12
Effective income tax rate, %	50	
Fixed charge rate on capital, ^b %	10.1	15.8
Heavy-water fixed charge rate, ^b %	10.2	18.6

^aNormal utility practice, including inflation at 5.5% per year.

^bFixed charge rate breakdown:

	Power plant (%)		D ₂ O (%)	
	Uninflated	Actual	Uninflated	Actual
Return (effective interest rate)	4.525	10.26	4.5	10.3
Sinking fund depreciation	1.632	0.58		
Income tax	0.75	1.73	3.2	5.8
Property tax	2.50	2.50	2.5	2.5
Property insurance	0.25	0.25		
Interim replacement	0.35	0.35		
Decommissioning sinking fund	0.08	0.14		
Total fixed charge rate	10.1	15.8	10.2	18.6

Table 9. Additional data

Reference U ₃ O ₈ prices, \$/lb	40, 100, 160
Fissile material price, \$/g	
LWR indifference value	
Fissile Pu	22, ^a 46, ^b 69 ^c
²³³ U	24, ^a 62, ^b 101 ^c
Cost of converting U ₃ O ₈ to UF ₆ , \$/kg·U	4
Enrichment cost, \$/kg·SWU	100
Thorium cost, \$/kg·Th	38
HWR initial heavy-water cost, \$/kWe	
Reference	160
Range	130–190
Tails enrichment, %	0.2
Capacity factor, %	70
Fissile material losses, %	
Conversion	0.5
Fabrication	1.0
Reprocessing	1.0
Out of reactor time for recycle, years	2
(procurement + fabrication lead time + reprocessing lag time)	

^aAt U₃O₈ price of \$40/lb.

^bAt U₃O₈ price of \$100/lb.

^cAt U₃O₈ price of \$160/lb.

FISSILE MATERIAL VALUES

An important concern in the calculation of the power generation cost for a nuclear reactor is the price or value to assign to fissile plutonium and ²³³U. Two methods for estimating these values were considered. The first method bases the price of the fissile materials on the so-called "economic indifference value" for recycle in PWR reactors. The second method estimates the recovery value of the fissile material based on the cost of recovery from spent fuel assemblies.

Economic Indifference Value

The economic indifference values for fissile materials are those values which cause the power generation cost of interdependent fuel cycles to be the same. The fuel cycles are interdependent in that one is a net producer of fissile material which is needed by the other fuel cycle to operate. If a reactor has the option of using alternate fissile material as its fuel, the indifference value for the fissile material is that value which results in the same fuel cost as the normal fuel. Such a reactor system could be a PWR. It could alternately operate on low-enriched uranium (LEU), plutonium, or denatured ^{233}U fuel. If the price of plutonium is too cheap, it will be used as the fuel; if it is too expensive, lower power costs will be achieved using a uranium fuel and selling the plutonium. However, at the indifference value there is equal economic incentive for using plutonium as there is for using uranium fuels.

The long run price of the fissile materials, it is reasoned, will stabilize at such a price that the total power generation costs of the alternate options will be indifferent (i.e., the same). Assumptions implicit in this method are that the reactor operator will have the option of using any of the alternate fuel cycles, that the reactor operator will select that option which results in the lowest costs, and that a market exists for the fissile material.

In our analysis, the fissile material prices were established from the indifference value in LWR systems. Since the LWR is the predominant system at this time and probably will be for some time into the future, all alternate scenarios must start from the LWR base. If the use of Pu and ^{233}U is allowed in reactors, it will almost certainly be allowed in LWRs. Therefore, the price of Pu and ^{233}U will have some relation to its value as an alternate LWR fuel.

The indifference method assumes that the price of a fissile material will stabilize at such a price that the power generation cost of a net producer of the material will equal that of a net consumer. The power generation cost consists of three components: capital investment, operation and maintenance, and fuel cycle costs. If the competing systems are for the same type of reactor and if no additional cost to capital and O&M

are entailed in the use of alternate fuel cycles, the capital and O&M costs cancel out. Therefore, the indifference value in competing PWRs depends only on the fuel cycle cost components.

The fuel cycle cost may be expressed in the form of a generalized equation as follows,

$$FC = A \cdot V_{U_3O_8} + B \cdot V_C + C \cdot V_S + D \cdot V_F + E \cdot V_R + F \cdot V_{Pu} + G \cdot V^{233}U + H \cdot V_{Th} .$$

The V terms are the values of different services and commodities needed for the fuel cycle (i.e., U_3O_8 , UF_6 conversion, separative duty, fabrication, fuel recovery, plutonium, ^{233}U , and thorium respectively). The coefficients A through H were estimated using the REFCO fuel cycle cost code. They are, in essence, the sensitivity of the fuel cost to variations in the price of the various services and commodities. They include the effect of the direct cost and the indirect or carrying charges.

The indifference value for fissile plutonium was estimated from the fuel cycle cost equations for standard PWRs operating on

1. a low-enriched uranium feed (LEU),
2. a plutonium in natural uranium feed [Pu(U)].

The LEU fuel cycle is assumed to sell its recovered plutonium to the Pu(U) fuel cycle which also recycles its plutonium. Recovered uranium from the LEU reactor is returned to the diffusion plant for reenrichment. No credit is taken for uranium recovered from the Pu(U) fuel cycle.

The two unknowns, fuel cycle cost and plutonium value, are established from the two fuel cycle cost equations. The fuel cycle cost and the plutonium value were then used with the derived fuel cycle cost equation for a denatured (medium enriched) ^{233}U in thorium [MEU3(Th)] fueled PWR to establish a price for ^{233}U . By estimating the value of ^{233}U in this manner, without specifying the source of the ^{233}U , we are saying that this must be the value of ^{233}U , no matter what the source, for it to be competitive with plutonium and low-enriched uranium.

Table 10 shows the coefficients of the fuel cycle cost equation for each of the three fuels in this analysis. The values used for the costs of materials and services are the reference values given in the Economic

Table 10. Fuel cost equation coefficients

Coefficient	Cost multiplier	Units	Coefficients for reactor fuel cycle		
			LEU	Pu/U	DU/Th
A	U ₃ O ₈	\$/lb	0.06158	0.01308	0.0
B	UF ₆ conversion	\$/kg·U	0.02369	0.0	0.0
C	Separative work	\$/SWU	0.02101	0.0	0.0
D	Fabrication	\$/kg	0.00529	0.00532	0.00484
E	Back end ^a	\$/kg	0.00348	0.00349	0.00318
F	Fissile Pu	\$/g	-0.02257	0.10150	-0.00822
G	²³³ U	\$/g	0.0	0.0	0.08688
H	Thorium	\$/kg	0.0	0.0	0.00356

^aIncludes reprocessing, shipping, and waste disposal.

Factors section of this report. The resultant values for fissile plutonium and ²³³U are given in Table 11. Values at other U₃O₈ prices may be obtained by linear extrapolation. The prices obtained for fissile plutonium and ²³³U in this analysis (rounded to the nearest dollar) are the reference values used in the fuel cost and power generation cost calculations.

These reference plutonium and ²³³U values were used for the high- and low-uncertainty range calculations described in Appendix A as well as the calculations at the reference parameter values. The indifference values for fissile plutonium and ²³³U calculated using the reprocessing and refabrication cost numbers at the upper end of the uncertainty range are less than the reference plutonium and ²³³U prices. The resultant plutonium and ²³³U prices using fuel cycle service costs at the lower end of the uncertainty range are greater than the reference values. This effect would tend to reduce the fuel cycle and power generation cost uncertainties shown in Appendix A for fuel cycles using recycled fissile material.

Table 11. Fissile material value
using indifference method

U ₃ O ₈ price (\$/lb)	Fissile material value (\$/g)	
	²³⁹ Pu + ²⁴¹ Pu	²³³ U
40	22	24
100	46	62
160	69	101

Recovery Method

A second method, which is sometimes used for estimating the cost of plutonium to a plutonium fueled reactor, is the recovery cost method. This method is appropriate if there is a large stockpile of unprocessed spent PWR-LEU fuel assemblies and/or if a free, balanced supply-and-demand market for plutonium does not exist. These conditions are likely to occur in the early days of commercial reprocessing. There may be variations in the cost method depending on who is given credit (or charged) for what, but in essence, the fuel cycle using the recovered plutonium is charged (or credited) with the incremental costs (or savings) to the overall system of utilizing the plutonium recovered from the spent PWR-LEU fuel.

The incremental costs incurred include the cost of reprocessing the spent fuel to obtain the fuel cycle's plutonium needs which are not directly met by recycle in the plutonium consuming fuel cycle. There are also the costs of fabrication of this fuel and the cost of disposal of reprocessing plant wastes. Various cost savings and credits are also obtained by reprocessing the spent fuel. These savings include the value of the uranium recovered by reprocessing and the reduced disposal requirements for spent PWR-LEU fuel assemblies. In this analysis, these savings are credited to the system utilizing the recovered plutonium.

The net cost to the fuel cycle of obtaining fabricated plutonium fuel is the cost of fabrication, plus the cost of reprocessing PWR-LEU fuel (includes reprocessing, shipping, and waste disposal), minus the value of

recovered uranium (U_3O_8 , SWU, and conversion equivalence), minus the reduced cost of disposing spent PWR-LEU fuel assemblies.

It is assumed that all bred fissile material is produced and used internally by a utility system. There are no direct cash payments for plutonium, and the value of plutonium is nominally taken to be zero. Credit is not taken for surplus plutonium created in a breeder system since this plutonium is assumed to be used in future breeders within the same utility system.

If a free, balanced supply-and-demand market were to exist in plutonium, the value of plutonium would adjust to some economic indifference values. A utility may then find it more economically advantageous to sell plutonium from its spent PWR fuel or to buy it for its plutonium consuming fuel cycle. Even with a free market, a utility with a large supply of spent PWR-LEU fuel may find it advantageous to use plutonium obtained from this fuel within the utility system.

The power generation cost calculations, based on the recovery method contained in this report, assume plutonium is recovered from spent standard PWR fuel assemblies. The 30-year average recoverable content of standard PWR fuel is summarized in Table 12.

Table 12. Recoverable content of
standard PWR spent fuel

Cost item	Average ^a equivalent content (per kg·HM of spent fuel)
Fissile plutonium, g	6.51
U_3O_8 , lb	3.44
Conversion, kg·U	1.32
Enrichment, SWU	0.236

^aAverage over 30-year reactor life.

As uranium prices rise, the credit for recovered uranium increases, and the resulting power generation costs of the plutonium using system decreases. This is in contrast to the rising power costs as a function

of the U_3O_8 estimated price when the economic indifference method is used to obtain a plutonium price.

As shown in Fig. 3 for PWRs, the power cost calculated using the recovery method is equal to that using the indifference method at about the U_3O_8 price where economic transition from the PWR-LEU once-through fuel cycle occurs. If carrying charges are not included in the cost calculation, these three lines would meet at exactly the same point.

Although a plutonium price is not calculated directly when using the recovery method evaluation procedure, a shadow price can be estimated. This is the price of plutonium which causes the reprocessing of the PWR-LEU spent fuel to break even financially. It is the minimum price which the plutonium can have for reprocessing to be economic. This price decreases with increasing U_3O_8 prices. It will be zero at the U_3O_8 price where reprocessing is economic with only uranium recovery.

Fig. 3. PWR power generation costs for alternate plutonium valuation.

It should be emphasized that the price of fissile materials and/or the economics of recycle are dependent on the future costs for fuel cycle services as well as the reactor and fuel cycle scenarios. Assumptions other than those used here for fabrication and reprocessing unit costs, money costs, the dominant LWR-LEU spent fuel (standard, 15% improved), or the dominant symbiotic system for determining fissile material indifference values will produce different plutonium and ^{233}U prices and different economic transition points than those found here. The purpose of this analysis was not to obtain values for all systems and fuels, but to obtain a reasonable value for plutonium and ^{233}U with which a survey cost analysis could be made.

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APPENDIXES

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Appendix A

POWER GENERATION COST RANGES

It is difficult to determine the unit prices for services that have never been routinely implemented (i.e., spent fuel shipping). The task of assigning prices to services that have yet to be utilized (i.e., permanent waste disposal) is even more difficult. In order to examine the effects of uncertainties, the fuel and power generation costs were estimated using values for the material and service prices at the high and low end of the estimated range of uncertainty.

The uncertainty range in the fuel cycle cost is shown in Table A.1, and the corresponding range for the power generation cost is given in Table A.2. These are the same reactor systems whose reference costs were given in Tables 3 and 4. The fuel and power generation costs at the low and high end of the range were computed, using the set of unit prices at the low and high ends, respectively, of the range of uncertainty as presented in Tables 5 through 7.

The reactors are identified by the description supplied under the reactor-fuel type description heading (Tables A.1 and A.2). The first abbreviation describes the reactor type followed by an abbreviation which describes the fuel type used. The fuel costs were computed using the mass balances for each system along with the necessary unit cost information. The Methodology section of this report describes in detail how the fuel cycle costs were computed.

There are three categories by which each of the systems can be characterized. Once-through systems dispose of the spent fuel after a certain cool-down period, taking no credit for the remaining or bred fissile materials. Uranium-only recycle systems take credit only for fissile uranium, ^{235}U , and/or ^{233}U , in the spent fuel. No credit is assumed for discharged fissile plutonium. Full recycle systems take credit for all fissile material in the spent fuel, except in cases where the fissile enrichment of the ^{235}U is less than tails. Some systems, such as the PWR-LEU(5), can operate in more than one of the categories, whereas other systems, such as the LMFBRs, are limited to only one type of characterization.

Table A.1. Fuel cycle costs
(mills/kWh)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
A. Once-through systems			
PWR — LEU5(U)	6.0—6.5	10.4—10.9	14.8—15.2
PWR — LEU5(U) — X	5.6—6.0	9.6—10.0	13.6—14.0
PWR — LEU5(U) — 15%	5.3—5.8	9.2—9.6	13.1—13.5
PWR — LEU5(U) — 30%	4.5—4.9	7.8—8.2	11.1—11.5
HWR — LEU5(U)	3.1—3.6	5.6—6.1	8.0—8.5
HTGR — MEU5(U,Th)	5.6—6.3	8.9—9.6	12.2—13.0
HTGR — MEU5(U,Th) — 6	5.1—6.0	8.1—9.0	11.1—12.0
FMSR — LEU5(U)	5.3—5.8	8.8—9.3	12.3—12.8
B. Uranium only recycle			
PWR — LEU5(U)	6.3—6.9	9.9—10.6	13.6—14.3
PWR — LEU5(U) — X	5.7—6.2	9.4—9.9	13.0—13.5
PWR — LEU5(U) — 15%	5.5—6.0	9.0—9.5	12.5—13.0
PWR — LEU5(U) — 30%	4.8—5.3	7.9—8.4	11.0—11.5
PWR — MEU5,U3(U,Th)	7.9—9.9	11.6—13.6	15.4—17.4
PWR — MEU3(U,Th)	5.3—7.9	8.6—11.2	12.0—14.6
HWR — LEU5(U)	4.4—5.6	6.8—8.1	9.3—10.5
HWR — MEU5,U3(U,Th)	9.8—14.9	12.2—17.4	14.7—19.8
HWR — MEU5,U3(U,Th) — X	5.1—6.9	7.1—8.9	9.1—10.9
HWR — MEU3(U,Th)	8.0—13.2	10.3—15.6	12.8—18.0
HTGR — MEU5,U3(U,Th)	4.7—5.8	7.2—8.3	9.7—10.8
HTGR — HEU5,U3(Th)	4.8—6.2	7.0—8.4	9.3—10.6
HTGR — HEU5,U3(Th) — S	5.3—7.1	7.5—9.3	9.7—11.5
HTGR — HEU3(Th)	4.2—7.7	6.0—9.6	8.0—11.5
HTGR — MEU3(U,Th)	4.4—6.9	7.1—9.5	9.8—12.2
LWPR — MEU5(Th) — B	7.9—8.7	11.0—11.8	14.2—15.0
LWPR — HEU5(Th) — B,S	9.4—11.9	12.6—15.1	15.7—18.2
LWPR — MEU5(U,Th) — HGC,B	10.8—13.5	15.3—17.9	19.6—22.3
LWPR — HEU5(Th) — HGC,B	9.9—12.5	13.1—15.8	16.3—19.0
LWPR — HEU5(Th) — HGC,S	12.3—19.8	15.6—23.1	18.7—26.2
LWPR — MEU5(U,Th) — TIM	15.2—22.0	19.8—26.6	24.3—31.1
LWBR — HEU3(Th) — SB	12.0—18.7	16.3—23.0	20.6—27.2
LWBR — HEU3(Th) — HGC	12.2—20.1	14.6—22.6	17.2—25.1
LWBR — HEU3(Th) — HGC,X	7.3—11.7	9.6—14.0	12.0—16.4
LWBR — MEU3(U,Th) — HGC	6.5—9.9	9.6—13.0	12.8—16.2
LWBR — HEU3(Th) — TIM	17.7—29.9	21.7—33.9	25.7—38.0

Table A.1 (continued)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
C. Full recycle credit			
PWR — LEU5(U)	5.8–6.4	8.9–9.6	12.1–12.7
PWR — LEU5(U) — X	5.4–5.9	8.7–9.2	12.0–12.6
PWR — LEU5(U) — 15%	5.2–5.7	8.3–8.8	11.4–11.9
PWR — LEU5(U) — 30%	4.5–5.0	7.3–7.8	10.2–10.7
PWR — MEU5, U3(U, Th)	7.7–9.7	11.3–13.3	14.8–16.8
PWR — MEU3(U, Th)	5.1–7.7	8.2–10.8	11.4–14.0
PWR — LEU5, Pu(U)	5.6–6.6	8.7–9.7	11.8–12.7
PWR — LEU5, Pu(U) — S	5.8–7.1	8.9–10.2	12.0–13.3
PWR — LEU5, Pu(U) — X	5.3–5.9	8.7–9.3	12.0–12.6
PWR — LEU5, Pu(U) — X, S	5.4–6.1	8.7–9.4	12.1–12.8
PWR — Pu(U)	5.3–7.3	8.5–10.5	11.6–13.6
PWR — Pu(U) — S	6.1–9.0	9.3–12.3	12.5–15.4
PWR — Pu(U) — X	4.8–6.1	8.4–9.7	11.9–13.2
PWR — Pu(U) — X, S	5.4–7.3	9.0–10.9	12.4–14.3
PWR — Pu(Th)	5.6–7.5	8.4–10.3	11.0–13.0
PWR — Pu(Th) — S	6.2–8.9	9.1–11.7	11.7–14.4
HWR — LEU5(U)	4.0–5.2	5.9–7.1	7.9–9.1
HWR — MEU5, U3(U, Th)	9.7–14.8	12.1–17.2	14.5–19.6
HWR — MEU5, U3(U, Th) — X	5.1–6.8	7.0–8.8	9.0–10.8
HWR — MEU3(U, Th)	7.9–13.2	10.2–15.4	12.5–17.8
HTGR — MEU5, U3(U, Th)	4.6–5.8	7.0–8.2	9.5–10.6
HTGR — MEU3(U, Th)	4.3–6.7	6.8–9.2	9.3–11.7
HTGR — Pu(Th)	3.9–5.6	5.8–7.5	7.5–9.2
LMFBR — Pu(U)/U/U — HT	5.6–8.5	7.3–10.2	8.9–11.8
LMFBR — Pu(U)/U/U — HT, S	6.7–10.6	8.4–12.3	10.0–13.9
LMFBR — Pu(U)/Th/Th — HT	6.1–9.1	7.3–10.4	8.4–11.4
LMFBR — Pu(U)/Th/Th/ — HT, S	7.0–10.9	8.3–12.2	9.4–13.3
LMFBR — Pu(U)/U/U — HM	4.3–6.8	5.4–7.9	6.4–8.9
LMFBR — Pu(U)/U/U — HM, s	5.4–8.8	6.5–9.8	7.5–10.9
LMFBR — Pu(U)/Th/Th — HM	4.4–6.9	5.0–7.5	5.5–7.9
LMFBR — Pu(U)/Th/Th — HM, S	5.3–8.5	5.9–9.1	6.4–9.6
LMFBR — Pu(Th)/Th/Th — HM	5.4–8.1	6.0–8.6	6.2–8.9
LMFBR — Pu(Th)/Th/Th — HM, S	6.6–10.3	7.1–10.8	7.3–11.1
LMFBR — MEU3(U)/Th/Th — HM	6.5–10.3	9.4–13.2	12.4–16.3
LWPR — MEU5(U, Th) — HGC, B	10.4–13.0	14.3–16.9	18.2–20.8
LWPR — Pu(Th) — HGC	6.8–9.4	9.6–12.2	12.1–14.7
LWPR — Pu(Th) — HGC, S	7.6–11.0	10.4–13.8	12.9–16.4
LWPR — MEU5(U, Th) — T1M	15.0–21.8	19.3–26.1	23.7–30.4
LWBR — MEU3(U, Th) — HGC	6.2–9.6	9.1–12.5	12.0–15.4

Table A.2. Power generation costs
(mills/kWh)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
A. Once-through systems			
PWR — LEU5(U)	21.4–21.9	25.8–26.3	30.2–30.7
PWR — LEU5(U) — X	21.0–21.4	25.0–25.4	29.0–29.4
PWR — LEU5(U) — 15%	20.8–21.2	24.6–25.0	28.5–28.9
PWR — LEU5(U) — 30%	19.9–20.4	23.2–23.6	26.5–26.9
HWR — LEU5(U)	21.1–25.3	23.6–27.8	26.1–30.3
HTGR — MEU5(U,Th)	20.8–24.2	24.1–27.5	27.5–30.8
HTGR — MEU5(U,Th) — 6	21.0–21.9	24.1–24.9	27.1–27.9
FMSR — LEU5(U)	24.7–28.5	28.2–31.9	31.6–35.4
B. Uranium-only recycle			
PWR — LEU5(U)	21.7–22.3	25.4–26.0	29.1–29.7
PWR — LEU5(U) — X	21.1–21.7	24.8–25.3	28.4–29.0
PWR — LEU5(U) — 15%	20.9–21.4	24.4–24.9	27.9–28.4
PWR — LEU5(U) — 30%	20.2–20.7	23.3–23.8	26.4–27.0
PWR — MEU5,U3(U,Th)	23.3–25.3	27.0–29.1	30.8–32.8
PWR — MEU3(U,Th)	20.7–23.3	24.0–26.6	27.4–30.0
HWR — LEU5(U)	22.4–27.3	24.9–29.8	27.3–32.2
HWR — MEU5,U3(U,Th)	27.8–36.6	30.2–39.1	32.7–41.5
HWR — MEU5,U3(U,Th) — X	23.1–28.6	25.1–30.6	27.1–32.6
HWR — MEU3(U,Th)	26.0–35.0	28.4–37.3	30.8–39.7
HTGR — MEU5,U3(U,Th)	19.9–23.7	22.4–26.2	24.9–28.7
HTGR — HEU5,U3(Th)	20.1–24.1	22.3–26.3	24.5–28.5
HTGR — HEU5,U3(Th) — S	20.5–24.9	22.7–27.2	24.9–29.4
HTGR — HEU3(Th)	19.4–25.6	21.3–27.4	23.2–29.3
HTGR — MEU3(U,Th)	19.7–24.7	22.3–27.4	25.0–30.0
LWPR — MEU5(Th) — B	23.9–26.1	27.1–29.2	30.2–32.3
LWPR — HEU5(Th) — B,S	25.5–29.3	28.6–32.5	31.7–35.6
LWPR — MEU5(U,Th) — HGC,B	26.6–30.2	31.1–34.7	35.4–39.0
LWPR — HEU5(Th) — HGC,B	25.7–29.3	28.9–32.5	32.1–35.7
LWPR — HEU5(Th) — HGC,S	28.1–36.6	31.4–39.8	34.5–43.0
LWPR — MEU5(U,Th) — TIM	31.2–39.4	35.8–43.9	40.4–48.5
LWBR — HEU3(Th) — SB	28.1–36.1	32.3–40.3	36.6–44.6
LWBR — HEU3(Th) — HGC	28.0–36.9	30.4–39.3	33.0–41.8
LWBR — HEU3(Th) — HGC,X	23.1–28.4	25.4–30.8	27.8–33.2
LWBR — MEU3(U,Th) — HGC	22.3–26.6	25.4–29.7	28.6–32.9
LWBR — HEU3(Th) — TIM	33.8–47.3	37.8–51.3	41.8–55.3

Table A.2 (continued)

Reactor-fuel type description	U ₃ O ₈ price (\$/lb)		
	40	100	160
C. Full recycle credit			
PWR — LEU5(U)	21.2–21.8	24.3–25.0	27.5–28.2
PWR — LEU5(U) — X	20.8–21.3	24.1–24.6	27.4–28.0
PWR — LEU5(U) — 15%	20.6–21.1	23.7–24.2	26.8–27.3
PWR — LEU5(U) — 30%	19.9–20.4	22.7–23.3	25.6–26.1
PWR — MEU5,U3(U,Th)	23.1–25.2	26.7–28.7	30.2–32.3
PWR — MEU3(U,Th)	20.5–23.1	23.6–26.2	26.8–29.4
PWR — LEU5,Pu(U)	21.0–22.0	24.1–25.0	27.2–28.2
PWR — LEU5,Pu(U) — S	21.3–22.5	24.3–25.6	27.4–28.7
PWR — LEU5,Pu(U) — X	20.7–21.3	24.1–24.7	27.4–28.0
PWR — LEU5,Pu(U) — X,S	20.8–21.5	24.2–24.8	27.5–28.2
PWR — Pu(U)	20.7–22.7	23.9–25.9	27.0–29.1
PWR — Pu(U) — S	21.5–24.4	24.8–27.7	27.9–30.8
PWR — Pu(U) — X	20.2–21.5	23.8–25.1	27.3–28.6
PWR — Pu(U) — X,S	20.8–22.7	24.4–26.3	27.8–29.7
PWR — Pu(Th)	21.0–22.9	23.8–25.7	26.5–28.4
PWR — Pu(Th) — S	21.6–24.3	24.5–27.1	27.1–29.8
HWR — LEU5(U)	22.0–26.9	23.9–28.9	25.9–30.9
HWR — MEU5,U3(U,Th)	27.7–36.6	30.1–38.9	32.5–41.3
HWR — MEU5,U3(U,Th) — X	23.1–28.6	25.1–30.5	27.0–32.5
HWR — MEU3(U,Th)	26.0–34.9	28.2–37.2	30.6–39.5
HTGR — MEU5,U3(U,Th)	19.9–23.6	22.3–26.1	24.7–28.5
HTGR — MEU3(U,Th)	19.6–24.6	22.0–27.1	24.6–29.6
HTGR — Pu(Th)	19.2–23.5	21.0–25.4	22.7–27.1
LMFBR — Pu(U)/U/U — HT	25.0–31.2	26.6–32.9	28.2–34.5
LMFBR — Pu(U)/U/U — HT, S	26.1–33.3	27.8–35.0	29.4–36.6
LMFBR — Pu(U)/Th/Th — HT	25.4–31.7	26.7–33.0	27.8–34.1
LMFBR — Pu(U)/Th/Th/ — HT,S	26.4–33.6	27.7–34.8	28.7–35.9
LMFBR — Pu(U)/U/U — HM	23.7–29.5	24.8–30.6	25.8–31.6
LMFBR — Pu(U)/U/U — HM,s	24.8–31.4	25.8–32.5	26.9–33.5
LMFBR — Pu(U)/Th/Th — HM	23.8–29.5	24.4–30.1	24.8–30.6
LMFBR — Pu(U)/Th/Th — HM,S	24.7–31.2	25.3–31.8	25.7–32.3
LMFBR — Pu(Th)/Th/Th — HM	24.8–30.8	25.3–31.3	25.6–31.5
LMFBR — Pu(Th)/Th/Th — HM,S	25.9–33.0	26.5–33.5	26.7–33.7
LMFBR — MEU3(U)/Th/Th — HM	25.9–33.0	28.7–35.9	31.8–38.9
LWPR — MEU5(U,Th) — HGC,B	26.2–29.8	30.1–33.7	34.0–37.6
LWPR — Pu(Th) — HGC	22.6–26.1	25.4–28.9	27.9–31.5
LWPR — Pu(Th) — HGC,S	23.4–27.8	26.2–30.6	28.7–33.1
LWPR — MEU5(U,Th) — TIM	31.0–39.1	35.4–43.5	39.7–47.8
LWBR — MEU3(U,Th) — HGC	22.0–26.4	24.9–29.2	27.8–32.1

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Appendix B

COST SENSITIVITY PARAMETERS

The fuel cost for an oil- or coal-fired power plant is composed of the cost of the oil or coal plus the necessary transportation costs. Even though the cost of fueling a nuclear power plant is a much smaller percentage of the total power generating cost when compared to the cost of fueling a fossil plant, the nuclear fuel cost is generally more complicated to estimate. This difficulty is due to the fact that the nuclear fuel must undergo several costly operations before it is ready to use and after it has been removed from the reactor.

The fuel cycle cost may be expressed in the form of a generalized equation as follows,

$$FC = \sum C_i V_i .$$

The V terms are the values of the various services and commodities needed for the fuel cycle (i.e., U_3O_8 , enrichment, plutonium). The C terms were estimated using the REFCO fuel cycle cost code. They are, in essence, the sensitivity of the fuel cost to variations in the price of the various services and commodities. They include the effect of the direct cost and the indirect or carrying charges. These sensitivity parameters are given in Table B.1 for each of the fuel cycles considered in this report.

These coefficients are a function of the mass flow information, timing of the service or purchase, and money costs. As long as these are constant, the coefficients will adequately describe the cost of each component after multiplying by a chosen unit cost. Each heading in Table B.1 describes what the coefficient is for, and the units under the heading prescribe the proper units of the unit cost so that after multiplying, the resulting cost will be correct. Starting at the left-hand side, activities that usually occur first are specified, such as thorium purchase through enrichment, fabrication, back end cost, and material credits. When asterisks appear in place of the coefficient, the credit is negative and should be assumed to be a zero coefficient.

For those systems which have two different types of fabrication streams (e.g., self-generated recycle in PWRs), the sensitivity parameter

Table B.1. Fuel cycle cost equations
(0.200% tails)

REACTOR-FUEL TYPE DESCRIPTION	THORIUM \$/KG-TH	PL-FISS \$/G-PU	U-233 \$/G-U23	U308 \$/LB	CONV \$/KG-U	SWU \$/KG	FAB1 \$/KG-HM	FAB2 \$/KG-HM	BACKEND \$/KG-HM	PU-FISS CREDIT \$/G-PU	U-233 CREDIT \$/G-U23	U308 CREDIT \$/LB	CONV CREDIT \$/KG-U	SWU CREDIT \$/KG
ONCE-THROUGH SYSTEMS														
PWR-LEU5(U)	.0	.C	.0	.073061	.028100	.021678	.005294	.0	.003484	.0	.0	.0	.0	.0
PWR-LEU5(U)-X	.0	.C	.0	.067176	.025837	.022466	.003570	.0	.002032	.0	.0	.0	.0	.0
PWR-LEU5(U)-15%	.0	.C	.0	.064522	.024815	.021307	.003578	.0	.002039	.0	.0	.0	.0	.0
PWR-LEU5(U)-30%	.0	.C	.0	.054921	.021123	.017898	.003152	.0	.001679	.0	.0	.0	.0	.0
HWR-LEU5(U)	.0	.C	.0	.041241	.015862	.005143	.008691	.0	.006020	.0	.0	.0	.0	.0
HTGR-MEU5(U,TH)	.000645	.C	.0	.055519	.021354	.025062	.001199	.0	.000681	.0	.0	.0	.0	.0
HTGR-MEU5(U,TH)-6	.000794	.C	.0	.050038	.019245	.022587	.001293	.0	.000743	.0	.0	.0	.0	.0
FMSR-LEU5(U)	.0	.C	.0	.057866	.020935	.019895	.003941	.0	.001165	.0	.0	.0	.0	.0
URANIUM ONLY RECYCLE														
PWR-LEU5(U)	.0	.C	.0	.073061	.028100	.021678	.005294	.0	.003484	.0	.0	.011479	.004415	.000665
PWR-LEU5(U)-X	.0	.C	.0	.067176	.025837	.022466	.003570	.0	.002032	.0	.0	.006343	.002440	.000409
PWR-LEU5(U)-15%	.0	.C	.0	.064522	.024815	.021307	.003578	.0	.002039	.0	.0	.006184	.002579	.000325
PWR-LEU5(U)-30%	.0	.C	.0	.054921	.021123	.017898	.003152	.0	.001679	.0	.0	.002893	.001113	*****
PWR-MEU5,U3(U,TH)	.003727	.C	.0	.046672	.017948	.029980	.034129	.001613	.003228	.003178	.0	.039834	.020139	.007746
PWR-MEU5(U,TH)	.005565	.C	.0	.147170	.0	.0	.004845	.0	.003181	.0	.0	.060287	.0	.0
HWR-LEU5(U)	.0	.C	.0	.041241	.015862	.005143	.008691	.0	.006020	.0	.0	.000393	.000151	*****
HWR-MEU5,U3(U,TH)	.010178	.C	.0	.102444	.052907	.020349	.021652	.001793	.009768	.008329	.0	.096984	.015664	.006025
HWR-MEU5,U3(U,TH)-X	.003993	.C	.0	.037161	.036527	.014049	.015595	.001463	.003202	.002927	.0	.037261	.003270	.001258
HWR-MEU3(U,TH)	.009822	.C	.0	.178175	.001243	.0	.0	.010407	.0	.008148	.0	.116002	.001341	.0
HTGR-MEU5,U3(U,TH)	.000655	.C	.0	.015156	.044131	.016973	.019553	.001121	.000283	.000798	.0	.013246	.003743	.001440
HTGR-MEU5,U3(TH)	.002230	.C	.0	.039830	.038901	.014962	.018956	.001259	.001131	.001392	.0	.033808	.005872	.002759
HTGR-MEU3(TH)	.003618	.C	.0	.110985	.0	.0	.0	.003989	.0	.002402	.0	.061974	.0	.0
HTGR-MEU3(U,TH)	.001193	.C	.0	.112626	.0	.0	.0	.002748	.0	.001749	.0	.043703	.0	.0
LWPR-MEU5(TH)-B	.004548	.C	.0	.097629	.037549	.048460	.004754	.0	.003110	.0	.0	.042411	.018095	.006959
LWPR-MEU5(U,TH)-HGC,B	.007452	.C	.0	.145575	.055990	.065774	.006127	.002744	.004053	.0	.0	.043198	.044367	.017064
LWPR-MEU5(TH)-HGC,B	.003603	.C	.0	.126430	.048627	.062749	.006127	.002744	.004031	.0	.0	.058850	.035432	.013629
LWPR-MEU5(U,TH)-TIM	.014387	.C	.0	.141847	.073787	.086681	.016282	.0	.010756	.0	.0	.052555	.081987	.031555
LWBR-MEU3(TH)-SB	.011936	.C	.0	.279265	.042788	.016457	.020152	.012468	.0	.008559	.0	.199389	.023142	.008901
LWBR-MEU3(TH)-HGC	.017488	.C	.0	.232951	.0	.0	.0	.012774	.004873	.013173	.0	.168277	.0	.0
LWBR-MEU3(TH)-HGC,X	.010006	.C	.0	.126666	.0	.0	.0	.007657	.002475	.006239	.0	.065304	.0	.0
LWBR-MEU3(U,TH)-HGC	.006549	.C	.0	.152417	.0	.0	.0	.005743	.002475	.005060	.0	.070723	.0	.0
LWBR-MEU3(TH)-TIM	.022378	.C	.0	.330076	.0	.0	.0	.022766	.0	.015590	.0	.226180	.0	.0

Table B.1 (continued)

REACTOR-FUEL TYPE DESCRIPTION	THORIUM \$/KG-TH	PU-FISS \$/G-PU	U-233 \$/G-U23	U308 \$/LB	CONV \$/KG-U	SWU \$/KG	FAB1 \$/KG-HM	FAB2 \$/KG-HM	BACKEND \$/KG-HM	PU-FISS CREDIT \$/G-PU	U-233 CREDIT \$/G-U23	U308 CREDIT \$/LB	CONV CREDIT \$/KG-U	SWU CREDIT \$/KG
FULL RECYCLE														
PWR-LEU5(U)	.0	.0	.0	.073061	.028100	.021678	.005294	.0	.003484	.022567	.0	.011479	.004415	.000665
PWR-LEU5(U)-X	.0	.0	.0	.067176	.025837	.022466	.003570	.0	.002032	.014378	.0	.006343	.002440	.000409
PWR-LEU5(U)-15%	.0	.0	.0	.064522	.024816	.021307	.003578	.0	.002039	.015998	.0	.006184	.002379	.000323
PWR-LEU5(U)-30%	.0	.0	.0	.054921	.021123	.017898	.003152	.0	.001679	.012513	.0	.002893	.001113	*****
PWR-MEU5,U3(U,TH)	.003727	.0	.046672	.077948	.029980	.034129	.001613	.003228	.003178	.007755	.039834	.020139	.007746	.007774
PWR-MEU5(U,TH)	.003565	.0	.147170	.0	.0	.0	.004843	.0	.003181	.008215	.060287	.0	.0	.0
PWR-LEU5,PU(U)	.0	.032472	.0	.060762	.022192	.017322	.004069	.001221	.003480	.031564	.0	.009669	.003719	.000744
PWR-LEU5,PU(U)-X	.0	.022659	.0	.060753	.023057	.019974	.003225	.000345	.002051	.021607	.0	.005611	.002158	.000528
PWR-PU(U)	.0	.195655	.0	.013085	.0	.0	.005319	.0	.003492	.094154	.0	.0	.0	.0
PWR-PU(U)-X	.0	.208317	.0	.008473	.0	.0	.003595	.0	.002038	.079345	.0	.0	.0	.0
PWR-PU(TH)	.004587	.262824	.0	.0	.0	.0	.004840	.0	.003168	.087952	.035334	.0	.0	.0
HWR-LEU5(U)	.0	.0	.0	.041241	.015862	.005143	.008691	.0	.006020	.020158	.0	.000393	.000151	*****
HWR-MEU5,U3(U,TH)	.010178	.0	.102444	.052907	.020349	.021652	.001793	.009768	.008529	.002749	.096984	.015664	.006025	.005313
HWR-MEU5,U3(U,TH)-X	.003993	.0	.037161	.036527	.014049	.015595	.001463	.003202	.002927	.001436	.037261	.003270	.001258	.000788
HWR-MEU3(U,TH)	.009822	.0	.178175	.001243	.0	.0	.010407	.0	.008148	.003161	.116002	.001341	.0	.0
HTGR-MEU5,U3(U,TH)	.000853	.0	.015156	.044131	.016973	.019555	.001121	.000283	.000798	.003055	.013246	.003743	.001440	.001156
HTGR-MEU3(U,TH)	.001793	.0	.112626	.0	.0	.0	.002748	.0	.001749	.006300	.043703	.0	.0	.0
HTGR-PU(TH)	.001175	.135996	.0	.0	.0	.0	.001369	.0	.000821	.024294	.022155	.0	.0	.0
LMFBR-PU(U)/U/U-HT	.0	.331378	.0	.0	.0	.0	.003546	.003552	.004653	.261651	.0	.0	.0	.0
LMFBR-PU(U)/T/T-HT	.003378	.356150	.0	.0	.0	.0	.003549	.003378	.004529	.220986	.051841	.0	.0	.0
LMFBR-PU(U)/U/U-HM	.0	.255175	.0	.0	.0	.0	.003399	.002086	.003586	.208338	.0	.0	.0	.0
LMFBR-PU(U)/T/T-HM	.003072	.255257	.0	.0	.0	.0	.003283	.001898	.003388	.169371	.038767	.0	.0	.0
LMFBR-PU(T)/T/T-HM	.005261	.318090	.0	.0	.0	.0	.003557	.002111	.003709	.158226	.099905	.0	.0	.0
LMFBR-MEU3(U)/T/T-HM	.003538	.0	.234834	.0	.0	.0	.003793	.002177	.003756	.062245	.119542	.0	.0	.0
LWPR-MEU5(U,TH)-HGC,B	.007432	.0	.0	.145575	.055990	.065774	.006127	.002744	.004053	.021286	.043198	.044367	.017064	.018550
LWPR-PU(TH)-HGC	.007948	.275184	.0	.0	.0	.0	.005745	.002475	.005060	.091029	.042792	.0	.0	.0
LWPR-MEU5(U,TH)-T1M	.014387	.0	.0	.191847	.073787	.086681	.016282	.0	.010756	.009631	.052553	.081987	.031533	.035918
LWPR-MEU3(U,TH)-HGC	.006949	.0	.152417	.0	.0	.0	.005743	.002475	.005060	.011521	.070723	.0	.0	.0

given under the FAB1 heading is that for the fresh fuel [e.g., LEU5(U)], while the cost sensitivity parameter under FAB2 represents the recycle fuel [e.g., Pu(U)] or the radial blanket fuel in the case of the breeder.

These sensitivities give valuable insight into how the fuel costs would respond to rising unit prices. They also enable the reader to estimate fuel and power generation costs for commodity and service prices other than those presented in this report.

Appendix C

TABLE OF NOMENCLATURE

Reactor/Fuel DescriptionsReactor types

PWR	Pressurized water reactor
HWR	Heavy-water reactor
HTGR	High-temperature gas-cooled reactor
LMFBR	Liquid-metal fast breeder reactor
LWPR	Light water pre-breeder reactor
LWBR	Light water breeder reactor
FMSR	Fast mixed spectrum reactor

Fuel types

LE	Low enriched (<10%)
ME	Medium enriched (10-20%)
HE	High enriched (>20%)
Pu	Plutonium
U3	²³³ U
U5	²³⁵ U
(Th)	Mixed with thorium or in thorium as MEU3(Th) = medium enriched ²³³ U in thorium
(U)	Mixed with uranium or in uranium as Pu(U) = plutonium in uranium

Miscellaneous

X	Extended burnup
15%	Burnup to achieve 15% savings in U ₃ O ₈
30%	Burnup to achieve 30% savings in U ₃ O ₈
6	Semiannual refueling
B	Reactor is of backfit design
T1M	Type 1 module fuel (Shippingport Reactor)
SB	Seed blanket
HGC	High-gain converter
HT	Heterogeneous fuel
HM	Homogeneous fuel
S	Spiked fuel

Fuel Cost Economics

$D_{B,C,t}^T$	Tax deduction for depreciation at time t of investment $K_{B,C}$
$K_{B,C,t}$	Investment in cost item C for fuel batch B at time t
$P_{B,C}$	Levelized cost of item C in batch B
$Q_{B,t}$	Power produced in batch B at time t
X	Tax adjusted discount rate
X'	Exponential discount rate
r	Income tax rate
f_b	Fraction of capital from debt
f_e	Fraction of capital from equity
i_b	Interest on debt
i_e	Return on equity

Miscellaneous

LWR	Light-water reactor
C/HM	Carbon-to-heavy-metal ratio
HM	Heavy metal
MT	Metric tonne
SWU	Separation work unit
OT	Once-through

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